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Abstract

In this paper we explore the variety of monetary policy transmission channels in an agent-based macroeconomic model. We identify eight transmission channels and present a model based on Caiani et al. Caiani et al., 2016, extended with an inter-bank market. We then analyze model simulation results of interest rate shocks in terms of GDP and inflation for four of the transmission channels. We find these effects to be small, in line with the view that monetary policy is an weak tool to control inflation.

Keywords: Agent-based modelling, Stock Flow Consistent modelling, Monetary transmission, Inflation.

1 Introduction

The behavior of inflation is a mystery to central bankers, as Federal Reserve Chair Janet Yellen recently put it Yellen, 2017. One contributing reason may be the structure of the New Keynesian Dynamics Stochastic General Equilibrium (DSGE) models typically used in central bank to model inflation Blanchard, 2016, and dissatisfaction with their unrealistic assumptions is now widespread Caballero, 2010; Romer, 2016; Stiglitz, 2017. Blanchard Blanchard, 2016 calls for the economics profession to explore different model types.

Agent-based models (ABM) are one such alternative. Fagiolo and Roventini Fagiolo and Roventini, 2017 provide an overview of AB models which have been applied to study the effects of monetary policy. Monetary policy transmission is modelled in different ways across these models. For example, in Raberto et al. Raberto, Teglio, and Cincotti, 2008, Salle et al. Salle, Yıldızoğlu, and Sénégas, 2013, Salle Salle, 2015, Dosi et al. Dosi et al., 2015, and Popoyan et al. Popoyan, Napoletano, and Roventini, 2017 the central bank inflation target influences household inflation expectations, feeding into wage demands, costs, and output prices. Bouchaud et al. Bouchaud et al., 2017 follow the same approach; in addition, past inflation affects expectations. In Delli Gatti and Desiderio Delli Gatti and Desiderio, 2015, more fragile firms pay higher interest rates, leading to credit rationing. Furthermore, like in Gualdi et al. Gualdi et al., 2015, higher interest rates decrease the demand for credit. In many models central bank rates affect household consumption through wealth effects Gualdi et al., 2015; Salle, 2015, or changes in the propensity to consume Bouchaud et al., 2017.

Thus, different models implement different channels. In order to enhance the comparability of findings in the agent-based literature, we present a taxonomy of monetary policy transmission channels. We then simulate four transmission channels in a modified version of the Caiani et al. Caiani et al., 2016 benchmark model. We highlight a variety of behavioural and structural assumptions which affect outcomes in terms of GDP and inflation. Model outcomes are consistent with a relatively small efficacy of monetary policy in controlling inflation.

2 Transmission Channels

Monetary policy is usually interpreted as setting the central bank interest rate. In practice, this means changing two rates: one as a compensation for depositing reserves and another charged to counterparties who borrow reserves from the central bank. Together, these are known as the Standing Lending Facilities (SLF). Lee and Sarkar Lee and Sarkar, 2017 provide a detailed discussion and comparison for major central banks.

Typically, central banks change the interest rate based on an inflation target. The transmission of monetary policy refers to the process of interest rate changes working their way through the economy, ultimately to affect the rate of inflation Bank of Canada, 2012. There are several channels through which this transmission can occur.

First, in the expectations channel, private sector behaviour depends on the expected course of monetary policy, as well as on the current policy. Agents might change their behaviour as they anticipate the effects of monetary policy Bernanke, 2004. For example, inflation expectations might directly influence household consumption and firm pricing decisions. If households expect higher inflation in the future, they increase consumption now, increasing inflationary pressures. Or, if firms expect higher inflation in the future, they might increase their prices now. Figure 1 summarizes these effects.
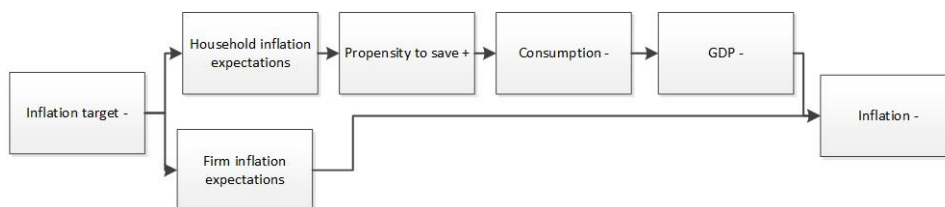

Figure 1: Expectations channel

Different from the expectations channel, the other transmission channels describe behavioural changes in response to changes in current interest rates. For these channels to work it is vital that SLF rate changes induce changes in other key interest rates in the economy. This is known in the literature as interest rate pass-through Von Borstel, Eickmeier, and Krippner, 2016.

If there is some pass-through, the literature identifies at least seven channels by which changes in policy rates affect inflation: a bank lending channel Disyatat, 2011, a balance sheet channel Bernanke and Gertler, 1989, an investment channel Mojon, Smets, and Vermeulen, 2002, an asset price channel Bernanke and Gertler, 1995, a consumption channel Lettau, Ludvigson, and Steindel, 2002, a cost channel Barth III and Ramey, 2002, and an exchange rate channel Svensson, 1999.

The bank lending and balance sheet channels, collectively known as the credit channel, describe how banks reduce credit supply after a policy rate hike. According to the bank lending channel, as banks' funding costs increase and their profitability falls, they reduce the quantity of credit they are willing to lend Disyatat, 2011. Through the balance sheet channel, an increase in interest rate lowers firms' future revenues, reducing the net worth of firms. In response, banks reduce the credit supply to these firms.

On the credit demand side, firms' desire to invest might decrease as a consequence of monetary policy tightening. The investment channel Mishkin,

1995 describes how higher bank lending rates discourage business investment by reducing the value of investment, and therefore the value of assets reflecting these investments. This asset price channel suggests that the resulting decrease in firms' net worth reduces investment demand by firms Mishkin, 1996.

In the consumption channel Mishkin, 1995, changes in interest rates might affect household consumption decisions through a wealth effect, as interest rates hikes affect asset values.Lettau, Ludvigson, and Steindel, 2002. Also, a rate increase makes it more worthwhile to save, decreasing the propensity to consume.

In addition, Barth and Ramey Barth III and Ramey, 2002 propose the existence of a cost channel in which changes in interest rates transmit to changes in funding costs for firms which then translate into higher output prices.

With the exception of the cost channel and the wealth effect in the consumption channel, in all of the channels described above, SLF policy rate increases are expected to reduce GDP relative to its potential level, thereby increasing the output gap "New Perspectives on Monetary Policy, Inflation, and the Business Cycle" and reducing inflationary pressures.

Figure 2 provides an overview of all interest rate channels and shows that the net effect of these channels combined is *not* clear *a priori*. the strenght of individual effects is unknown, effects may have opposite signs, and there may be interaction effects between different channels. For example, increased consumption through the consumption channel might amplify the balance sheet channel: it causes an increase in firm's net-worth.

This makes it challenging to open the 'black box' of conditions in which policy transmission does or does not occur Bernanke and Gertler, 1995. Nonetheless, we will attempt to take a peek inside the black box and simulate an interest rate hike in an agent-based model in which the consumption, investment, bank lending, and cost channel are active.

3   The Model

To analyse monetary policy transmission, we modify the Caiani et al. Caiani et al., 2016 benchmark model of a closed economy (i.e. without foreign or 'rest of world' sector).

We add the ability to shock the central bank SLF policy rates. To simulate interest rate pass-through, we add an inter-bank market in which banks operate between the central bank determined upper and lower limits. We also add and change several behavioural rules related to bank lending, interest rates, firm pricing, dividends, liquidity, and capital ratios. Finally, to distinguish more between short-term and long-term debt, we change the time-scale so that periods represent months instead of quarters, we updated
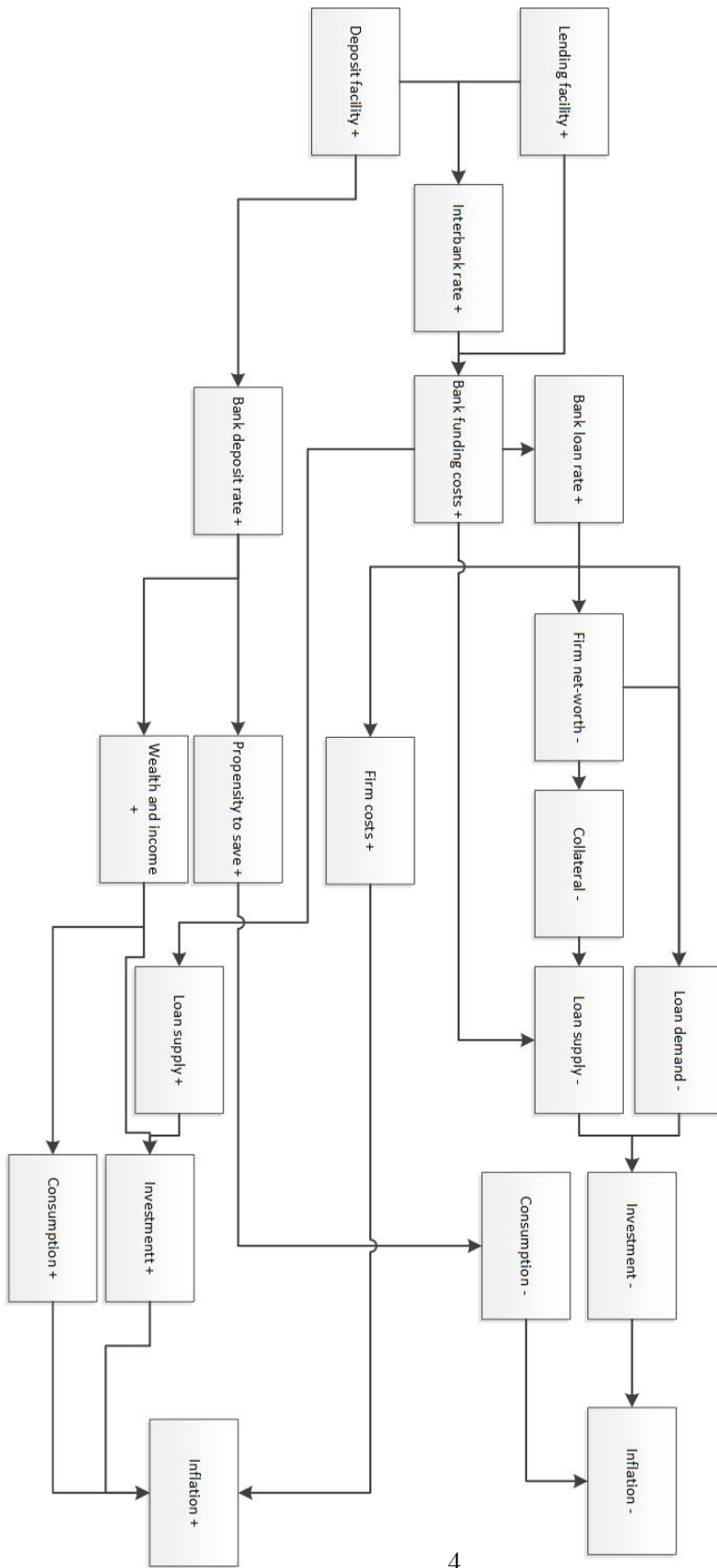
Figure 2: Domestic monetary policy transmission channels

interest rates accordingly. The updated model is able to simulate the bank lending channel, investment channel, consumption channel, and cost channel along with their interactions.

The balance sheet channel is not operational in the model because banks do not discount the value of collateral. The asset price channel does not exist because firm investment decisions are based on desired growth of output which in turn is based on real factors. Then, they try to finance investment with retained earnings before turning to loans. Therefore, a reduction in networth does not reduce investment demand. Finally, inflation expectations are formed adaptively, as a consequence of past inflation. Consequently, there is no expectations channel through which the central bank can influence agent expectations directly. We implement the model using the Java Macro Agent-Based (JMAB) package. [1]

3.1   Agents

There are six types of agents x: households hh, firms f (divided into consumption goods firms cf and capital goods firms kf), banks b, a central bank cb, and a government g. All agents have state variables which are represented by a matrix V_x. Table 3 (in the Appendix) provides an overview of the state variables V_x and their domains. In the notation of variables, subscripts indicate the agent and time step of the variable. Superscripts indicate if the variable or parameter refers to another variable, or is an expectation (e), demanded (d), supplied (s), or targeted (tr) variable.

3.2   Markets

All markets use a common matching protocol. This lets a demand agent observe a random subset of suppliers, the size of which is determined by parameter χ representing information asymmetry in that market. Demand agents pick the supplier who offers the best price; but if the demand agent has a previous supplier it sticks to this supplier with a probability of changing suppliers $(1 - \theta^{\Delta k})$,

$$\theta^{\Delta k} = \begin{cases} e^{\frac{\epsilon p_\chi p_k}{p_\chi}} & \text{if} \quad p_\chi > p_k \\ 0 & \text{otherwise} \end{cases}, \tag{1}$$

where ϵ represents the intensity of choice, p_χ the lowest observed supplier price, and p_k the price of the selected supplier. In case the preferred supplier has run out of inventory, the agent picks the supplier with the next best price. If the agent demand was filled or the supplier has run out of inventory, the protocol stops. In some markets, when the supplier has run out of inventory, the demand agent can select a new random supplier from the subset. Figure 3 below depicts the market matching protocol.

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[1] the source code for this model can be found at: https://github.com/S120/Interbank
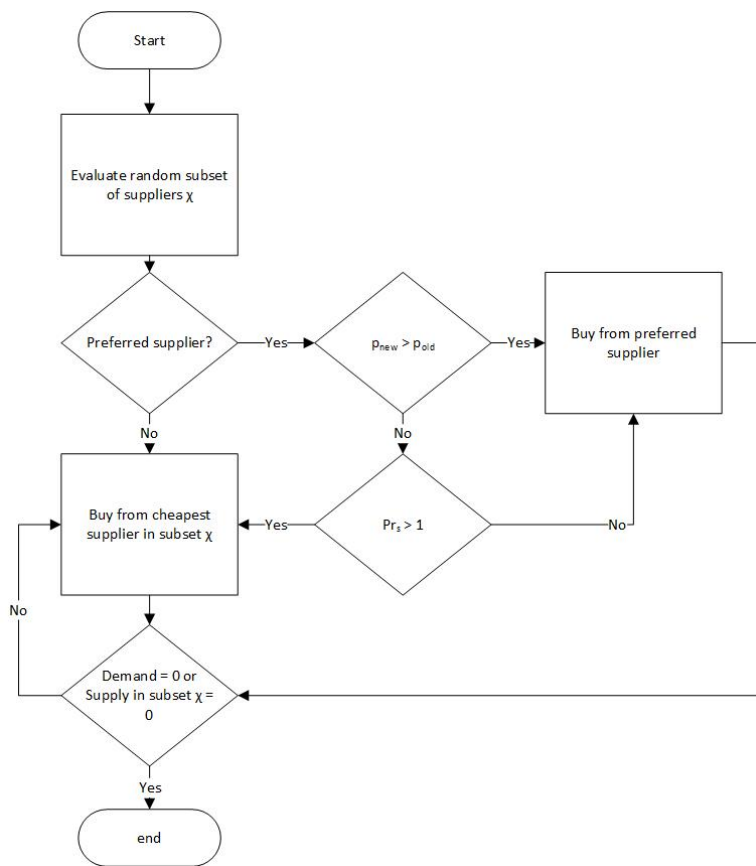
Figure 3: Market matching protocol

3.3 Simulation overview

We simulate agent actions and interactions over n periods. As a consequence of these actions and interactions, the state variables of the agents are immediately updated. Unless stated otherwise, agents are processed in a random order. Each period represents a month in which we simulate the following sequence of events:

1. expectation formation,

2. firms' output determination,

3. bad debts removal,

4. firms' price determination,

5. capital goods market - first interaction,

6. investment demand,

7. bank's internal interest rates,

8. deposit rates,

9. credit demand,

10. firms' labour demand,

11. credit market interactions,

12. labour supply,

13. government labour demand,

14. central bank policy,

15. labour market interactions,

16. firms' production,

17. consumption demand,

18. consumption goods market interaction,

19. capital goods market - second interaction,

20. tax rate determination

21. payments on obligations,

22. deposit market interactions,

23. defaults,

24. bond market - first interaction,

25. interbank market interactions,

26. central bank bond demand,

27. bond market - second interaction,

28. central bank lending facilities.

3.4 Simulation scheduling

In this section, we describe in detail the simulation algorithm for every period. Agents are boundedly rational Gigerenzer and Selten, 2002. They can observe their own state variables, the values of their state variables in the previous period, and some state variables of other agents. In their decision making, they follow simple heuristics based on limited information.

3.4.1 Expectation formation

At the start of every period, each agent computes expected values for state variables in V_x based on the simple adaptive rule:

$$V_{x,t}^e = V_{x,t-1}^e + \gamma(V_{x,t-1} - V_{x,t-1}^e), \qquad (2)$$

where γ is an adaptive parameter.

3.4.2 Firms' output determination

Firms compute an output target, $o_{f,t}^{tr}$, by subtracting current inventories $X = \{KG, CG\}$ (capital or consumption goods depending on firm type), from the inventories needed to satisfy expected sales, $y_{f,t}^e$, and a percentage inventory buffer, $G_{f,t}^{tr}$

$$o_{f,t}^{tr} = y_t^e(1 + G_{f,t}^{tr}) - X_t \quad \text{with} \quad X = \{KG, CG\}. \qquad (3)$$

3.4.3 Bad debts removal

In the next step, banks remove any loans from bankrupt debtors, $n_{b,t}^L$, from their balance sheets.

$$L_{b,t} = L_{b,t-1} - n_{b,t}^L. \qquad (4)$$

If the debtor is a consumption firm, the bank recovers collateral C by forcing its sale, from which it recovers the proceeds, $C = KG\iota_{cf}$. Since capital firms do not have collateral, the loss from their bad loans is fully

borne by banks, who try to diminish this through sale of the firm's physical capital to households.

3.4.4 Firms' price determination

To determine output prices $p_{f,t}$, firms often take into account costs as well as market conditions Alvarez and Hernando, 2005. Firms apply a mark-up $\Psi_{f,t}^{uc}$ over their expected unit labour costs $(uc_{f,t}^e)$ times the foreseen amount of labour $l_{f,t}^{tr}$, plus the interest payments over last period, all divided by the targeted output level.

$$p_{f,t} = \left(1 + \Psi_{f,t}^{uc}\right) \frac{uc_{f,t}^e l_{f,t}^{tr} + i_{f,t-1}^L L_{f,t}}{o_{xt}^t}. \tag{5}$$

Firms revise their mark-up adaptively depending on their inventory and capacity utilization, reflecting market conditions. If current inventory $G_{x,t-1}$, or production capacity o_{t-1} are below (above) targets $G_{f,t}^{tr}$, o_{t-1}^*, the mark-up is increased (decreased) by a stochastic amount FN,

$$\Psi_{x,t}^{ulc} = \begin{cases} \Psi_{x,t-1}^{ulc}\left(1 + FN\right) & \text{if} \quad \frac{CG_{x,t-1}}{y_{x,t-1}} \le G_{f,t}^{tr} \quad \text{or} \quad \frac{o_{t-1}}{o_{t-1}^*} \ge G_{f,t}^{tr} \\ \Psi_{x,t-1}^{ulc}\left(1 - FN\right) & \text{otherwise} \end{cases}, \tag{6}$$

where FN is a random number drawn from a folded normal distribution with parameters μ_{FN}, σ_{FN}^2.

3.4.5 Capital market - first interaction

Consumption firms try to find the cheapest capital supplier. They observe a subset of suppliers and then select the cheapest, following the market procedure presented in Figure 3.

3.4.6 Investment demand

Consumption firms now determine investment demand. They target a desired production capacity rate of growth $\kappa_{cf,t}^{tr}$ based on their target rate of capacity utilization $u_{c,t}^{tr}$ and the previous period rate of return on capital, $r_{c,t-1}$:

$$\kappa_{cf,t}^{tr} = \Omega_1 \frac{r_{cf,t-1} - \bar{r}}{\bar{r}} + \Omega_2 \frac{u_{cf,t}^{tr} - \bar{u}}{\bar{u}}. \tag{7}$$

Firms then derive demand for capital goods $kg_{c,t}^t r$ based on their target output growth, taking into account capital replacement. This results in their nominal investment demand $KG_{c,t}^d$ as the product of units of capital demanded and the price asked by the chosen supplier $p_{k,t}$.

$$KG_{c,t}^d = p_{k,t} kg_{c,t}^d. \tag{8}$$

9

3.4.7 Bank's internal interest rates

In the next step, banks determine their internal interest rate on loans, $i_{b,t}^L$. First, banks calculate their funding rate $fc_b = \overline{(i_b^A + i_b^{IB} + i_b^D)}$. To this rate they either add or subtract a stochastic amount FN. This depends on whether they meet their capital ratio target. Thus, well capitalized banks decrease their rate to attract more borrowers and vice versa.

$$i_{b,t}^L = \begin{cases} fc_{b,t}(1+FN) & \text{if} \quad CR_{b,t} < CR_{b,t}^{tr} \\ fc_{b,t}(1-FN) & \text{otherwise} \end{cases}, \tag{9}$$

where the capital ratio is calculated by dividing equity value by the value of assets, $CR = \frac{E}{R+B+L}$. Bank credit supply is limited only by demand, regulation, and bank's own rationing policy McLeay, Radia, and Thomas, 2014 as explained below.

3.4.8 Deposit rates

Banks try to attract deposits by setting deposit interest rates $i_{b,t}^D$ based on the values of their liquidity ratio, $LR = \frac{R}{D}$, funding costs, fc, and profitability, r:

$$\chi^{LR} = \begin{cases} 1 & \text{if} \quad \frac{(LR_t - LR_t^t)}{(LR_t^t)} \geq 0 \\ -1 & \text{otherwise} \end{cases};$$

$$\chi^{fc} = \begin{cases} 1 & \text{if} \quad \Delta fc_b \geq 0 \\ -1 & \text{otherwise} \end{cases};$$

$$\chi^{r} = \begin{cases} 1 & \text{if} \quad \Delta r_t \geq 0 \\ -1 & \text{otherwise} \end{cases}.$$

If the combined values are sufficiently small, a bank will attempt to attract deposits by increasing its interest rate by the stochastic term FN. Otherwise, it will decrease the rate.

$$i_{b,t}^D = \begin{cases} i_{b,t-1}^D(1+FN) & \text{if} \quad \chi^{LR} + \chi^r + \chi^{fu} \geq 0 \\ i_{b,t-1}^D(1-FN) & \text{otherwise} \end{cases}. \tag{10}$$

3.4.9 Credit demand

Then, firms compute their need for credit, $L_{f,t}^d$. They compute their expected expenditures as nominal desired investment, $I_{f,t}^{tr}$, plus the dividends they expect to distribute, $dv_{f,t}^e$, plus the labour use, $l_{f,t}lc_{f,t}$. Then, adhering to the pecking order theory, they try to fund investment using their operating cash flows and deposits $D_{f,t}$ first. Furthermore, firms try to keep an extra liquidity buffer for loan payments ζ^w. The remainder is asked on the credit markets.

$$L_{c,t}^d = \max\{I_{f,t}^d + dv_{f,t}^e + \zeta^w l_{f,t} lc_{f,t} - OCF_{f,t}^e - D_{f,t}, 0\}, \qquad (11)$$

where OCF represents operating cash flows after taxes. Computed as after-tax profits plus capital amortization costs, minus changes in inventories and debt repayments.

3.4.10 Labour demand

Firms hire workers. Capital goods firms calculate the output level they can achieve based on their capital stock, and then set labour hiring needs $\Delta l_{kf,t}^d$. If negative, some random workers are laid off until there are just enough to produce the target output.

$$\Delta l_{k,t}^d = \frac{o_{ck,t}^t}{\mu_l}, \qquad (12)$$

where μ_l is the productivity of labour.

Consumption firms review their desired capacity utilization, $u_{cf,t}$ and calculate their labour demand as

$$l_{cf,t}^d = u_{cf,t}^{tr} \frac{KG_{cf,t}}{\delta_k}, \qquad (13)$$

where δ_k is the constant capital labour ratio and $u_{cf,t}$ is the rate of capacity utilization needed to produce the target level of output $u_{cf,t} = \min\left(1, \frac{o_{cf,t}^{tr}}{\mu_k KG_{cf,t}}\right)$.

3.4.11 Credit market

Firms then enter the credit market and request a loan from the cheapest supplier. The bank responds by calculating expected profit r^e as the net present value of future cash flows minus the expected loss:

$$r^e = \sum_{n=1}^{m} \frac{ds(i)}{(1+i^L)^n} - \Delta L - (LGD * \theta^{df} * L), \qquad (14)$$

where $LGD = \frac{L-C}{L}$, is the loss given default, $ds = (i_{b,t}^L + \frac{1}{n})L_f$ is the debt service, and $\theta^{df} = \frac{1}{1+exp(\frac{OCF_{f,t}-\beta ds}{ds})}$ is the probability of default, where β is a parameter of risk-aversion. If expected profit is positive, banks grant the loan in full. Otherwise, the loan is denied.

3.4.12 Labour supply

Households which are unemployed for longer than their threshold, $m_{hh,t} > \phi^m$ update their desired wage $w_{hh,t}^{tr}$ by subtracting stochastic amount FN

from the last period's level. Employed households increase their asked wage by this stochastic amount,

$$w_{hh,t}^{tr} = \begin{cases} w_{hh,t-1}(1 - FN) & \text{if} \quad \sum_{n=1}^{4} m_{hh,t-n} > \phi^m \\ w_{hh,t-1}(1 + FN) & \text{otherwise} \end{cases} . \quad (15)$$

Additionally, every period a share of workers ζ^u, leave their current employer and look for a new job.

3.4.13 Government labour demand

The government is committed to hiring a constant number of households, l_g^d. Government labour demand is therefore equal to the labour turnover share ζ^u,

$$l_{g,t}^d = l_{g,t-1}\zeta^u. \quad (16)$$

3.4.14 Central bank policy

The supply of central bank advances is not limited or rationed. The central bank has a fixed lending facility rate $i_{cb,t}^R$. In periods t_{mon} in which monetary policy changes occur, the lending facility rate changes by an amount Ψ_{mon}.

$$i_{cb,t}^R = \begin{cases} i_{cb,t-1}^R + \Psi_{mon} & \text{if} \quad t = t_{mon} \\ i_{cb,t-1}^R & \text{otherwise} \end{cases} . \quad (17)$$

Much like the Bank of England Bank of England, 2012, it sets the rate on advances $i_{cb,t}^A$ as a mark-up, Ψ_{iR} over the official bank rate,

$$i_{cb,t}^A = i_{cb,t}^R + \Psi_{iR}. \quad (18)$$

The central bank also sets a countercyclical capital buffer based on the credit-to-GDP ratio European System Risk Board, 2014. In line with the Basel III capital requirements:

$$CR_t^{tr} = \begin{cases} CR_{t-1}^{tr} + \Psi_{pru} & \text{if} \quad \frac{L_t}{Y_t} > \phi^{pru} \\ CR_{t-1}^{tr} - \Psi_{pru} & \text{if} \quad \frac{L_t}{Y_t} < \phi^{pru} \\ CR_{t-1}^{tr} & \text{otherwise} \end{cases} , \quad (19)$$

where Y is nominal GDP. The central bank also aims to minimize systemic liquidity risk, defined as a situation in which banks' normal funding and refinancing channels fail European System Risk Board, 2014, prompting the central bank to act as lender of last resort. Therefore, it sets a countercyclical liquidity ratio target based on total private credit L_t to GDP.

$$LR_t^T = \begin{cases} LR_{t-1}^T + \Psi_{pru} & \text{if} \quad \frac{L_t}{Y_t} > \phi^{pru} \\ LR_{t-1}^T - \Psi_{pru} & \text{if} \quad \frac{L_t}{Y_t} < \phi^{pru} \\ LR_{t-1}^T & \text{otherwise} \end{cases} . \quad (20)$$

3.4.15 Labour market

Now potential employers and employees enter the labour market. Employers select the employee with the lowest wage demands, according to the market selection algorithm.

3.4.16 Production

Consumption firms produce consumption goods, using their most productive capital goods first. Since they already chose the amount of labour necessary for production, they produce using all available labour and capital.

$$\Delta CG_{cf,t} = \mu_l l_{cf,t} KG_{cf,t} \mu_k. \tag{21}$$

Capital firms produce according to:

$$\Delta KG_{kf,t} = \mu_l l_{kf,t}. \tag{22}$$

3.4.17 Consumption demand

Households set desired consumption $c_{hh,t}^d$ as a fixed share α^y of their expected net income plus a share α^q of their expected net wealth, $D_{hh,t} + CG_{hh,t}$. The propensity to consume out of wealth responds to interest rate changes $\alpha_t^q = \alpha_{t-1}^q + i_t - i_{t-1}$. Both income and wealth are adjusted for expected inflation $\Delta p_{cf,t}^{e,CG}$.

$$c_{hh,t}^d = \alpha^y \frac{y_{hh,t}^e}{\Delta p_{cf,t}^{e,CG}} + \alpha^q \frac{q_{hh,t}^e}{\Delta p_{cf,t}^{e,CG}}. \tag{23}$$

3.4.18 Consumption market

In the consumption market, consumers are matched to the cheapest consumption firm according to the common matching protocol.

3.4.19 Capital market - round 2

With the supplier fixed and credit obtained, consumption firms enter the capital market again to purchase their desired capital goods.

3.5 Tax rate determination

To limit the government debt to GDP ratio, the government updates its tax rate every period.

$$mp_t^{tr} = \begin{cases} mp_{t-1}^{tr} + adj_{pru} & \text{if} \quad \frac{B_t}{Y_t} > \phi^{pru} \\ mp_{t-1}^{tr} - adj_{pru} & \text{if} \quad \frac{B_t}{Y_t} < \phi^{pru} \\ mp_{t-1}^{tr} & \text{otherwise} \end{cases}, \tag{24}$$

3.5.1 Payment on obligations

Then, interactions take place as a consequence of equity, credit, deposits, and other contractual claims. There are several types of credit claims in the model. Banks have loan claims on firms, interbank claims on other banks, and they may own government bonds. The central bank may own government bonds and in addition might have lent reserves to deficit banks in the form of advances. Every period, these credit claims cause repayment and interest payments from debtors to creditors.

There are two types of transferable debt claims in the model. Banks and the government hold reserves at the central bank. Households and firms hold deposit accounts at banks. This leads to payments of interest on these claims. Furthermore, reserves and deposits are used to settle payments by the government; reserves are used for inter-bank payments; deposits are used to settle household and firm payments.

Finally, some debt claims are off-balance sheet but are implied by contracts. These are tax, social benefits, and wage claims. Households, banks and firms are all obliged to pay income taxes to the government; all employers (the government, firms and banks) are obliged to pay wages to their household employees. The government has an obligation to pay social security to unemployed households.

We now describe the payments due on every obligation, j, in every set of obligations, P. First, firms pay interests due on outstanding loans to banks, where each individual loans carries its own interest rate.

$$\Delta D_{f,t} = - \sum_{j \in P} i^L_{j,f,t} L_{j,f,t}. \tag{25}$$

Then, firms and the government pay wages to each household employee j, in its set of employees P.

$$\Delta D_{x,t} = - \sum_{j \in P} w_{j,x,t}. \tag{26}$$

The government pays unemployment benefits to unemployed workers at a fixed rate σ_m of average wage.

$$\Delta D_{x,t} = - \sum_{n \in P} \sigma_m \overline{w}. \tag{27}$$

The government pays interest i^B on its outstanding bonds:

$$\Delta D_{g,t} = \sum_{j \in P} i^B_{j,x,t} B_{j,x,t}. \tag{28}$$

The central bank pays interest over outstanding reserves:

$$\Delta R_{g,t} = \sum_{j \in P} i^R_{j,cb,t} R_{j,x,t}. \tag{29}$$

Banks pay interest to the central bank on outstanding advances,

$$\Delta R_{b,t} = -\sum_{j \in P} i^A_{cb,t} A_{j,b,t}, \tag{30}$$

and on inter-bank loans,

$$\Delta R_{b,t} = -\sum_{j \in P} i^{IB}_{j,b,t} IB_{j,b,t}. \tag{31}$$

Banks also pay interest to households and firms over their deposit liabilities, as the agreed interest rate $i^D_{b,t-1}$ times the deposit D_{xt-1}.

$$\Delta D_{b,t} = \sum_{j \in P} i^D_{j,b,t-1} D_{j,t-1}. \tag{32}$$

At the end of each period, the central banks calculates its profits $r_{cb,t}$ by subtracting the interest it pays on excess reserve deposits $i^R R_{b,t-1}$ from the interest receipts on government bonds $\bar{i}^B B_{t-1}$ and from advances $\bar{i}^A_{cb,t} A_{cb,t}$.

$$r_{cb,t} = \bar{i}^B B_{t-1} + \bar{i}^A_{cb,t} A_{cb,t} - i^R R_{b,t-1}. \tag{33}$$

After that, the central banks transfers its profit to the government.

$$\Delta R_{b,t} = r_{cb,t}. \tag{34}$$

Firms pay dividends to their capital suppliers by multiplying their after-tax profit with the dividend pay-out ratio:

$$\Delta D_{f,t} = \rho_x r_{f,t}. \tag{35}$$

They distribute these dividends among households proportionally to net wealth. Banks determine the amount of dividends they distribute based on their desired capital ratio,

$$\Delta D_{f,t} = \begin{cases} (1 + \alpha^\rho) \rho_b r & \text{if} \quad CR_{bt} > CR^T_t \\ \rho_b r_{b,t} & \text{otherwise} \end{cases}. \tag{36}$$

After that, firms pay taxes to the government by multiplying their profits by the tax rate.

$$\Delta D_{f,t} = \tau^r r. \tag{37}$$

Finally, households pay a flat tax rate τ^y over their wages $w_{hh,t}$, dividends $div_{hh,t}$ and interest received on deposits $i^D_{b,t-1} D_{hh,t-1}$,

$$\Delta D_{hh,t} = \tau_y \left(w_{hh,t} + dv_{hh,t} + i^D_{hh,t-1} D_{hh,t-1} \right). \tag{38}$$

3.5.2 Deposit market

In the next step, consumers switch banks if they observe a more favourable deposit rate than the one they receive from their current bank.

3.5.3 Bankruptcies

If, at any point, a firm's or a bank's assets minus its liabilities are below zero, it enters a state of default,

$$df_{f,t} = \begin{cases} True & \text{if} \quad D_f + CG_f + KG_f - L_f < 0 \\ False & \text{otherwise} \end{cases}, \qquad (39)$$

$$df_b = \begin{cases} True & \text{if} \quad R_b + IB_b + L_b + B_b - D_b - A_b < 0 \\ False & , \quad \text{otherwise} \end{cases}. \qquad (40)$$

If in default, firms and banks are bailed in by their household owners and their depositors, see Caiani et al. Caiani et al., 2016 for an extended description of this process. This happens so that the total number of firms and banks remains constant.

3.5.4 Bond supply

The government calculates its deficit as tax revenues plus central bank profits, minus wages, unemployment benefits and interest on bonds. To cover the deficit, it issues bonds to the amount ΔB_t at a fixed price p^B.

$$\Delta B_{g,t}^s = \frac{tx_{g,t} + r_{cb,t} - \sum_{j \in l_{g,t}} wl_j - um_t d_t - i^b B_{t-1}}{p^B}. \qquad (41)$$

3.5.5 Bond market

Banks try to buy government bonds with their excess reserves.

$$B_{b,t}^d = \begin{cases} LR_{b,t} - LR_{b,t}^t & \text{if} \quad LR_{b,t} < LR_{b,t}^t \\ 0 & , \quad \text{otherwise} \end{cases}. \qquad (42)$$

3.5.6 Inter-bank market

After that, if a bank still has excess reserves, it determines its demand for reserves, or supply of inter-bank loans, on the inter-bank market as the difference between reserve requirement $R_{bt}^d = D_{bt} LR_{b,t}^d$ and current reserves $R_b t$:

$$IB_{bt}^s = \left(LR_{bt} - LR_{bt}^d \right) D_{bt}. \qquad (43)$$

Subsequently, reserve-supplying banks adjust their mark up on the price of reserves. This mark-up is the difference between their average generic interest rate $\bar{i}^l_{b,t}L$ and the risk free reserves rate i^R_{bt}, divided by the maturity of credit η^L:

$$i^{IB}_{bt} = \frac{\bar{i}^L_{b,t} - i^R_{b,t}}{\bar{X}i^L},\tag{44}$$

Reserve–supplying and reserve–demanding banks are then matched on the interbank market according to the general matching protocol.

3.5.7 Government bond market -second interaction

Any bonds which were not purchased by private banks will then be purchased by the central bank, so that central bank demand for bonds will be equal to any government bond supply left:

$$\Delta B_{cb,t} = B^s_{g,t}.\tag{45}$$

3.5.8 Central bank lending facilities

Finally, if banks cannot obtain enough reserves on the inter-bank market, they borrow the remainder from the central bank as advances. The central bank always supplies the amount asked.

$$A^d_{b,t} = \left(LR_{b,t} - LR^d_{b,t}\right) D_{b,t}\tag{46}$$

3.6 Initialization

We initialze the model with 4,000 households, 100 consumption firms, 20 capital firms, 10 banks, a single central bank, and a single government. We apply the six–step strategy for initializing the model described in Caiani et al. (2016) Caiani et al., 2016. For model consistency, it is important that for all agents, assets equal liabilities plus net worth. We determine initial values of all parameters and state variables consistent with an aggregate stock-flow consistent model in a steady state. Next, we distribute the aggregated variables homogeneously and symmetrically across agents. We create for the first period a 'memory' of fictitious past sales, past wages, past profits and so on, as the basis for backward–looking expectations. We also define a historical structure. That is, we assume that in the periods before the simulation starts, firms obtained loans and consumption firms invested in new capital to maintain their productive capacity.

We further assume that the real value (i.e. corrected for inflation) of the new loans or of the new capital goods was constant in each of these periods. Based on a constant inflation rate and an amortization schedules for capital

goods and loans, we derive the outstanding value for each of these stocks, so that their total value sums up to the amount determined in the previous step. Using this set-up, no agent starts the simulation with an advantage over other agents. Initial values are reported in Table 2 in the appendix.

4 Results

To control for stochastic effects introduced in several equations and during the market matching mechanism, we run fifty Monte Carlo simulations of the baseline model.

4.1 Model dynamics

Starting from completely homogeneous initial conditions the models starts to evolve to a more heterogeneous distribution of firms, banks and households. The model does not converge to an equilibrium state in which all competing influences are exactly balanced. Even though it is pretty stable, the simulated economy fits the description of Arthur Arthur, 2013 and is always in a state of flux, constantly evolving and changing.

4.1.1 Business cycles

Figure 4 shows that real GDP is relatively stable. The model generates endogenous business cycles which are characterized by pro-cyclical consumption and investment, see Figure 8 for a comparison of these properties to U.S. data. Following Eq. 8, consumption firms investment demand is driven by their desired rate of capacity growth, which in turn is driven by returns on capital and the current rate of capacity utilization. If consumption firms are not denied credit by banks, they will buy machines from capital firms. Investment by consumption firms drives down unemployment, both as consumption firms hire employees to work the machines and as capital firms hire employees to produce machines.

However, rising wages do not always translate into rising consumption. The trend in consumption is largely mirrored by the trend in net-income. Net-income is the sum of wage, dole, dividend, and interest income minus taxes. As households are both workers and capital owners, wages may rise at the expense of dividend income, balancing changes in net-income.

Figure 4 (top-left panel) shows that unemployment fluctuates between 0% and 12% on average. It might happen that, the economy temporarily reaches full employment. Such periods of full-employment are accompanied by stable consumption levels. Full employment puts a cap on the investment boom. Firms cannot expand production any further as they cannot hire new employees. At that point, any negative development in bank lending

behaviour, firm profitability, or reversal of fortunes for investment driving firms might usher in a decrease in investment.
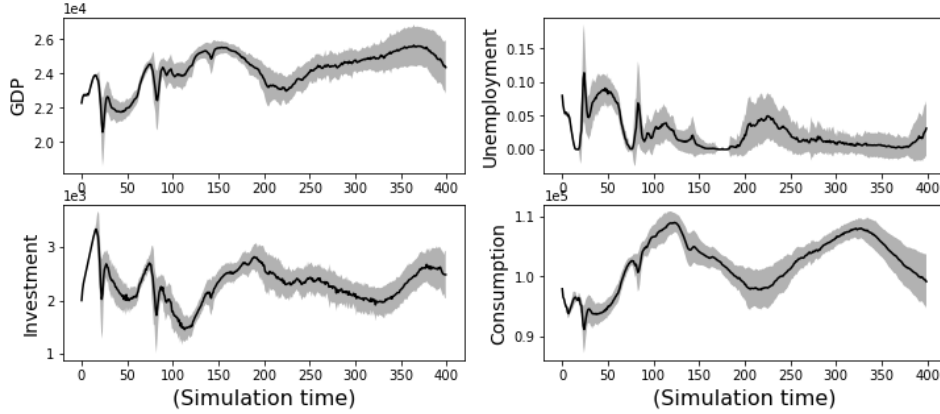

Figure 4: Monte Carlo average and standard deviation of: (top-left) real GDP, (top-right) unemployment, (bottom-left) real investment, and (bottom-right) real consumption.

Once that happens, falling investment leads to falling sales for capital firms and a couple them go bankrupt. This causes a reduction in household wealth and dividend income which in turn leads to falling consumption. Falling operating cash flows lead to a further reduction in investment demand and unemployment starts to rise.

Eventually investment downturns do turn around. Here heterogeneity plays a crucial role. While average capacity and return on capital decreases some firms continue to do well. These firms keep investing in a downturn. As weak firms de-investment is constrained at the depreciation rate of capital, the investment of strong firms might overtake the de-investment of the majority of smaller firms at a certain point. When this happens, the cycle reverses.

4.1.2 Consumer price inflation

During the simulation the evolution of consumer prices switches twice from deflation to inflation.

To understand inflation dynamics, we start by inspecting the pricing behaviour of consumption firms. Eq. 5 shows that pricing behaviour is determined by cost prices and an inventory based mark-up (Eq. 6). The costs price term depends on several factors: labour costs and debt-service costs over desired output. At any point in time inflation is driven by the combination of these two factors.

During the first phase, prices generally fall. To understand the initial deflation, we inspect changes in firm-mark ups -mark-up inflation- and cost

prices -cost price inflation. The fall in cost prices is largely driven by a drop in debt-service levels, as real investment is largely funded by retained earnings. With low unemployment, wages increase across the board.

Then, while deflation is stable, its drivers change. Falling real sales cause profits to decrease. This forces firms to borrow more to invest, increasing debt service costs. Along with continued wage increases, firms cost price increases. At the same time, falling real sales and expanding capacity cause firms mark-ups to decrease, causing overall prices to continue to fall.

As profitability and capacity utilization shrink, firms invest less. Near the end of the first deflationary phase, this dampens mark-up deflation until it eventually flips to mark-up inflation. This ushers in the start of an inflationary phase.

As real desired consumption is significantly above output capacity, firms increase their mark-up. As firms are profitable and operate above desired capacity utilization, they start investing heavily, steadily increasing debt service costs. At the same time, unemployment is low and wages are increasing steadily.

A tipping point in mark-up inflation occurs as the economy hits full employment, slowing demand growth. The increase in debt-service costs as a result of increased investment keeps overall inflation high for a while.

This persistent inflation decreases real demand. As demand drops, sales and investment follow. This then affects the two primary inflation drivers. Cost prices start to decline along with debt service and, as firms start producing under desired capacity levels, mark-ups start falling as well, ushering in another deflationary phase.

In this phase, mark-up deflation is the primary driver of consumer price deflation. Even as demand starts to recover, firm capacity utilization is consistently below target. General price deflation is a consequence of mark-up deflation. Cost prices increase during this period. Cost price inflation is somewhat more stable with a constantly increasing wage bill as its primary driver. Along with the wage bill, nominal consumption and sales also increase.

Finally, the model enters a new inflationary phase. Both mark-up and cost price inflation pick up and contribute roughly the same to overall inflation. In this phase, the behaviour of mark-up inflation is quite different from the first inflationary phase. Firms are still substantially below capacity. However, as real sales slowly increase, firms increase output, leaving inventories very small. As a result, firms start investing more. Over the course of this phase, while nominal consumption is still rising due to fast rising consumer prices, real consumption starts dropping. Output follows and so does the need for further investment. As investment drops, firms start firing employees. Figure 5 shows the the changes in mark-up and cost-price components along with inflation in each phase.
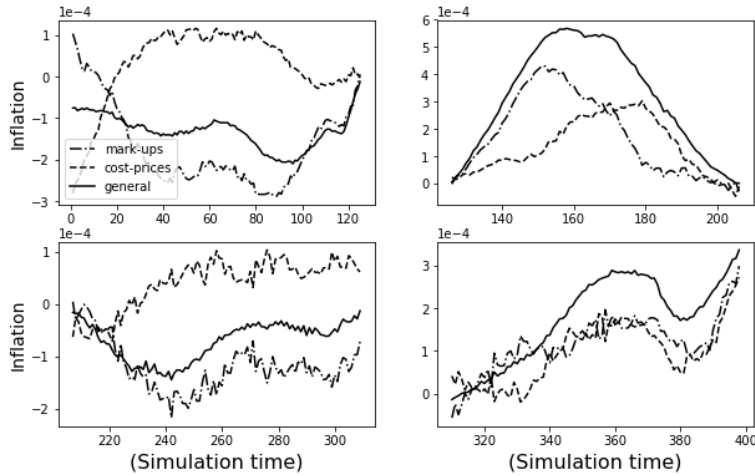
Figure 5: Changes in consumer prices, and its components: (top-left) phase 1, (top-right) phase 2, (bottom-left) phase 3, and (bottom-right) phase 4.

4.1.3 The labour market

Household wages are largely determined by the amount asked by households following Eq. 15. Because, unemployment is always relatively low, nominal wages increase over the simulation.

4.1.4 Financial markets

Loan interest rates generally increase over the course of the simulation because capital ratios are consistently below target until they stabilize when bank profitability rises as a consequence of increased interest rates. When capital ratios are above target, banks no longer try to raise their prices to increase capital. As a result, loan rates stabilize. Furthermore, deposit rates are generally stable until funding costs of banks start to fall. The interbank rate converges to the loan rate mark-up when liquidity ratios are consistently above target. Finally, following Eq. 14, banks ration credit quite consistently throughout the simulation. As expected, upturns in credit rationing largely coincide with upturns in investment demand. The beginning of the simulation stands out though, when capital firms do not yet have sufficient operating cash flows and are thus disproportionally denied credit.

4.1.5 Balance sheets

Figure 7 shows how aggregate sector stocks evolve over the course of the simulation. We observe wealth accumulation by households and, to a lesser extend, capital firms. The flip side is government debt accumulation. Interbank loans are not visible in this overview as they net out on the banking
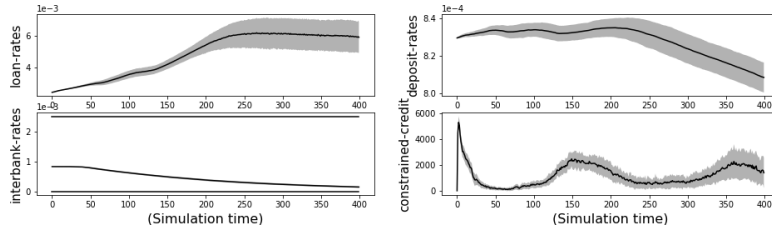
Figure 6: Average and standard deviation of: (left) loan rates, (middle) deposit rates, and (right) interbank rates and the SLF corridor.

sector balance sheet. Furthermore, while loans are important to firms, they are dwarfed by the amount of bonds and reserves which banks hold.
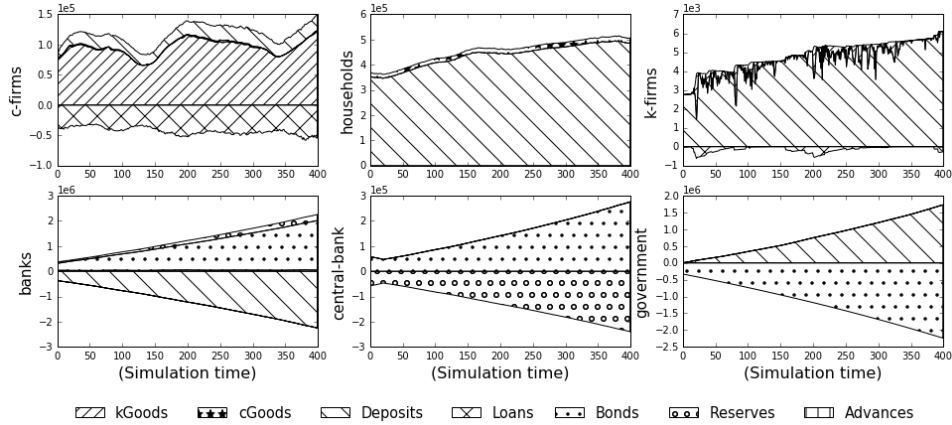
Figure 7: Sectoral balance sheet compositions of (1) consumption firms, (2) households, (3) capital firms, (4) banks, (5) the central bank, and (6) the government.

4.2   Validation

As the purpose of our model is mainly to illustrate the workings of four monetary transmission channels in an agent-based model, we do not perform a full scale validation exercise.

We do compare autocorrelation and cross-correlation properties of simulated time series for real-GDP, real investment, real consumption and unemployment with those of the United States. In spite of the model not being calibrated to fit this data, the model is able to replicate these properties reasonably well, similar[2] to the benchmark model Caiani et al., 2016.

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[2]the main differences come from the timescale change.

From The Federal Reserve Economic Data (FRED) database, we retrieve data for unemployment, real GDP, real consumption, and real investment. Like the artificial time-series, the observed data covers a period of 33 years (approximately 400 months). Since the observed data is quarterly, we transform our simulated data series to a quarterly time-scale first. Then, we apply a HP Hodrick and Prescott, 1997 filter to separate the cyclical and trend components for both the actual and simulated data series. Following Caiani et al. (2016) Caiani et al., 2016, we compare the moments for the cyclical component of the time series.

Figure 8 shows the simulated and observed auto-correlations and cross-correlations of the cyclical series with real-GDP. The auto-correlation structure of simulated and observed times series both have strong first order autocorrelations. Furthermore, as in the real-world data, simulated consumption and investment are pro-cyclical while unemployment is counter-cyclical. These dynamics are robust across multiple Monte-Carlo simulations.
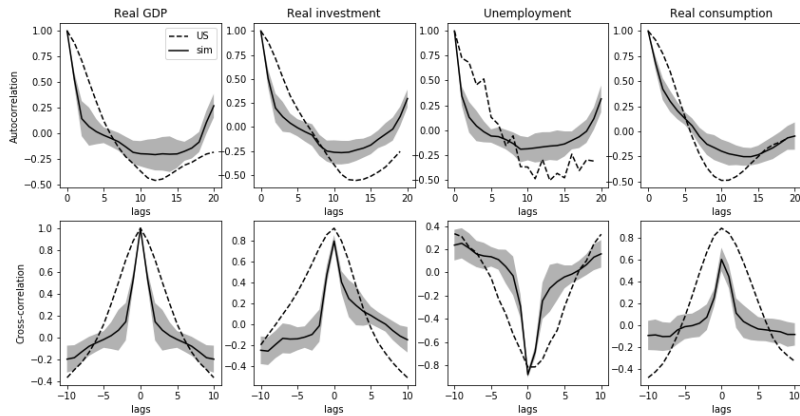
Figure 8: Auto- and cross correlations of (from left to right) real GDP, real investment, unemployment, and real consumption for U.S. and simulated data (Monte Carlo average and standard deviations).

4.3 Monetary transmission

We run several experiments to probe the effects of a monetary policy rate hike on key variables. We are interested in variables from interest-rate pass-through, the bank lending channel L^s, the investment channel I^D, consumption channel C_{hh}^D, the cost channel $i^L L$, and finally inflation p_{CG}.

At different points in time, we apply a change to the deposit facility rate, and with it the marginal lending facility rate (see Eq. 18) at different shock sizes. Combining these, we perform sixteen unique experiments. For every

experiment, we run fifteen Monte Carlo simulations.

Table 1 shows the Monte Carlo average effect of each rate hike, Ψ_{mon}, at times t_{mon}, on each variable, averaged over 40 periods after the shock. Using a two-sided t-test, we measure if the Monte-Carlo Average over these period was significantly (at 5 percent significance level) different from the baseline, marked with a $*$ in the table.

4.3.1   Interest rate pass-through

The monetary transmission mechanism starts when the monetary policy shock influences the interbank market, see Figure 9 for an impression of how this works. Following Eq. 44, banks determine their interbank ask price i_b^{IB} as the difference between the rate they charge on loans and the risk free rate corrected for maturity. The central bank rate hike increases banks' funding costs through the interbank market by increasing the cost of advances. As the risk free rate rises, interbank rates follow. Table 1 shows the impact of all shocks on interbank rates is positive and significant.
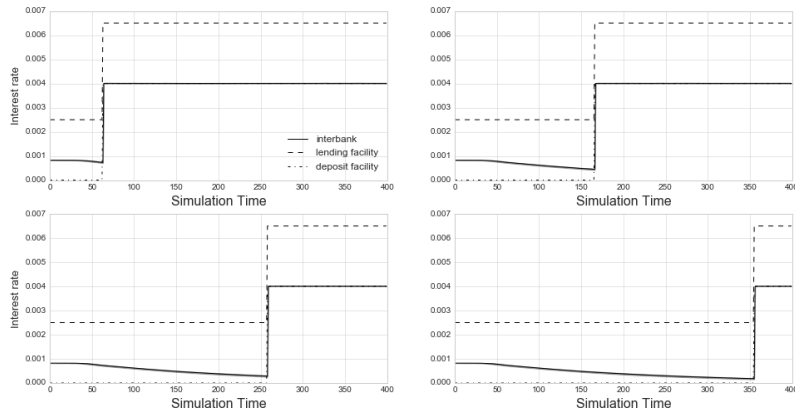
Figure 9: Monte Carlo average and standard deviations inter-bank rates in the standing lending facility corridor with shock Ψ_{mon}^4, for t_{mon}^1 (top-left), t_{mon}^2 (top-right), t_{mon}^3 (bottom-left), and t_{mon}^4 (bottom-right).

Banks set deposit rates according to Eq. 10, increasing or decreasing their rates based on profitability, χ^p, liquidity, χ^{LR}, and funding costs, χ^{fu}. Of these, only funding costs are directly affected. These increase, especially for those banks who derive a large part of their funding from advances or interbank loans. Yet, as in our simulation, banks do not rely heavily on either. Pass through is limited. Furthermore, as the interest rate affects profitability and liquidity through other variables, pass-through to deposit rates is uncertain, sometimes positive, sometimes negative, mostly insignificant.

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		t^1_{mon}	t^2_{mon}	t^3_{mon}	t^4_{mon}
i^{IB}_b	Ψ^1_{mon}	0.49*	1.42*	2.76*	5.01*
	Ψ^2_{mon}	1.95*	3.81*	6.49*	11.00*
	Ψ^3_{mon}	3.42*	6.21*	10.23*	16.99*
	Ψ^4_{mon}	4.88*	8.60*	13.96*	22.98*
i^D_b	Ψ^1_{mon}	0.00	-0.00 0.0001*	0.00	0.00
	Ψ^2_{mon}	0.00	-	0.00	0.00
	Ψ^3_{mon}	0.00	-0.0001*	0.00	0.00
	Ψ^4_{mon}	0.0001*	0.00	0.00	0.0001*
i^L_b	Ψ^1_{mon}	0.00	0.00	0.00	0.00
	Ψ^2_{mon}	0.00	0.00	0.00	0.00
	Ψ^3_{mon}	-0.04*	0.00	0.00	0.00
	Ψ^4_{mon}	0.13*	0.00	0.00	0.00
L^s	Ψ^1_{mon}	0.20	0.00	0.31	-0.02
	Ψ^2_{mon}	0.48*	0.00	0.53*	-0.01
	Ψ^3_{mon}	14.15*	0.00	0.54*	0.04
	Ψ^4_{mon}	43.49*	0.00	0.87*	0.03
I^D	Ψ^1_{mon}	0.04	0.03	0.02*	0.03
	Ψ^2_{mon}	0.06	0.03	0.03	0.03
	Ψ^3_{mon}	0.16*	0.04*	0.05	0.03
	Ψ^4_{mon}	0.45*	0.07	0.05	0.04*
C^D_{hh}	Ψ^1_{mon}	0.00	0.00	0.00	0.00
	Ψ^2_{mon}	0.00	-0.01*	0.00	0.00
	Ψ^3_{mon}	-0.01*	-0.002*	0.00	0.00
	Ψ^4_{mon}	0.02*	0.003*	0.002*	0.00
$i^L L$	Ψ^1_{mon}	0.00	0.00	0.00	0.00
	Ψ^2_{mon}	0.00	-0.02*	-0.01*	-0.01*
	Ψ^3_{mon}	-0.18*	-0.03*	-0.03*	-0.03*
	Ψ^4_{mon}	0.65*	0.08*	0.04*	0.04*
p_{CG}	Ψ^1_{mon}	0.00	0.00	0.00	0.00
	Ψ^2_{mon}	0.00	0.00	0.00	0.00
	Ψ^3_{mon}	0.00	0.00	0.00	0.00
	Ψ^4_{mon}	0.01*	0.00	0.00	0.00

Table 1: Average 40 period impact of monetary policy rate hikes on selected variables, at different points in time, * notes a significant (0.05) deviation from the baseline. We apply shocks of size: $\Psi^{1,2,3,4}_{mon} = 0.001, 0.002, 0.003, 0.004$; at times: $t^{1,2,3,4}_{mon} = 63, 166, 258, 355$

Regarding loan rates, banks follow Eq. 9 and respond to changes in their funding costs and capital ratio relative to their targeted capital ratio. As

funding costs increase, loan rates increase. However, interbank and advances rates are only a small part of the total funding cost mix for banks. Deposits are a much more important source of funding. The effects of the rate hike on the difference between actual and target capital ratios is not straightforward. Therefore, similar to deposit rates, pass-through to loan rates is limited and uncertain.

4.3.2 The bank lending channel

The bank lending channel describes how monetary policy affects the credit supply. Following Eq. 14, banks only extend credit if they believe the expected return is bigger than the expected loss. The central bank rate hike influences the expected return, since cash flows are now discounted at a higher rate. Therefore, if the bank interest rate is increased above a threshold after which it is no longer profitable to lend, banks constrain credit. The effect is especially non-linear if firms have similar cash flows and collateral values. Indirectly, the rate hike also influences the interest rates on loans and therefore the debt service and the value of collateral. However, since interest-rate pass through is weak, this effect is similarly weak.

Therefore, in our simulations, monetary policy is only effective when firms are relatively homogeneous, at t_{mon}^1, and when the hike is big enough, at Ψ_{mon}^3 or Ψ_{mon}^4. The rate hike increases banks discount factor, making it so that from one moment to the next most firm credit applications are negatively valued. In other simulations, these thresholds are not crossed and as a result constrained credit is not significantly different from the baseline simulation.

4.3.3 The investment channel

In our model, firm investment decisions are motivated by real factors. Following Eq. 7, firms determine a desired rate of growth based on expected profit and capacity utilization. Both are indirectly affected by interest changes. Following Eq. 11, firms try to finance their investment first with equity. All terms in this equation are indirectly affected by the changes in deposit and loan interest rates. Furthermore, weak bank rate pass-through reduces the potency of the investment channel.

Table 1 shows that the effects of monetary policy on desired investment is not clear cut. In the case of an early rate hike, investment demand actually increases for high rate hikes. This happens because credit is constrained in this scenario. Denied credit applications leave the firms demanding credit.

4.3.4 The consumption channel

In the model, monetary policy influences households desired consumption directly by changing the propensity to consume out of wealth, and the ab-

solute value of wealth and income (Eq. 23).

If interest-rate pass-through to deposits was positive: higher interest rates on deposits would make consumption less attractive relative to saving. On the other hand, increased interest rates receipts on deposit holdings would increase household income and wealth. Note that, since there is no household lending in the model, this effect is always positive. These sub-mechanisms have opposite signs. A change in interest payments on deposits causes increased income and increased consumption while at the same time increasing the willingness to hold deposits rather than spending on consumption.

Further, the effect of expected inflation depends on actual inflation, which in turn depends on the strength of all transmission channels. The strength and sign of the effect of the rate hike thus depends on the change in propensity to consume, the importance of interest rate income for households and the total effect on inflation. The net effect is typically very small since interest payments compared to other income are so small. Table 1 shows the effects of monetary policy on desired real consumption which are typically small and indirect. Notably, the early rate hikes do impact desired consumption significantly but primarily as the sudden credit crunch causes an early downturn in the business cycle.

4.3.5 The cost channel

In our model, the cost channel operates as firms follow Eq. 5. Firms prices are a mark-up of unit labour and interest rate costs. Changes in interest rates charged by banks result in changes interest payments for firms. However, as pass-through is weak this effects is also weak. Conflicting mechanisms are at work, since credit is rationed at higher interest rates, higher rates lead to reduced debt-service costs for firms. Even if banks would pass-through increased interest rates, overall costs would fall. The strength of the cost channel thus depends greatly on the size of interest costs compared to other costs, the amount of credit rationed through the bank lending channel, and the other interaction effects. Table 1, therefore, shows that increased interest rates on average reduce firm's debt-service costs.

4.3.6 Inflation

We now analyse the effects of the shock on inflation. Table 1 shows that monetary policy rate hikes can cause higher, lower or virtually unchanged consumer prices, depending on the circumstances. Because of the various simultaneous interaction effects, it is difficult to determine the effects on inflation in most experiments. However, as interest-rate pass through is very weak, monetary policy has no significant effect on consumer prices.

5 Summary and Discussion

In this paper, we reviewed several policy transmission channels for monetary policy. Based on existing literature, we identified eight channels. An expectations channel, which operates purely through agent expectations, and seven interest rate based channels: the bank lending, balance sheet, investment, asset-price, consumption, cost, and exchange rate channels. For these last six channels, we argued that the amount of interest rate pass-through is of importance.

To illustrate how several transmission channels can interact in an agent-based model, we presented a modified version of the Caiani et al. (2016) Caiani et al., 2016 benchmark model which includes an interbank market and four transmission channels: the bank lending channel, investment channel, consumption channel, and the cost channel. Using this model, we simulated the transmission of an interest rate shock through these channels.

The bank lending model is the strongest channel in our model as a consequence of the structural and behavioural assumptions we made. Regarding our structural assumptions, the balance sheet and asset price channels are not modelled since the lack of a stock market makes it difficult to calculate the market value of a firms equity. Similarly, the consumption channel is weak because there are no asset markets that can be inflated to boost consumption and there is no household lending. The investment channel is weak because we assume that firm investment decisions are primarily driven by non-interest rate factors and the bank lending channel is strong because we assume banks make net-present value type calculations when rationing credit.

In our model, monetary policy is not very effective. Several consequences of a monetary policy shock stand out. First, the bank lending channel appears the strongest. Second, monetary policy effects are non-linear. Monetary policy non-linearity in our model comes from agent heterogeneity and macroeconomic feedback effects. In the bank lending channel, the lack of agent heterogeneity causes non-linearity. Once the interest rate reaches a certain threshold the majority of firm credit applications will not be funded.

This is also a contributing factor to the relevance of timing for policy effects. As firm heterogeneity increases the effects of larger monetary policy shocks get less extreme. Also contributing to this is that price changes have different drivers over the course of the simulation. Inflation is driven by slack in the consumer goods market –via the mark-up– or by slack in the labour market -via the labour costs– or by changes in debt-service costs. These are not equally affected by changes in monetary policy rates. Furthermore, while the simulated economy shows some resilience to small shocks, large shocks can change its macroeconomic dynamics significantly.

When monetary policy does not cause a credit crunch through the bank lending channel, we find that the effects of monetary policy are weak. This

is consistent with the view that monetary policy is not an effective tool to control inflation Arestis and Sawyer, 1998; Arestis and Sawyer, 2008.

Yet, we are cautious to translate these findings to policy advice, as our model might not be an accurate representation of the real world. Notably, it is lacking an asset market. Furthermore, there is no foreign sector which nullifies the exchange rate channel. Finally, this model has not been extensively validated.

In the agent-based modelling literature validation is still an open issue Lamperti, 2017b. Validation can be split in two parts, output validation and structural validation Manson, 2002. Structural validation concerns how well agent-based model represents the conceptual model of the real-world system. Output validation concerns how well the model output represents output of the real-world. As discussed in the previous section, we believe this model has most structural features of a monetary economy barring an asset market and a foreign sector.

Regarding output validation, a consensus seems to be that policy oriented agent-based models should at least be able to replicate a number of stylized facts that characterize the relevant subject area. Ideally, the model should be able to reproduce multiple stylized facts at both the macro and micro level Axtell and Epstein, 1994.

One drawback of this focus on different stylized facts is that it is hard to compare models. Therefore, Lamperti (2017) Lamperti, 2017a suggest another approach to directly compare to the degree of similarity between the dynamics observed in the data and those generated by the different models based.

Furthermore, Guerini and Moneta (2017) Guerini and Moneta, 2017 note, models that incorporate different causal structures may replicate the same stylized facts. They therefore propose a method to focus only on representing causal structures among aggregate variables of the ABM and test whether they significantly differ from the causal structures that can be found in the real-world from observed aggregate variables. As the purpose of our model is to explore the monetary transmission mechanisms, we do not subject it to a these validation exercises.

That being said, we do constrast our findings with those of contemporary agent-based monetary models. We see that they reach widely diverging conclusions. Models which assume a strong direct monetary policy transmission through the expectations channel come to the conclusion that the monetary policy rule has a strong effect on inflation Raberto, Teglio, and Cincotti, 2008 Salle, Yıldızoğlu, and Sénégas, 2013, Salle, 2015, Dosi et al., 2015, Popoyan, Napoletano, and Roventini, 2017.

In contrast to experiments Delli Gatti et al. Delli Gatti et al., 2011 performed, Delli Gatti and Desiderio Delli Gatti and Desiderio, 2015 find a clear non-neutrality of monetary policy once they include an investment channel: firm credit demand is decreasing step-wise with the interest rate.

Finally, in the model of Bouchaud et al. Bouchaud et al., 2017 a high number of transmission channels are active. First is the expectations channel, which assumes that individual expectations are formed using both the central bank target and actually realised inflation. Through this channel the central bank inflation target and its credibility directly influence household consumption and firm pricing decisions. Furthermore, firms hiring and firing decisions are influenced by the interest rate through financial fragility, which increases if interest rates rise. Since both models assume interest pass-through is one-to-one, monetary policy has a major impact on the modeled economies.

If, we compare these conclusions to our own conclusions it becomes apparent that the transmission channels that we chose to model have a major influence on model conclusions about the effectiveness of monetary policy. Therefore, we believe it is important modelers take into account empirical work on the potency of different channels. After all, channels long taken for granted might not always hold. We refer to interesting work on the ability of central banks to anchor inflation expectations Mankiw, Reis, and Wolfers, 2003; Kumar et al., 2015 and on interest rate pass-through which is typically less than one-to-one Kleimeier and Sander, 2006.

In future work, besides adding more empirically grounded channels, we want to validate the model, presented here, in more detail. First, we want our model to be able to reproduce empirical regularities on different time scales. Furthermore, we would like to asses if the model to be able to reproduce causal structures among aggregate variables similar to the causal structures that can be found in the real-world.

Other options for future work include following clusters of firms, bank and households through simulation time, observing how their balance sheets and activities change due to the Central Bank rate shock, and due to their interactions with other agents. This heterogeneity in response is key to understanding aggregate impacts, as Yellen (2016) Yellen, 2016 stressed.

Other promising avenues are to observe the effects of negative rate shocks and even negative interest rates at different points in time. Furthermore, we believe extending the economy with an asset market and household debt would uncover other important channels. Yet another extension of the analysis is to take the simulation data and tease out the key patterns and correlations with econometric methods. This is one way to assess the role of channels of monetary policy transmission in this artificial economy, just as is often done with actual data.

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A   Variables and parameters

Symbol	Description	Initial value
ΔY_{ss}	Nominal rate of growth in the steady state	0.0024
$Popsize_{hh}$	Number of households	4000
$Popsize_{cf}$	Number of consumption firms	100
$Popsize_{kf}$	Number of capital firms	20
$Popsize_b$	Number of banks	10
$Popsize_g$	Number of governments	1
$Popsize_{cb}$	Number of central banks	1
$l_{kf,cf,g}$	Consumption firms initial workers	500, 2600, 780
m	Initial unemployment	0.08
$p_{kf,cf}$	Goods prices by type	1.2625, 0.1643
$i_b^{L,D,A,B,R}$	Initial interest rate on debt	0.0024, 0.0008, 0.0008, 0.0008, 0
CR^{tr}, LR^{tr}	Initial banks' target prudential measure	0.08422, 0.1551
i_{cb}^R	CB interest rate on reserves (bank rate)	0
w	Initial wages	5
$\Delta p^C G$	Inflation	0.00246627
ρ_{hh}	Dividends received	1022.7246
Y	Nominal GDP	18303.8210132755
$r_{kf,cf,b}$	Profits received by sector	18.68515, 1102.4699, 47.1388
$y_{kf,cf}$	Sales by sector	2525, 15778.8210
$uc_{kf,cf}$	Unit costs by sector	1.25, 0.1494
$OCF_{kf,cf}$	Operating cash flows for firms	17.5140, 2100.9267
A	Initial quantity of advances	0
$B_{c,cb}$	Bonds held by sector	269845.1258, 56965.5549
$L_{kf,cf}$	Initial loans per sector	1990.5041, 42037.8831
$R_{b,g}$	Reserves held by sector	56965.5549, 0
$D_{hh,kf,cf}$	Initial deposits per sector	352630.6774, 2500, 12000
$G_{kf,cf}$	Initial inventory per sector	200, 9600
KG_{cf}	Initial machines	120000
Ψ_{cf}^{uc}	Initial mark-up on unit labour costs for consumption firms	0.3188
Ψ_{kf}^{uc}	Initial mark-up on unit labour costs for capital firms	0.075

Table 2: Global Variables

Symbol	Description	Possible values
id_x	Unique agent identifier	1 - 8121
D_x	Amount of deposits	$0 - \infty$
CG_x	Amount of consumption goods	$0 - \infty$
KG_x	Amount of capital goods	$0 - \infty$
L_x	Amount of loans	$0 - \infty$
R_x	Amount of reserves	$0 - \infty$
B_x	Amount of bonds	$0 - \infty$
A_x	Amount of advances	$0 - \infty$
IB_x	Amount of interbank loans	$0 - \infty$
df_x	Indicates whether an agent has defaulted	True, False
ep_{hh}	Identifier of the employer	Bank, firm, or government
l_x	List of identities of workers	List of households
vc	Variable costs	$0 - \infty$
lc	Unit labour costs	$0 - \infty$
o	Output	$0 - \infty$
u	Capacity utilization	0% - 100%
y	Sales	$0 - \infty$
k	Selected supplier	Firm identifier
n_b^L	Non performing loans	List of loans
i_b^L	Internal benchmark rate bank charges on loans	0% - 100%
i_b^D	Rate on deposits	0% - 100%
i_b^{IB}	Rate for extending an interbank loan	0% - 100%
CR	Capital adequacy ratio	0% - 100%
LR	Liquidity ratio	0% - 100%
p^B	Face value at which the government is willing to release bonds	100%
i^B	The percentage the government pays on the face value of government bonds	0% - 100%
i^R	Rate on central bank reserve deposits	-10% - 10%
CR	Capital adequacy ratio	0% - 100%
LR	Liquidity Ratio	0% - 100%

Table 3: Agent State Variables

Symbol	Description	Initial value
$\alpha^{q,y}$	Propensity to consume out of wealth, income	0.25, 0.38581
α^ρ	Propensity to distribute dividends out of excess capital	0.2
β	Risk aversion	0.01
γ	Adaptive expectations weight	0.25
$\epsilon^D = \epsilon^L = \epsilon^B$	Intensity of choice in the deposit, credit, and interbank markets	2.00687
$\epsilon^{CF} = \epsilon^{KF}$	Intensity of choice in the consumption and capital goods markets	1.50515
$\zeta^{u,w}$	Share of workers leaving their employer, wage costs kept as a liquidity buffer	0.01, 1
$\eta^{L,B,M}$	Loans, Bonds, Machines duration	20, 5, 20
$\theta^{\Delta k}$	given a a 15% and 20% price difference between old and new	50%
θ^{df}	Probability of default	free
ι_{cf}	Haircut on defaulted firms' capital value	0.5
κ_{cf}^{tr}	Desired capacity rate of growth	free
μ_l	Productivity of labour for capital, consumption firms	2, 1
$G_{f,t}^{tr}$	inventory buffer target	0.1
$u_{c,t}^{tr}$	Desired rate of capacity utilization	0.8
ξ	Number of potential partners interbank market, goods markets, deposit and credit markets, labour market	10, 5, 3, 10
ρ	Dividend pay-out ratio firms, banks	0.9, 0.6
σ_m	unemployment benefits as a share of average wage	0.3
$\tau^y = \tau^r$	Tax rate on income and profit	0.18
ϕ^u	Unemployment threshold (wage revision function)	0.08
ϕ^{pru}	Prudential threshold	0.1
ϕ^{mon}	Monetary threshold	0.01
$\chi^{CG,KG,D,L,W}$	Information asymmetry in consumption / capital goods, credit / deposit and labour markets	5, 3, 10
Ψ_{pru}	Policy mark-up for prudential policy	0.0025
Ψ_{iR}	Bank rate mark-up	0.025
Ω_1	Profit rate weight (Investment function)	0.01
Ω_2	Capacity utilization rate weight (Investment function)	0.02
μ_{FN}, σ_{FN}^2	Folded normal distribution mean and standard deviation	(1, 0.0094)

Table 4: Initialization of Parameters

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