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Abstract

In this paper, we analyse the transmission channels of monetary policy. We do this by simulation in an agent-based, stock-flow consistent model. A unique feature of the model compared to other work is its inter-bank market, which allows for a realistic treatment of monetary policy implementation. We trace the effects through banks, firms and households of interest rate shocks of different sizes and at different stages of the business cycle. Three findings stand out. Of all transmission channels, the bank lending channel appears the strongest. Second, the effects are highly non-linear. Third, since the model economy exhibits path-dependency, timing matters: changes to the monetary policy rate in a boom have markedly different impacts from interest rate shocks in a down-swing of the business cycle.

Keywords: Agent-based modelling, Monetary transmission, Inflation.

1 Introduction

We analyze the transmission channels of monetary policy by simulation in an agent-based, stock-flow consistent (AB-SFC) model. The monetary transmission mechanism describes how central bank interest rate influences inflation, output and employment. The mechanism is extensively investigated in central bank publications [1, 2, 3] and macroeconomic textbooks [4, 5]. There is also an extensive literature on the different channels through which this mechanism might operate; for an early overview, see Mishkin [6]. For discussions and analysis, see e.g. Chowdhury et al. and Disyatat [7, 8] on the cost and bank lending channels, respectively. A common challenge is to open the 'black box' of conditions in which policy transmission does or does not occur [9]. As Federal Reserve Chairwoman Janet Yellen [10] recently said, in order to analyse these channels we need a detailed understanding of how 'spending by households and firms responds to changes in labour income, business sales, or the value of collateral'. The present model is designed to trace these responses, which in turn determine policy impacts on inflation, output and employment.

From the literature, we identify six channels through which monetary policy can influence inflation in a closed economy: the consumption channel, the investment channel, the asset-price channel, the bank lending channel, the balance-sheet channel, and the cost channel. The combined effect of these channels on inflation is not clear a priori. They might run in opposite directions. In addition, there may be interaction effects and feedback between different channels. 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.

These myriad and interacting effects make it difficult to precisely trace and model the effects of monetary policy on inflation in a model that is solved for an equilibrium, as in the commonly applied general-equilibrium framework. This framework suffers from aggregation problems and challenges in incorporating complex dynamics. Although in this New-Keynesian DSGE modelling tradition, there are now several somewhat disaggregated models [11, 12, 13], these models still aggregate whole sectors. This means crucial information might remain unexplored. [14] Gabaix shows that idiosyncratic firm-level shocks can explain an important part of aggregate movements due to, for instance, inter-sectoral input-output linkages [15].

Examples of dynamic stochastic general equilibrium DSGE models, which analyse transmission, include the following. In Preston and Eusepi [16], current and expected future interest rates regulate spending and savings plans which in turn influence aggregate demand and inflation (i.e. the consumption and investment channels). Fiore and Tristani [17] model households, wholesale firms, retail firms, entrepreneurs, and a central bank. They find that in the presence of some exogenous disturbances (labelled 'technology shock') and financial market imperfections (sticky prices), there is a trade-off between output and inflation stabilization. The model of Ravenna and Walsh[18] includes households, firms, financial intermediaries, a government and central bank. They model the cost channel, in which firms' marginal costs depend directly on the nominal rate of interest. Cost-push inflation arises in response to an interest rate shock. For more detailed discussions of progress and challenges in DSGE and other general-equilibrium models, we refer to Blanchard et al., Blanchard, and Kaplan et al. [4, 19, 12].

Our approach represents a departure from the general-equilibrium framework. Bonabeau [20] calls for an agent-based modelling approach to study social systems in general and Farmer and Foley and Tesfatsion [21, 22] for the economy in particullar. We set up an agent-based model to analyze the macroecoomic dynamics of monetary policy transmission. Fagiolo and Roventini[23] demonstrate the advantages of agent-based models for policy analysis. In particular, agent-based models help the analyst to deal with the fact that agents are heterogeneous, and that the economy's structure is subject to continuous change [24].

We do not specify which policy transmission channels will or will not operate. Instead, we specify an economy in which, in principle, all channels can be operational. In our model, agents interact directly, in a decentralized way, rather than via a market clearing mechanism, which revises prices to equalize demand and supply. Furthermore, the focus is on agents' complete balance sheet, rather than on a subset of assets or liabilities traded on specific markets. The AB-SFC model structure allows for decision-making under uncertainty (as opposed to perfect rationality and full information), agents interactions within economic structures (as opposed to single-agent analysis), path-dependency [25], and explicit modelling of the financial nature of the economy [26].

The paper is part of a developing strand of research on macroeconomic agent-based models. Other examples of such models include work by the 'Eurace' modelling group [27, 28], the 'Complexity Research Initiative for Systemic Instabilities' (CRISIS) model [29], the 'Schumpeter + Keynes' model (Dosi and others, 2015), and the work developed around the 'JAMEL' model [30, 31]. Agent-based models are also starting to be applied in central banks [32]. In this paper we present and AB-SFC macroeconomic model, which builds on the model presented by Caiani et al. [33].

A unique feature of the model is its detailed interbank market, which allows for a realistic treatment of monetary policy implementation. We trace the effects of interest rate shocks of different sizes and at different stages of the business cycle on banks, firms and households. In our simulations, three findings stand out. Of all transmission channels, the bank lending channel appears the strongest. Second, the effects of a shock are highly non-linear. And third, since the model economy exhibits path-dependency, timing matters: changes to monetary policy rates in a boom have markedly different impacts from interest rate shocks in a quasi steady state. We also demonstrate how the model structure allows us to link transmission channels and their outcomes to the model‘s behavioural rules and its structure. This opens up possibilities to analyse the determinants of transmission channels in more detail.

In the next section, we describe the model. In section 3, we analyse model simulations. Section 4 concludes with a summary and discussion of limitations and future work.

2 The Model

We model a closed economy (i.e. without foreign sector). All model dynamics are endogenous. The model was implemented using the Java Macro Agent-Based (JMAB) [1] modelling software and is based on the AB-SFC benchmark model presented by Caiani et al. [33].

2.1 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 $V_{x,t}$ 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.

2.2 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 - $\theta^{\Delta k}$), where

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

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.

[1] the source code for jmab can be found at: https://github.com/S120/jmab, the source code for this model at: https://github.com/S120/Interbank

If either the agent has no more demand or there are no more suppliers, then the algorithm stops. Depending on the market, the demand agent can then select a new random supplier subset. In that case, the algorithm will run again. Figure 1 below depicts the market matching protocol.

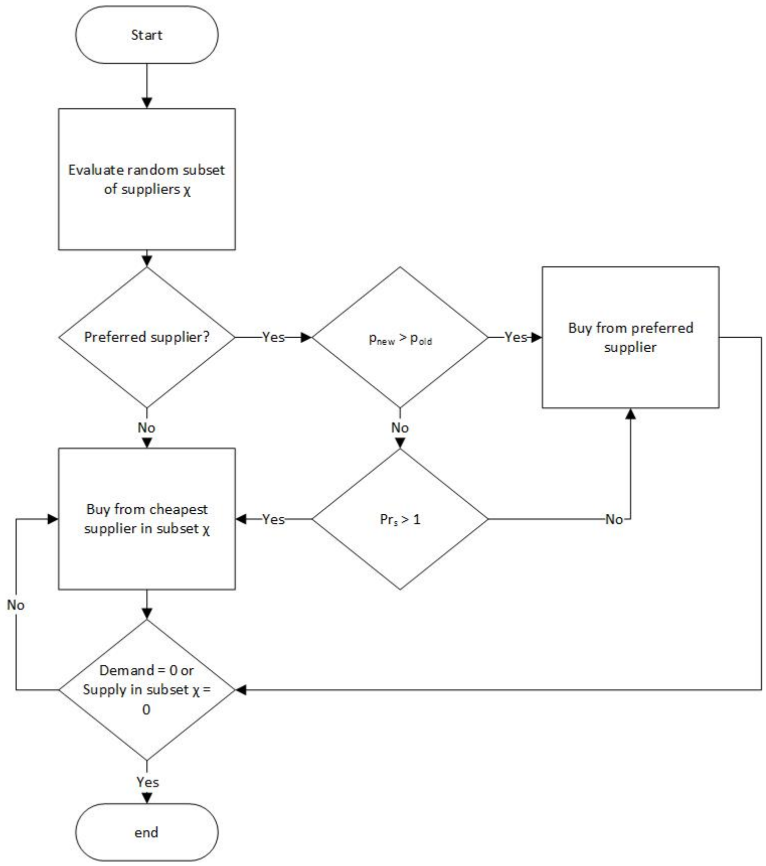

Figure 1: Market matching protocol.

2.3 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. Expectations;
2. Firms' price determination;
3. Capital goods market - first interaction;

4. Investment demand;
5. Credit supply;
6. Deposit rates;
7. Credit demand;
8. Firm labour demand;
9. Credit market interactions;
10. Labour supply;
11. Government labour demand;
12. Central bank policy;
13. Labour market interactions;
14. Firms production;
15. Consumption demand;
16. Capital goods market - second interaction;
17. Consumption goods market interaction;
18. Payments on obligations;
19. Deposit market interactions;
20. Defaults;
21. Bond market - first interaction;
22. Interbank market interactions;
23. Central bank bond demand;
24. Bond market - second interaction;
25. Central bank lending facilities.

2.4 Simulation scheduling

In this section, we describe in detail the simulation algorithm for every period. Agents are boundedly rational [34]. 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.

2.4.1 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:

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

where γ is an adaptive parameter. Firms compute an output target, $o_{f,t}^{t}r$, by subtracting current inventories from the inventories needed to satisfy expected sales, $y_{f,t}^{e}$, and a percentage inventory buffer, ν,

$$o_{f,t}^{t}r = y_{t}^{e}(1+\nu) - XG_{t} \quad \text{with} \quad X = \{K, C\}. \tag{3}$$

In the next step, banks remove any loans from bankrupt debtors from their balance sheets.

$$L_{b,t} = L_{b,t} - n_{b}^{L}. \tag{4}$$

If the debtor is a consumption firm, the bank recovers collateral C by forcing its sale, from which it recovers the proceeds, $C = KG\iota_{x}$. 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.

2.4.2 Firms' price determination

To determine output prices $p_{f,t}$, firms apply a mark-up $\Psi_{f,t}^{XG}$ 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. If current inventory $XG_{x,t-1}$ is above (below) target $XG_{f,t}^{tr}$, the mark-up is increased (decreased) by a stochastic amount FN,

$$\Psi_{x,t}^{ulc} = \begin{cases} (\Psi_{x,t-1}^{ulc}(1+FN) & \text{if } \frac{XG_{x,t-1}}{XG_{x,t}^{d}} \leq \nu^{N} \\ \Psi_{x,t-1}^{ulc}(1-FN) & \text{if } \frac{XG_{xt-1}}{XG_{x,t}^{d}} > \nu^{N} \end{cases}, \tag{6}$$

where FN is a random number drawn from a folded normal distribution with parameters $\mu_{FN}, \sigma_{FN}^{2}$.

2.4.3 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 1.

2.4.4 Investment demand

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

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

Firms then derive demand for capital goods $KG_{c,t}^{d}$ based on their desired growth of output, taking into account capital replacement. This results in their nominal investment demand $KG_{c,t}^{d}$ as the product of per–unit capital good demand and supplier price $p_{k,t}$.

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

2.4.5 Credit supply

In the next step, banks update their internal interest rate on loans, $i_{b,t}^{L}$ by adding to their funding rate $fc_b = \frac{i_b^A + i_b^I B + i_b^D}{3}$ plus (minus) a stochastic amount FN depending on whether they meet their capital ratio target,

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

where the capital ratio is calculated by dividing the equity value of assets, $CR = \frac{E}{R+B+L}$. Bank credit supply is limited only by demand, regulation and banks‘ own rationing policy [35] as explained below.

2.4.6 Deposit rates

Banks then 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:

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

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

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

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

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

2.4.7 Credit demand

Then, firms calculate their need for credit, $\Delta L^d_{f,t}$. They calculate their expected expenditures as nominal desired investment, $I^{tr}_{f,t}$, plus the dividends they expect to distribute, $dv^e_{f,t}$, plus the share of expected wage levels, σ times 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 first. The remainder is asked on the credit markets.

$$L^d_{ct} = I^d_{f,t} + dv^e_{f,t} + \sigma l_{f,t} lc_{f,t} - OCF^e_{f,t}, \tag{11}$$

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

2.4.8 Labour demand

Firms hire workers. Capital goods firms calculate the output levels they can achieve based on their capital stock, and then set labour hiring needs $\delta l^d_{ck,t}$. If negative, workers are laid off on a last in, first out basis.

$$\Delta l^d_{k,t} = \frac{o^t_{ck,t}}{\mu_l}, \tag{12}$$

where μ_l is the productivity of labour.

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

$$l^d_{cf,t} = u^{tr}_{cf,t} \frac{KG_{cf,t}}{\delta_k}, \tag{13}$$

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 $u_{cf,t} = \min\left(1, \frac{o^{tr}_{cf,t}}{\mu_k KG_{cf,t}}\right)$.

2.4.9 Credit market

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

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

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

2.4.10 Labour supply

Households which are unemployed for longer than their threshold, $um_{hh,t} > \phi^u$ update their desired wage $w^d_{hh,t}$ by subtracting stochastic amount FN from the last period's level. Employed households increase their asked wage by this stochastic amount,

$$w^d_{hh,t} = \begin{cases} w_{hh,t-1}(1-FN) & \text{if} \quad \sum_{n=1}^{4} u_{hh,t-n} > \phi_u \\ w_{hh,t-1}(1+FN) & \text{otherwise} \end{cases}. \tag{15}$$

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

2.4.11 Government labour demand

The government is committed to hiring a constant share of all households, $\sigma^l_{g,t}$. Government labour demand is therefore equal to the labour turnover share ζ_t,

$$l^d_{g,t} = l_{g,t-1}\zeta_t. \tag{16}$$

2.4.12 Central bank policy

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

$$i^R_{cb,t} = \begin{cases} i^R_{cb,t-1} + \Psi_{mon} & \text{if} \quad t = t_{mon} \\ i^R_{cb,t-1} & \text{otherwise} \end{cases}. \tag{17}$$

Much like the Bank of England [36], it sets the rate on advances $i^A_{cb,t}$ as a mark-up, Ψ_A over the official bank rate,

$$i^A_{cb,t} = i^R_{cb,t} + \Psi_A. \tag{18}$$

The central bank also sets a countercyclical capital buffer based on the credit-to-GDP ratio [37]. In line with the Basel III capital requirements:

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

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 [37], prompting the central bank to act as lender of last resort.

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

2.4.13 Labour market

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

2.4.14 Production

Consumption firms produce consumption goods, using their most productive capital goods first:

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

Capital firms produce according to:

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

2.4.15 Consumption demand

Households set desired consumption $c^d_{hh,t}$ as a fixed share α^y of their net income plus a share α^q of their net wealth, $D_{hh,t} + CG_{hh,t}$. Desired consumption responds to interest rate changes $\alpha^q = \alpha^q + \frac{i_t - i_{t-1}}{i_{t-1}}$. Both income and wealth are adjusted for expected inflation $\Delta p^e_{cf,t}$.

$$c^d_{hh,t} = \alpha^y \frac{y_{hh,t}}{\Delta p^e_{cf,t}} + (\alpha^q) \frac{q_{hh,t}}{\Delta p^e_{cf,t}}. \tag{23}$$

2.4.16 Consumption market

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

2.4.17 Capital market - round 2

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

2.4.18 Payment on obligations

Then, interactions take place as a consequence of equity, credit, deposit and other contractual claims (Figure 2).

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 the banks. This leads to payments of interest on transferable debt claims and transfers of claims in settlement of payment transactions. Reserves and deposits are used to settle payments by the government and by banks; 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 over every obligation, j, in every set of obligations, P.

First, firms pay interest to banks, due on outstanding loans, where each individual loans carries its own interest rate.

$$\Delta D_{f,t} = -\sum_{j \in P} i^L_{j,f,t} L_{j,f,t}. \tag{24}$$

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

$$\Delta D_{x,t} = -\sum_{j \in P} w_{j,x,t}. \tag{25}$$

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

$$\Delta D_{x,t} = -\sum_{n \in P} sigma_w \overline{w}. \tag{26}$$

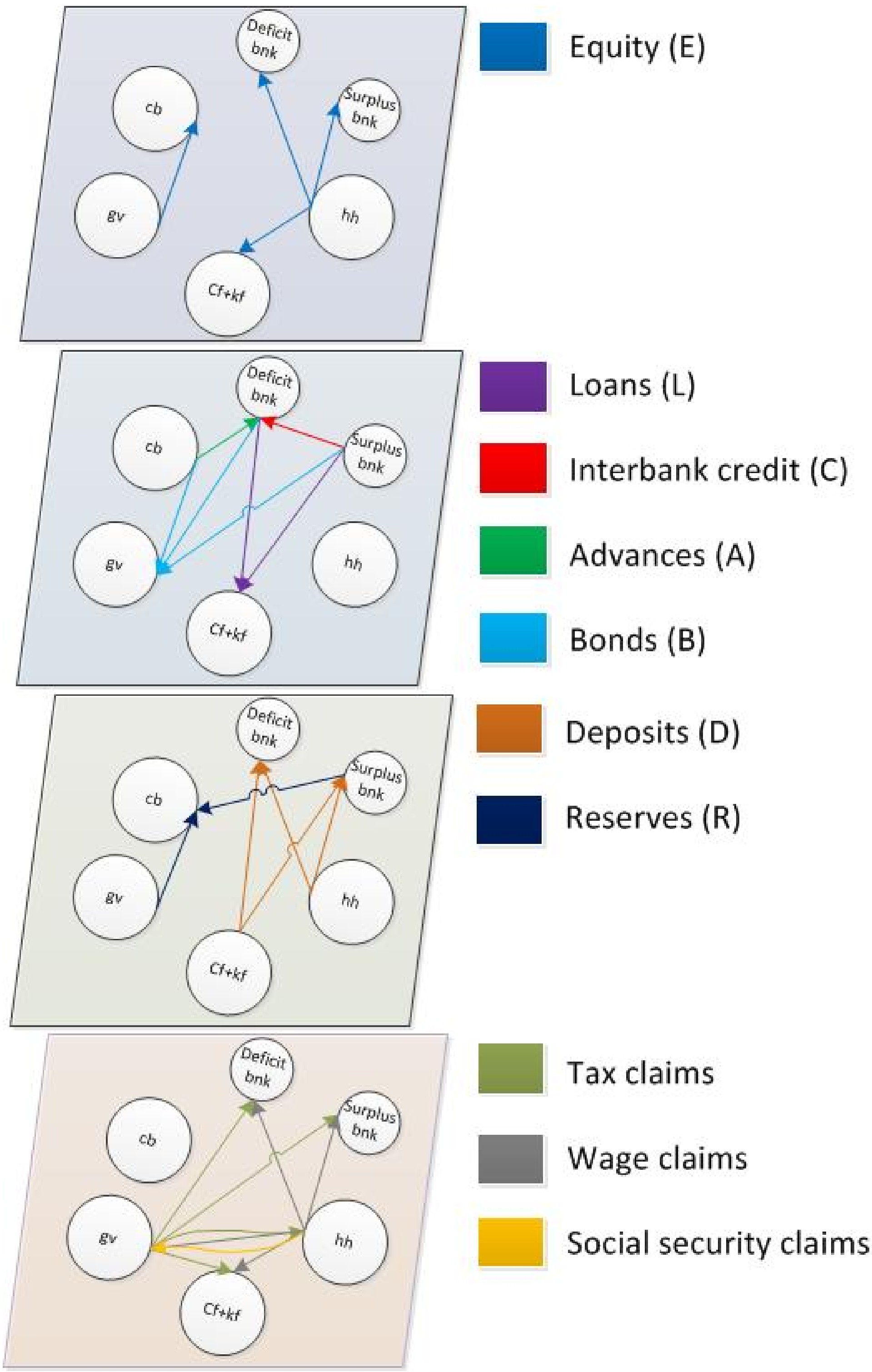

Figure 2: Stylized multi-layer network representation of contractual interaction channels between agents.

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

$$\Delta D_{g,t} = \sum_{j \in P} i^B_{j,x,t} B_{j,x,t}. \tag{27}$$

The central bank pays interest over outstanding reserves:

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

Banks pay interest to the central bank on outstanding advances,

$$\Delta R_{b,t} = \sum_{j \in P} i^A_{cb,t} A_{j,b,t}, \tag{29}$$

and on inter-bank loans,

$$\Delta R_{b,t} = \sum_{j \in P} i^I_{j,b,t} BIB_{j,b,t}. \tag{30}$$

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}.

$$\Delta D_{b,t} = \sum_{j \in D} i^D_{j,b,t-1} D_{j,t-1}. \tag{31}$$

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 $\bar{i}^A_{cb,t} A_{cb,t}$. After that, the central banks transfers its profit to the government.

$$\Delta R_{b,t} = r_{cb,t}. \tag{32}$$

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

$$\Delta D_{f,t} = \rho_x r_{f,t}. \tag{33}$$

They then distributes these dividends equally among all households. Banks determine the amount of dividends they pay based on their desired capital ratio,

$$\Delta D_{f,t} = \begin{cases} \left(1 + \alpha^d\right) \rho_b r & \text{if} \quad CR_{bt} > CR^T_t \\ \rho_b r_{b,t} & \text{otherwise} \end{cases}. \tag{34}$$

After that, firms pays taxes to the government by multiplying their profit by the tax rate.

$$\Delta D_{f,t} = \tau_r r. \tag{35}$$

Finally, households pay a flat tax rate τ_y over their wages w_{ht}, dividends div_{ht} and interest received on deposits $i^D_{bt-1}D_{ht-1}$.

$$\Delta D_{hh,t} = \tau_y \left(w_{hh,t} + dv_{hh,t} + i^D_{hh,t-1} D_{hh,t-1} \right). \tag{36}$$

2.4.19 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.

2.4.20 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.

$$df_{f,t} = \begin{cases} True & \text{if} \quad D_f + CG_f + KG_f - L_f < 0 \\ False & \text{otherwise} \end{cases}. \tag{37}$$

$$df_b = \begin{cases} True & \text{if} \quad R_b + IB_b + L_b + B_b - D_b - A_b < 0 \\ False \;, & \text{otherwise} \end{cases}. \tag{38}$$

If in default, firms and banks are bailed in by their household owners and their depositors. This happens so that the total number of firms and banks remains constant.

2.4.21 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.

$$\Delta B^s_{g,t} = \frac{tx_{g,t} + r_{cb,t} - \sum_{j \in l_{g,t}} wl_j - um_t d_t - i^b B_{t-1}}{p^B}. \tag{39}$$

2.4.22 Bond market

Banks buy government bonds with their excess reserves.

$$B^d_{b,t} = \begin{cases} LR_{b,t} - LR^t_{b,t} & \text{if} \quad LR_{b,t} < LR^t_{b,t} \\ 0 \;, & \text{otherwise} \end{cases}. \tag{40}$$

2.4.23 Inter-bank market

If a bank has excess reserves left, it determines its demand for reserves, or supply of reserves, on the inter-bank market as the difference between reserve requirement $R^d_{bt} = D_{bt} LR^d_{b,t}$ and current reserves $R_b t$:

$$IB^s_{bt} = \left(LR_{bt} - LR^d_{bt}\right) D_{bt}. \tag{41}$$

Subsequently, reserve-supplying banks adjust their mark up on the price of reserve. 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:

$$i^{IB}_{bt} = \frac{\bar{i}^L_{b,t} - i^R_{b,t}}{\bar{X} i^L}, \tag{42}$$

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

2.4.24 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:

$$\Delta B_{cb,t} = B^s_{g,t}. \tag{43}$$

2.4.25 Liquidity

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.

$$A^d_{b,t} = \left(LR_{b,t} - LR^d_{b,t}\right) D_{b,t} \tag{44}$$

2.5 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. [33]. For model consistency, it is important that for all agents, assets equal liabilities plus net worth at the start. We therefore determine initial values of all parameters and state variables consistent with an aggregate stock-flow consistent model in steady state satisfying these properties. Next, we distribute the aggregated variables homogeneously and symmetrically across agents. This creates for the first period a ‘memory‘ of fictitious past sales, past wages, past profits and so on, as the basis for first–period 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-u, no agent starts the simulation with an advantage over other agents. Initial values are reported in tables 2, 3, and **??** in the appendix.

3 Results

In this section, we explore the dynamics of the model. First, we characterize the baseline model dynamics. Then, we add an interest rate shock and explore the transmission channels in detail.

3.1 Model dynamics

Once the simulation starts, four distinct phases emerge: a bust, boom, another bust, and eventually a quasi steady state. Figure 3 shows how (1) GDP, (2) unemployment and (3) prices evolve over time. Figure 4 shows the aggregate balance sheets for each sector. Finally, figure 5 shows the evolution of prices in all six markets. The dotted vertical lines mark the beginning of each phase.

Initially, wages are rising as all workers start out employed labour costs rise and consumption goods price increase.

3.1.1 Period 10 - 62: Bust

In the first stage, some firms which have over-employed workers start to fail. They lay off workers, which leads to a fall in demand for consumption goods and then for capital goods, so that capital goods prices fall (Figure 5 panel 3). In spite of falling consumption, due to declines in wages and therefore costs, consumption prices remain relatively stable. On financial markets, low demand for credit means relatively high capital ratios and therefore falling interest rates on loans. Furthermore, deposit interest rates fall and interbank interest rates are relatively stable due to the central bank monetary policy interest rates.

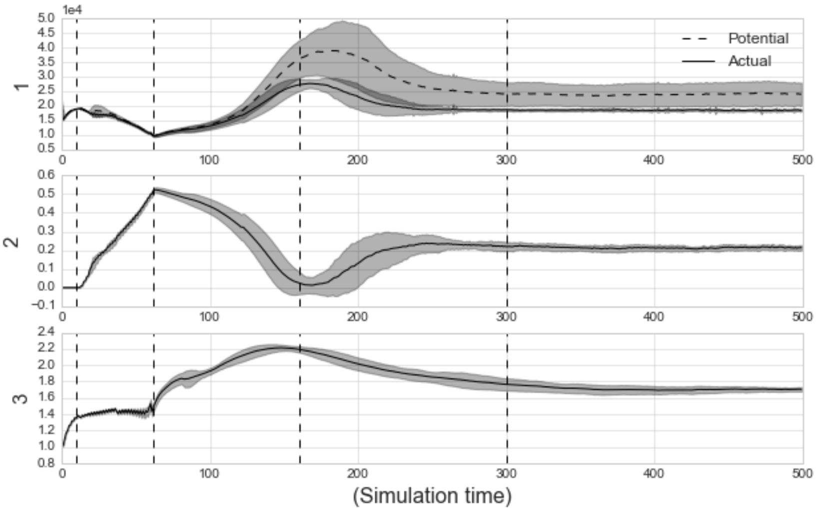

Figure 3: Mean and standard deviation of: (1) actual and potential GDP, (2) unemployment, and (3) consumption price index (base: $t = 0$).

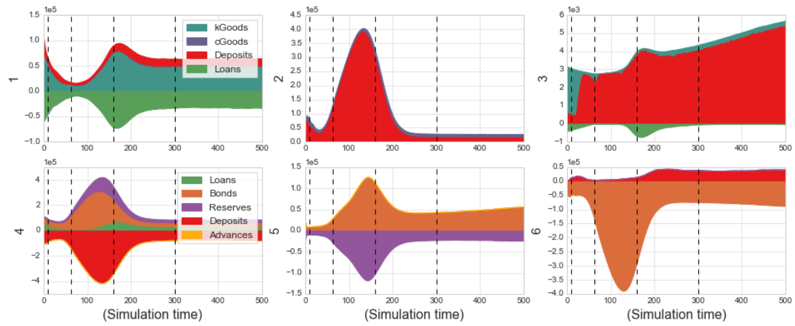

Figure 4: Sectoral balance sheet compositions of (1) consumption firms, (2) households, (3) capital firms, (4) banks, (5) the central bank, and the (6) government.

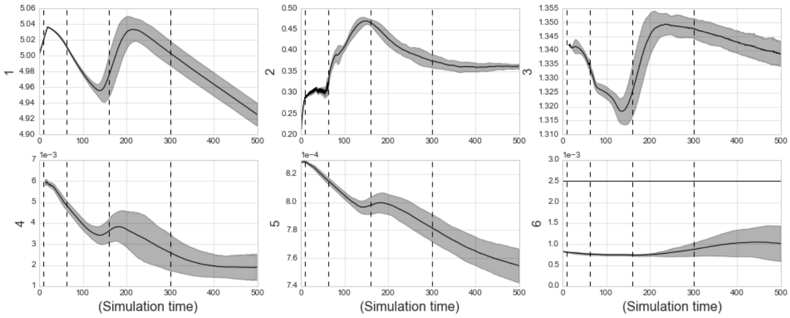

Figure 5: Mean and standard deviation of market prices of (1) labour, (2) consumption goods, (3) capital goods, (4) interest on loans, (5) interest on deposits, and (6) interest on inter-bank loans.

3.1.2 Period 62 - 160: Boom

In the 'boom' stage, government unemployment benefits and fixed labour demand acts as a floor on consumption, at the cost of heavy government borrowing (figure 4 panel 6. As firms extrapolate expectations, they disinvest a little below the government induced floor on consumption. With firms below capacity, consumption prices shoot up. Consumption firms see their profitability recover. Soon after, they start employing more households, paying more wages, increasing consumption and so on. In line with rising demand, investment and credit also pick up. Potential capacity starts to outpace sales.

3.1.3 Period 160 - 300: Bust Again

As the economy reaches full employment, labour becomes the bottleneck to growth. Consumption goods reach overcapacity. They experience high wage levels and declining revenues as their output prices start falling. Their reduction in investment triggers revenue declines in capital firms, rising unemployment and falling demand: the second bust. The dynamics are similar to those of the first bust, but at lower wages and higher price levels. Fewer firms fail this time around, and the downturn is less severe.

3.1.4 Period 300 - : Quasi Steady State

The second bust is followed by a moderate upswing, after which the economy reaches a quasi steady state. GDP, unemployment and prices are now relatively stable. Note that while the economy in aggregate seems to reach a quasi-steady-state, Figure 5 shows this does not apply to all markets. In the quasi-steady-state balance sheets are relatively stable with the exception of capital firms which continue to hoard deposits.

In sum, the JMAB model economy experiences an endogenous business cycle. The model is capable of reproducing real-world correlations across macroeconomic time series, as shown in detail in Caiani et al. [33]. This is the laboratory in which we will now conduct a monetary policy experiment.

3.2 Monetary transmission

Monetary policy transmission is the pass-through of changes in central bank policies (usually, in overnight interest rates) to target variables (usually, inflation). In our model, this may occur through a credit channel, an investment channel, a consumption channel, and a cost channel. With the exception of the cost channel, these channels work via changes in economic slack (the output gap), which has an impact on inflation [38]: inflation picks up when the economy is near capacity. We run two experiments to probe the strength of these channels. We are also interested in changes in the strength of the channels over the business cycle. In each experiment, we increase the central bank rate five times, see table 1. In the first experiment, this takes place in the boom period at $t_{mon} = 125$, when the economy is near full capacity. In the second experiment the central bank rate hike takes place in the quasi-steady-state at $t_{mon} = 300$.

Experiment	Ψ_{mon}	t_{mon}
A	0	(125, 300)
B	0.001	(125, 300)
C	0.002	(125, 300)
D	0.003	(125, 300)
E	0.004	(125, 300)

Table 1: Experiments

Regardless of the channels, monetary policy first affects banks. We consider a change in two standing facility interest rates - the deposit facility rate and the marginal lending facility rate [39]. The monetary transmission mechanism starts with a monetary policy shock on the interbank market at t=350, as shown in figure 6. Following equation 42, banks determine their interbank ask price 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, both through the interbank market and by increasing the cost of advances. The increase in funding costs are translated into higher loan and deposit rates. As the risk free rate rises so do interbank rates.

Banks set deposit rates according to equation 10, increasing or decreasing their rates based on profitability, χ^p, liquidity, χ^{LR}, and funding costs, χ^{fu}.

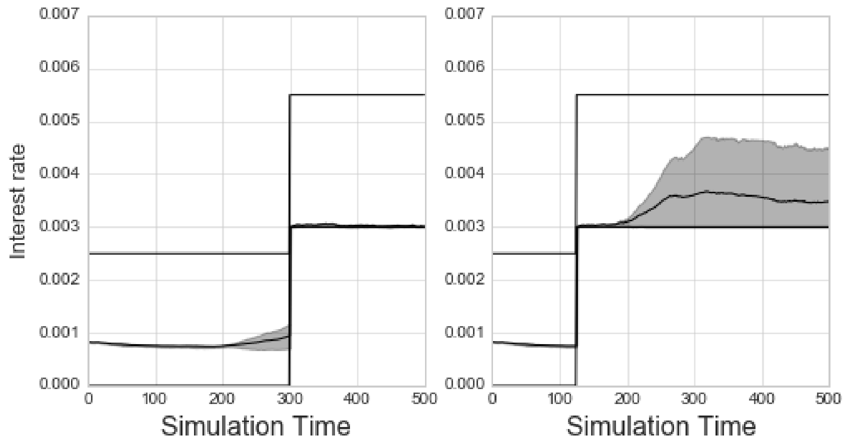

Figure 6: Central bank and interbank rates experiment 1 (left) and experiment 2 (right).

Of these, funding costs increase, especially for those banks who derive a large part of their funding from advances or interbank loans.

Regarding loan rates, banks follow equation 9 and respond to changes in their funding costs and capital ratio relative to target capital ratio. As their funding costs increase, loan rates increase. However, interbank and advances rates are only a small part of the total funding cost mix for banks. Furthermore, the effects of the rate hike on the difference between actual and target capital ratios is not straightforward. The target capital ratio is set by the central bank, which is based on the credit–to–GDP ratio. The actual capital ratio is determined by bank profitability. This moderates the effect.

Figures 7 and 8 show exactly that. On average, deposit and loan rates respond to the central bank rate but pass-through is weak and highly non-linear.

3.2.1 Credit channels

Bank credit supply is also affected. Following equation 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. Bernanke [40] identifies this effect as the bank lending channel. The lending channel describes the influence of short-term interest rates on bank lending volumes. As banks funding costs increase they reduce the quantity of credit [8]. This reduction in credit affects investment and inflation.

Indirectly, the rate hike also influences the interest rates on loans and

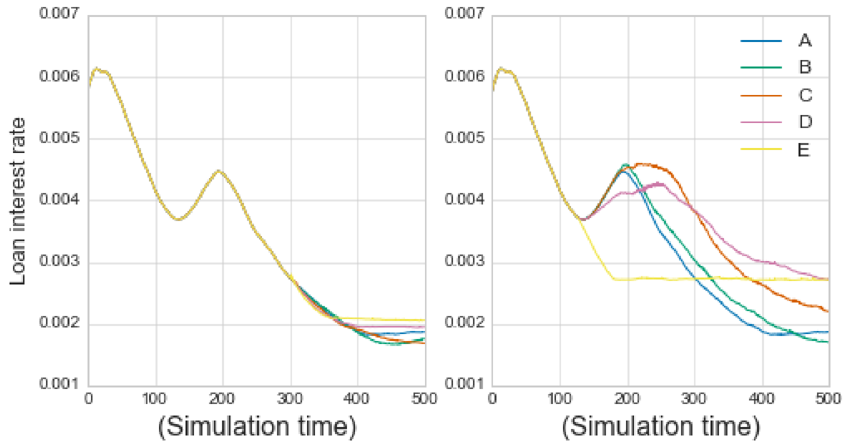

Figure 7: Interest on bank loans in experiment 1 (left) and experiment 2(right), where from A to E $\Psi_{mon} = \sum_{n=0}^{4} \frac{n}{1000}$.

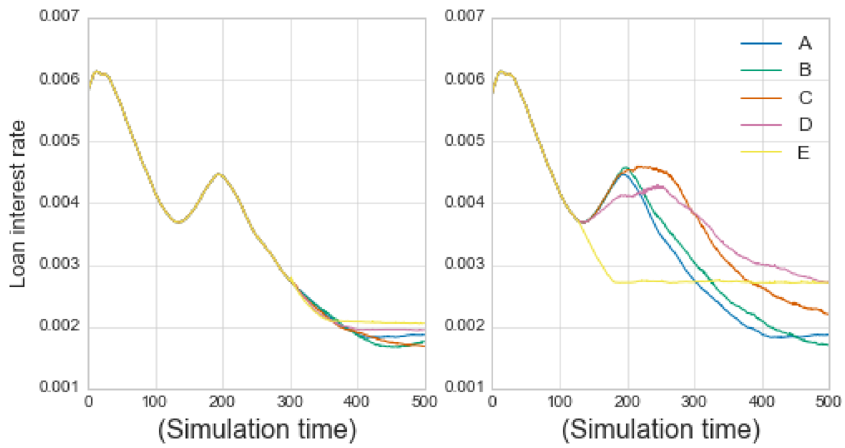

Figure 8: Bank deposit rates in experiment 1 (left) and experiment 2 (right), where from A to E $\Psi_{mon} = \sum_{n=0}^{4} \frac{n}{1000}$.

therefore the debt service and the value of collateral. Bernanke [40] also identifies a balance sheet channel. In the balance sheet channel, the reduced net worth of firms, after an interest rate hike, reduces credit. However, in our model banks do not discount the value of collateral. It is only indirectly effected through changes in interest payments on other loans.

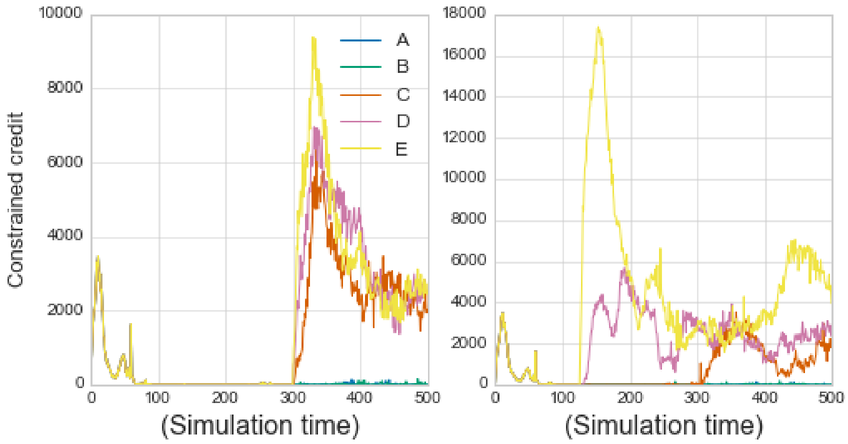

Figure 9: Constrained credit in experiment 1 (left) and experiment 2 (right), where from A to E $\Psi_{mon} = \sum_{n=0}^{4} \frac{n}{1000}$.

In summary, monetary policy transmission to the financial sector occurs largely via changes in funding costs, the risk-free rate of interest and credit rationing. Assumptions about banks decision rules (equations 7, 10, 14, and 42) are critical. The magnitude of reliance by banks on central bank advances and the interbank market determines the strength of funding cost effects. Furthermore, the relative reliance of firms on bank credit vis-a-vis equity influences the strength of the bank lending channel.

3.2.2 The investment channel

Firms‘ desire to invest might also be affected by monetary policy. In this investment channel [6], higher bank lending rates as a result of increased funding costs discourages business investment. This slows down the economy and reduces inflationary pressure. Additionally, Mishkin [41] identifies the asset price channel. An increase in bank funding costs, and subsequently loan rates, causes a decrease in firms’ net worth, reducing investment demand by firms through a wealth effect [42].

In our model, firm investment decisions are first and foremost motivated by real factors. Following equation 7, firms determine a desired rate of growth based on expected profit and capacity utilization. Both are indirectly affected by interest changes. Following equation 11, firms try to finance their

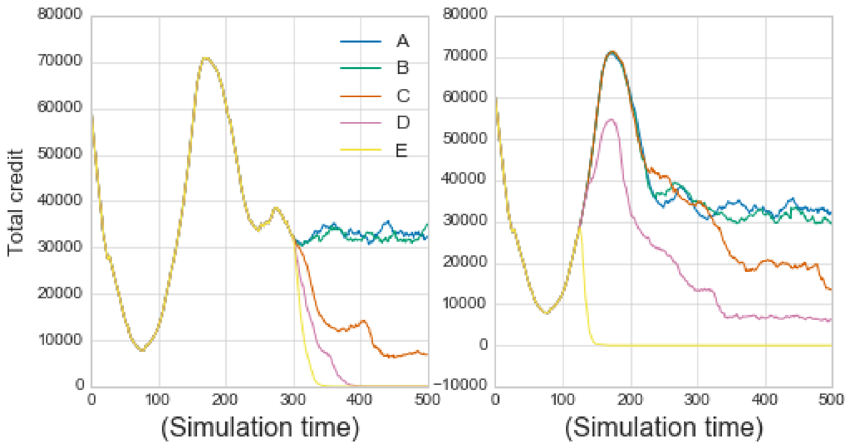

Figure 10: Total bank credit in experiment 1 (left) and experiment 2 (right), where from A to E $\Psi_{mon} = \sum_{n=0}^{4} \frac{n}{1000}$.

investment first with equity. All terms in this equation are indirectly affected by the changes in deposit and loan interest rates.

In the case of a rate rise in the steady–state phase, we see no clear downward trend relative to the baseline scenario in the share of firms that is credit constrained. However, in the case of bigger rate rises, we see larger increases in investment demand. This seems counter-intuitive; but it can be understood from interactions with the lending channel. As credit is constrained for all firms, inventories pile up as a consequence of insufficient investment, and this pushes up demand for investment.

Figure 12 summarizes the various credit and investment transmission mechanisms. In our model the transmission operates primarily through credit supply.

3.2.3 the consumption channel

In the consumption channel [6], changes in interest rates might effect household consumption decision through a wealth effect, or by changing the propensity to consume (equation 23). In the model, monetary policy influences households desired consumption through the propensity to consume out of wealth, expected inflation, and wealth plus income levels. Higher (expected) interest rates make consumption less attractive relative to saving.

A second consumption channel works through inflation expectations. As these are formed adaptively through equation 2, they depend on actual inflation, which is influenced through all channels. In our model, this effect is therefore difficult to quantify. Since there is no household lending in the model, there is no wealth effect. But there is an income effect of increased

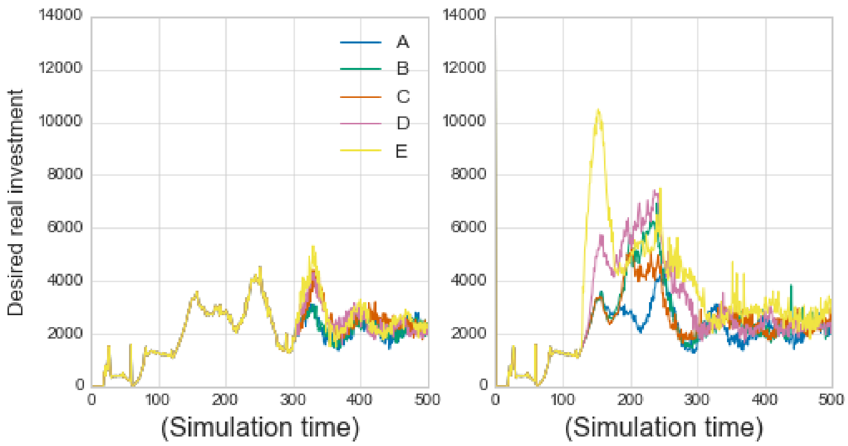

Figure 11: Desired real investment in experiment 1 (left) and experiment 2 (right), where from A to E $\Psi_{mon} = \sum_{n=0}^{4} \frac{n}{1000}$.

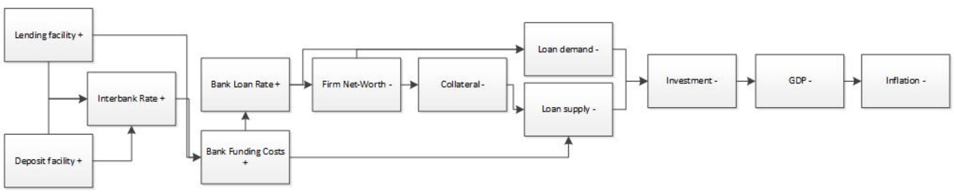

Figure 12: Credit and investment channels.

deposit rates [43].

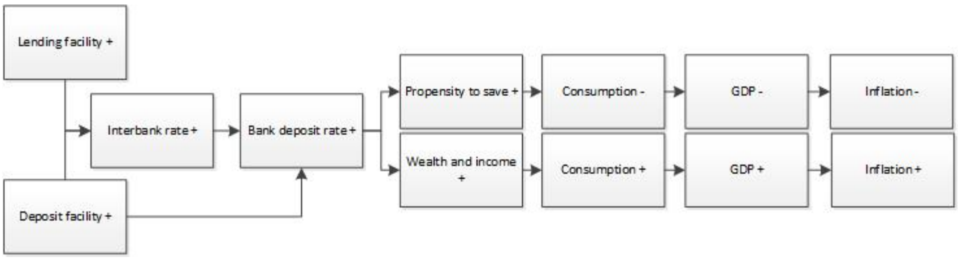

Figure 13: Consumption channels.

These mechanisms can be contradictory. A change in interest payments on deposits causes increased income and increased consumption, but also greater attraction to hold deposits rather than spending them 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. Figure 13 summarizes the consumption channels.

Figure 14 shows that these contradictory effects change desired consumption, but the effect is small.

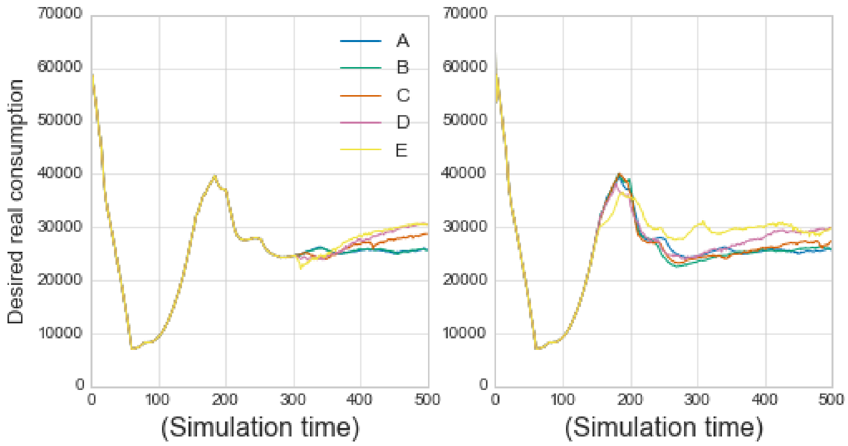

Figure 14: Desired real consumption in experiment 1 (left) and experiment 2 (right), where from A to E $\Psi_{mon} = \sum_{n=0}^{4} \frac{n}{1000}$.

3.2.4 Cost channels

In addition to the output gap type channels, Barth and Ramey[44] propose the existence of a cost channel in which changes in interest rates transmit to changes in funding costs for firms and then into higher prices (Figure 15). Tillman [45] and Gaiotti and Secchi[46] find empirical evidence for the existence of such a cost channel.

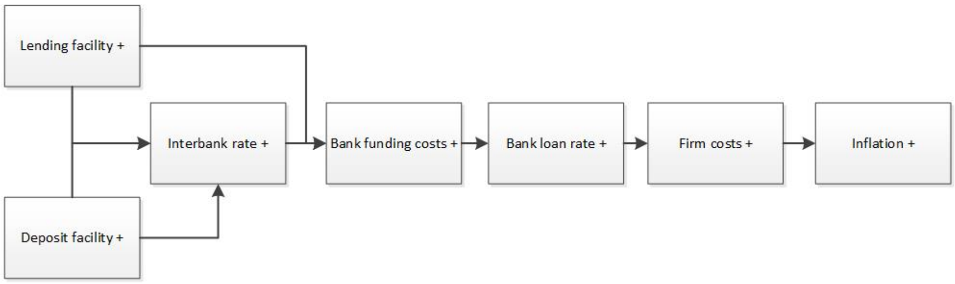

Figure 15: The cost channel.

In our model, the cost channel exists. Following equation 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. Figure 16 shows that these costs are small compared to wage costs and again conflicting mechanisms are at work. Since credit is rationed at higher interest rates, higher rates lead to reduced interest costs for those firms which are barred from the credit market. We find that the biggest rate hike leads to an increase in labour costs, but a decrease in debt service costs. As firm costs are only marginally impacted, profits are likewise almost unaffected, so that there is no discernible impact on firms' output or pricing behaviour. The strength of the cost channel 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.

3.3 GDP and inflation

We now look into the effect of the shock on GDP and inflation. Figure 17 shows that in experiment 1 the monetary policy shock impacts inflation and GDP but no clear trend emerges. Only consumer prices drop significantly more after the biggest rate shock. The effects of the same shock in experiment 2, in the steady state, are much bigger. We also observe an effect on GDP -a lower boom but convergence to the same steady state. Furthermore, there are larger changes in the consumer price index, also for smaller shocks.

While the central bank interest rate hikes do affect the dynamics of the economy, the clearest result appears to be the highly non-linear impact on the target variable inflation. To analyse this, we performed an additional

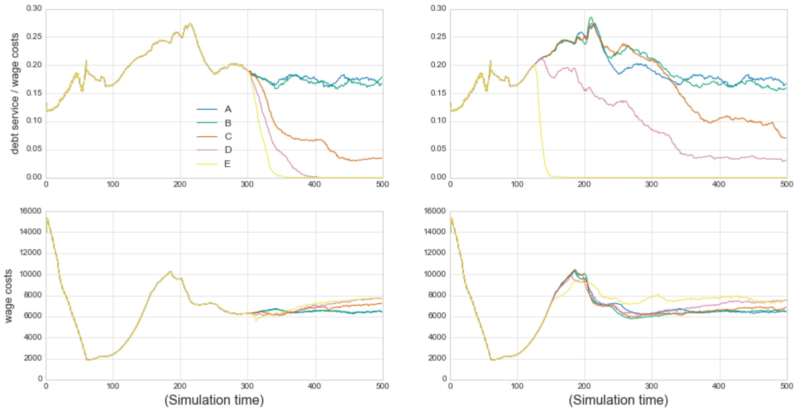

Figure 16: Top: debt service over wage costs for experiment 1 (left) and experiment 2 (right). Bottom: wage costs for experiment 1 (left) and 2 (right), where from A to E $\Psi_{mon} = \sum_{n=0}^{4} \frac{n}{1000}$.

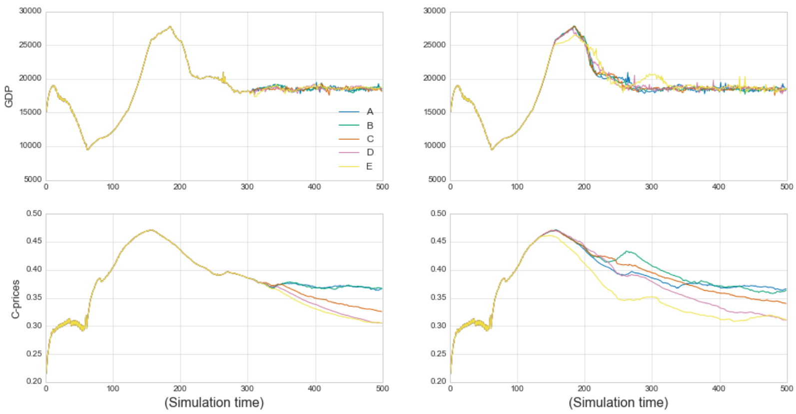

Figure 17: Top: GDP for experiment 1 (left) and 2 (right). Bottom: consumption goods prices for experiment 1 (left) and 2 (right), where from A to E $\Psi_{mon} = \sum_{n=0}^{4} \frac{n}{1000}$.

experiment in which we gradually increased the shock size Ψ_{mon} from zero to 0.008. Figure 18 shows how small rate hikes at first have large positive effect on the mean price levels. Between 0.0035 and 0.004, quite suddenly, there is a transition to a small negative effect ,which changes again between 0.0065 and 0.007.

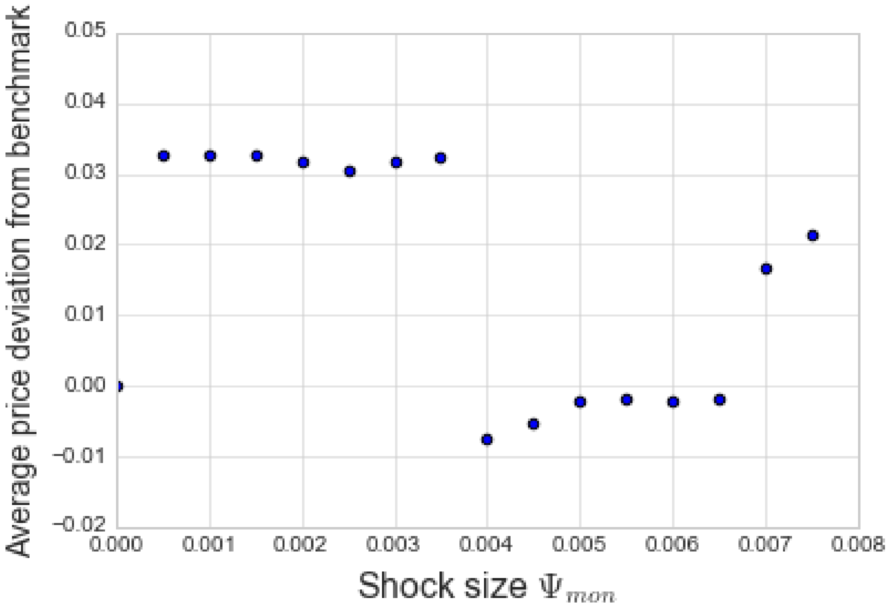

Figure 18: Rate hike increase versus the mean price change from baseline.

4 Summary, Discussion and Conclusion

In this paper we applied a financial complexity model to the question of monetary transmission mechanisms. We simulated a Central Bank policy rate shock and analysed how the monetary policy transmission channels, identified in the literature, operate in this model. A unique feature of the model, compared to other work, is its detailed inter-bank market, which allows for a realistic treatment of monetary policy implementation. We trace the effects through banks, firms and households of interest rate shocks of different sizes and at different stages of the business cycle. Three findings stand out. Of all transmission channels, the bank lending channel appears the strongest. Second, the effects are highly non-linear. Third, since the model economy exhibits path-dependency, timing matters: changes to Bank rate in a boom have markedly different impacts from interest rate shocks in macroeconomic stability.

The analyses presented here are only a beginning, and they do not yet fully exploit the potential of this agent-based, stock-flow consistent model. In future work, we aim to first explore the reasons for a number of model features, which differ markedly from reality: a zero GDP growth steady state (due to lack of technical progress in this model, we surmise), high unemployment (of about 20%), and complete deleveraging (credit stocks going to zero) after severe shocks. In short, we want to validate the model to empirical data. The aim should not be to completely mimic reality in all these respects, but to understand these features better.

Future research options include the following. One could follow 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 is key to understanding aggregate impacts, as the Yellen [10] quote in the introduction stressed.

Likewise, another promising avenue is to observe distributional outcomes of monetary policy. 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 provide evidence on the existence and channels of monetary policy transmission in this model world, 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	0.0075
$Popsize_{hh}$	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_{cf}	Consumption firms initial workers	4000
l_{kf}	Capital firms initial workers	1000
l_{g}	Government labour demand	1360
ν	Initial unemployment	0.08
i_b^l	Initial interest rate on loans	0.0075
i_b^d	Initial interest rate on deposits	0.0025
CR^{tr}	Initial banks' target capital ratio	0.17996
LR^{tr}	Initial banks' target liquidity ratio	0.258026342
i_{cb}^R	CB interest rate on reserves (bank rate)	0
w	Initial wages	5
$\bar{i}^B$	Bond interest rate	0.0025
$\bar{p}^B$	Bonds price	1
$\Delta p^C G$	Inflation	0.0075
L	Total private credit	53492.5
Y	Nominal GDP	45146.4

Table 2: Global Variables

Symbol	Description	Possible values
id_x	Unique agent identifier	1 - 8121
D_x	Amount of deposits	0 - ∞
CG_x	Amount of consumption goods	0 - ∞
KG_x	Amount of capital goods	0 - ∞
L_x	Amount of loans	0 - ∞
R_x	Amount of reserves	0 - ∞
B_x	Amount of bonds	0 - ∞
A_x	Amount of advances	0 - ∞
IB_x	Amount of interbank loans	0 - ∞
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 - ∞
lc	Unit labour costs	0 - ∞
o	Output	0 - ∞
y	Sales	0- ∞
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
α	Propensity to consume out of wealth, income	0.25, 0.38581
α^d	Propensity to distribute dividends out of excess capital	0.2
β^f	Risk aversion towards firms	0.01
γ_3	Adaptive expectations weight	0.25
$\epsilon^{bD} = \epsilon^{bL} = \epsilon^b$	Intensity of choice in the deposit, credit, and interbank markets	2.00687
$\epsilon^c = \epsilon^k$	Intensity of choice in the consumption and capital goods markets	1.50515
ζ	Share of workers leaving their employer	0.01
η_L	Loans duration	20
η_B	Bonds duration	5
η_M	Machines duration	20
$\theta^{\Delta k}$	Probability of changing suppliers	
θ^{df}	Probability of default	free
ι_c	Haircut on defaulted firms' capital value	0.5
κ_c^{tr}	Desired capacity rate of growth	free
μ	Productivity of labour for capital, consumption firms	2, 1
ν	Inflation, credit to GDP, profit, capacity utilization, inventory target	0.02, 1.5, 0.04345, 0.8, 0.1
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^D	Liquidity preference holding deposits as share of wage disbursements	1
$\tau_y = \tau_{profit}$	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
χ	Information asymmetry in markets	
$\Psi_{pru} = \Psi_{mon}$	Policy mark-up for prudential and monetary policy	0.0025 (ESRB calibrated)
Ψ_{iR}	Bank rate mark-up	0.025
$\Psi_{c,0}^{uc}$	Initial mark-up on unit labour costs for consumption firms	0.318857
$\Psi_{k,0}^{uc}$	Initial mark-up on unit labour costs for capital firms	0.075
Ω	Dole share of average wages	0.4
Ω_1	Profit rate weight (Investment function)	0.01
Ω_2	Capacity utilization rate weight (Investment function)	0.02
FN	Folded normal distribution mean and standard deviation	(1, 0.0094)

Table 4: Initialization of Parameters

List of research reports

12001-HRM&OB: Veltrop, D.B., C.L.M. Hermes, T.J.B.M. Postma and J. de Haan, A Tale of Two Factions: Exploring the Relationship between Factional Faultlines and Conflict Management in Pension Fund Boards

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