

Hess, Simon

Working Paper

What Difference Does Central Bank Digital Currency Make? Insights from an Agent-based Model

Thünen-Series of Applied Economic Theory - Working Paper, No. 171

Provided in Cooperation with:

University of Rostock, Institute of Economics

Suggested Citation: Hess, Simon (2025) : What Difference Does Central Bank Digital Currency Make? Insights from an Agent-based Model, Thünen-Series of Applied Economic Theory - Working Paper, No. 171, Universität Rostock, Wirtschafts- und Sozialwissenschaftliche Fakultät, Institut für Volkswirtschaftslehre, Rostock

This Version is available at:

<https://hdl.handle.net/10419/315807>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

Thünen-Series of Applied Economic Theory
Thünen-Reihe Angewandter Volkswirtschaftstheorie

Working Paper No. 171

**What Difference Does Central Bank Digital Currency
Make? Insights from an Agent-based Model**

von

Simon Hess

Universität Rostock
Wirtschafts- und Sozialwissenschaftliche Fakultät
Institut für Volkswirtschaftslehre 2025

What Difference Does Central Bank Digital Currency Make? Insights from an Agent-based Model

28.04.2025

Simon Hess¹

Abstract

This paper studies the effects of introducing a Central Bank Digital Currency (CBDC) on economic output, bank intermediation and financial stability in a closed economy using an Agent-based Stock Flow Consistent (AB-SFC) Model. Thereby a digital bank run is simulated across various economic environments with different monetary policy and bank bankruptcy regimes. According to the model, non-remunerated CBDC issued in a positive-interest environment with a corridor system may increase GDP through increased seigniorage income and government spending. Also bank funding becomes more expensive since bank deposit stickiness is prevented. Non-remunerated CBDC issued in a zero-interest environment has no impact since there is no distributional effect of the interest payments. In a floor-system where the interest rate on CBDC matches the policy rate, CBDC also counteracts deposit stickiness and redistributes bank profits from shareholders to depositors. Thereby CBDC improves the transmission of the policy rate to households and firms. The bank bankruptcy regime also affects the outcome. While CBDC makes no difference in a bailout regime it does in a bail-in regime where it decreases inequality and distributes bank rescue costs evenly among households and firms, potentially enhancing financial stability. Introducing CBDC within a deposit insurance system postpones bank rescue payments, which creates an additional dynamic in GDP.

JEL Codes: E42, E58, G21, G23, G28

Keywords: central bank digital currency, agent-based model, bank run, bailout, bail-in, financial stability

1 Introduction

Nowadays, bank deposits are the preferred type of money worldwide. Its global share in the broad money supply has considerably increased from 50 percent in the 1960s to around 90 percent in 2020 (World Bank, 2025a, 2025b). Nevertheless, bank deposits come with inherent issues for their owners, for which no fully satisfactory solutions have yet been found. One such issue is credit risk. Banks create loans and deposits simultaneously, implying that deposits are inherently exposed to risk. If a bank's loans default, the resulting losses must be covered by the bank's net wealth. If this is insufficient, the losses are borne by the bank's creditors, including depositors. To prevent

¹ The author is PhD candidate at the University of Rostock. simonhess@hotmail.de

potential losses for depositors and to safeguard financial stability, most countries have a deposit insurance system that covers deposits up to a specific limit. However, depositors with balances exceeding this limit are not protected, which can be problematic. During the most recent banking crisis in the U.S. in 2023, three banks—First Republic Bank, Silicon Valley Bank, and Signature Bank—became insolvent due to poor risk management, leading to potential losses for their depositors, including many corporations with uninsured amounts. Government agencies intervened at the last minute, extending the deposit insurance scheme to cover all deposits at the affected banks, ultimately calming the markets (Federal Reserve, 2023). However, the moral hazard associated with deposit insurance remains an ongoing concern (Keeley, 1990). Another issue for depositors is inadequate remuneration. Deposit interest rates tend to be asymmetrically sticky—while banks typically pass central bank policy rate cuts to depositors immediately, hikes are often delayed. As a result, depositors receive interest payments below the risk-free rate. After policy rates increased in 2020, many banks hesitated to pass on these higher rates to depositors. Historical trends also suggest that deposits have tended to be sticky (Driscoll and Judson, 2013). A third issue is efficiency. Transferring deposits requires balance sheet operations involving three parties: the payer’s bank, the payee’s bank, and the central bank. The overall costs of bank deposit payment systems are estimated to amount to around one percent of GDP (Norges Bank, 2022). By contrast, reserve payments between banks—requiring only a single balance sheet operation at the central bank—incur only a fraction of this cost (Niepelt, 2024).

In recent years, a potential solution to all those problems, central bank money for everyone—Central Bank Digital Currency (CBDC)—has gained traction. After Facebook announced its plans for a global private stablecoin called Libra in 2019, all major central banks around the world committed to researching CBDCs. Global stablecoins are considered as a threat to the monetary sovereignty of central banks and could negatively impact financial stability due to potential runs in and out of the private currency (FSB, 2022). CBDCs are discussed as one measure to counter these threats. In addition to financial stability, other motivations driving CBDC research include monetary policy implementation, financial inclusion, payment efficiency, and payment safety (Iorio et al., 2024).

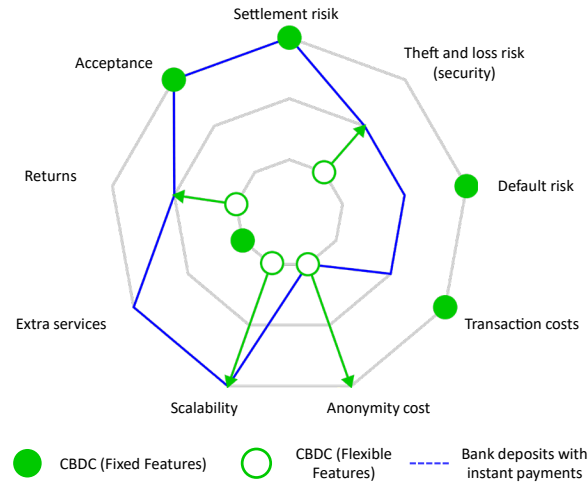


Figure 1: Comparison between CBDC and Bank Deposits with Instant Payments. Source: Mancini-Griffoli et al. (2018) with adjustments by the author.²

CBDC, as a medium of payment, is unique in that it shares properties with both today's bank deposits with instant payments and cash. Figure 1 shows a comparison between CBDC and bank deposits with instant payments. It has some fixed features: high acceptance and no settlement risk, like bank deposits, and no default risk, like cash (the default risk of bank deposits also depends on the bank's bankruptcy process, as discussed in chapter 3.7). The transaction costs are even lower than those of bank deposits, as payments are conducted internally within the central bank's ledger. Since CBDC is only a medium of payment, no additional services are available. The optional features can match those of deposits or cash, depending on their implementation. These features include security, anonymity cost, scalability, and interest returns. Interest return could be even higher if sticky deposits are present.

Some countries have already implemented limited versions of CBDC, such as the Bahamas, with holding limits and no remuneration. Almost all central banks have no plans to issue a CBDC without holding limits and remuneration (Iorio et al., 2024). This is because significant risks are associated with CBDC for banks and financial stability. The first risk is “disintermediation”: if bank deposits shift toward CBDC, banks will have fewer resources to finance loans. However, this risk would only materialize if banks were unable to rely on alternative sources of funding, such as

² In comparison to the original figure transaction costs of bank deposits are considered as higher than CBDC due to the involvement of multiple banks. The returns of CBDC are considered as higher than bank deposits due to stickiness of the latter.

central bank credit or term deposits. Authors like Bindseil (2020) and Mancini-Griffoli et al. (2018) argue that other funding sources would be more costly than deposits, forcing banks to increase their deposit rates, which, in turn, would decrease credit demand. The second major concern is the risk of a “digital” bank run (BIS, 2018; Kumhof and Noone, 2018). The introduction of CBDCs could facilitate bank runs during times of economic distress, as CBDCs are easier and less costly to withdraw than cash. Such runs are believed to have significant negative effects on banks' liquidity and overall financial stability.

The macroeconomic effects of a CBDC have been studied in multiple publications, without reaching a clear conclusion. Some argue that it may have positive effects (Andolfatto, 2018; Barrdear and Kumhof, 2016), while others suggest it may have no effect under certain circumstances (Brunnermeier and Niepelt, 2019). Still, others argue that there is a trade-off between positive and negative effects (Agur et al., 2022; Burlon et al., 2024; Keister and Sanches, 2022). However, all of these studies are based on different assumptions, some of which are questionable. For example, some studies rely on the loanable funds model, which lacks empirical support. Furthermore, the design of the CBDC—such as the issuance method and remuneration—varies across these studies. The context in which the CBDC is issued, including factors like the bank bankruptcy regime, monetary policy regime, and the market power of banks, also differs.

This paper assesses current literature on the macroeconomic effects of CBDC and develops a more realistic model which includes more realistic and more likely scenarios. Thereby, the research questions should be addressed: What economic effect does CBDC have in different monetary policy regimes and different bank bankruptcy regimes? Monetary policy regimes that are considered in this paper are a corridor-system, zero interest environment and floor system while related bankruptcy regimes are bail-out, bail-in and deposit insurance. The research focuses on economic output, bank lending and financial stability. To answer these research questions, an Agent-based Stock-Flow Consistent (SFC) model is applied, which offers multiple benefits over traditional DSGE approaches. These benefits include the heterogeneity of agents and the use of rules and heuristics to model agents' behavior instead of the optimization typically employed in traditional models. Additionally, stock-flow consistency allows for realistic modeling of monetary stocks, which helps study the implications of CBDC on agents' balance sheets. This research relies on the JMAB 2.0 model by (Hess, 2025), which incorporates endogenous money creation. This paper adapts the model and applies it to different scenarios. The scenarios differ in terms of the

monetary policy regime and the bank bankruptcy regime in place. In all scenarios there is a baseline run where households and firms prefer to hold only deposits. To study the effects of CBDC the economy is hit by a digital bank run where households and firms convert all their deposits to CBDC so that banks become illiquid and need to replace their funding from deposits to central bank loans. Furthermore, to investigate the effects of the different bank bankruptcy regimes a second shock, a bank asset-value shock is simulated which addresses solvency and makes one bank go bankrupt.

Within the scope of this paper, CBDC is defined as a central bank liability that is accessible to the broad public, has no restrictions or limits, and is fully convertible into bank deposits. There are multiple ways to implement CBDC, such as through direct, hybrid, and indirect models (Auer and Böhme, 2020; Dyson and Hodgson, 2016; Kahn et al., 2018), but this research focuses on CBDC as a direct central bank liability provided solely by the central bank, involving no third parties. Furthermore, in this paper, CBDC is equated with reserves held by households and firms, as they are identical from a bookkeeping perspective. Furthermore, this paper focuses on the economic effects of CBDC while efficiency and privacy aspects are excluded.

This paper underlies limitations. There are no collateral requirements for central bank loans and the central bank acts as lender of last resort by providing unlimited liquidity for banks. Moreover, only the case in which all deposits from households and firms are converted to CBDC is investigated. Thus, the demand for CBDC is exogenously given, and there is no dynamic competition between CBDC and bank deposits. Additionally, CBDC is created through two issuing methods, depending on the monetary policy regime that is in place: central bank loans to banks and bond purchases by the central bank. Unlike Full Reserve Banking proposals, CBDC designs do not intend to ban bank deposits.

The structure of this paper is as follows: Chapter two provides an overview of the current literature on the possible economic effects of CBDC. Chapter three explains the model used, including different agent behaviors. The various scenarios and model initialization are presented in chapter four. The results are outlined in chapter five, followed by a discussion of the findings in chapter six. Finally, chapter seven offers a conclusion.

2 Related literature

Economic literature has repeatedly covered the macroeconomic effects of CBDC (See Bindseil and Senner (2025) for an overview). Existing research can be broadly classified into four categories: Trade-Off, equivalence, study under imperfect market conditions and study of limited design.

Several studies highlight a trade-off between the benefits of CBDC and the negative effects resulting from disintermediation. Most of these studies abstract from central bank funding. By using a network-effect model Agur et al. (2022) find that while a shift from deposits to CBDC reduces bank funding due to loans fully financed by deposits, it improves payment efficiency. Keister and Sanches (2022) argue with a new monetarist model that CBDC enhances exchange efficiency but raises bank funding costs, reducing loan returns and investment. Thereby assuming the deposit rate directly affects loan returns and the loan grant decision. Burlon et al. (2024) incorporate central bank funding in their model and show that a CBDC remunerated below the return of central bank assets can boost GDP by increasing central bank profits and lowering taxes. On the other hand, banks require more collateral and are forced to replace loans with government bonds. This reduces banks' profit margin and lending capacities out of regulatory equity which reduces lending further and real GDP. Ahnert et al. (2023) analyze the impact of CBDC on financial stability in terms of bank run probability and finding again a trade-off: depending on the remuneration of CBDC it increases withdrawal incentives for bank depositors but at the same time increasing the interest rate of bank deposits and thereby decreasing the incentive. Schilling et al. (2024) present a trilemma, arguing that CBDC can only achieve two of three goals: efficiency, financial stability, and price stability.

Other studies suggest an equivalence between bank deposits and CBDC under certain conditions, implying minimal macroeconomic impact if these conditions hold. Thereby the central bank is usually the lender of last resort and can provide unlimited amounts of liquidity to banks without collateral requirements. Brunnermeier and Niepelt (2019) show in a generic model that public money (CBDC) and private money (deposits) can be equivalent if there are contingent transfers between households and the government. Fernández-Villaverde et al. (2021) use a Diamond-Dybvig model to establish equivalence when maturity transformation is absent. Gross and Schiller (2021) find with a DSGE model that unremunerated CBDC has little effect, while remunerated

CBDC may impact deposit rates by removing the zero lower bound. Frascini et al. (2024) show that CBDC is neutral under standard monetary policy but not under quantitative easing.

Studies under imperfect market conditions assume frictions in the deposit or lending market and make varying assumptions on central bank lending. Andolfatto (2018) suggests that CBDC increases deposit rates and reduces monopoly profits of banks but does not reduce lending since banks set loan rates independently of deposit rates. The increased deposit rate may increase lending if the unbanked population shifts from cash to deposits. Niepelt (2024) finds that CBDC could discipline banks more effectively than subsidies. Chiu et al. (2023) apply a general equilibrium model and argue that interest-bearing CBDC increases lending by setting a lower bound for deposit rates, forcing banks to compete. They assume that banks restrict their deposit supply to keep the deposit interest rate artificially low.

Some research examines limited CBDC with a fixed CBDC supply, issued only against government bonds or financed with it, avoiding the need for central bank liquidity support. Barrdear and Kumhof (2016) find that in a DSGE model such a design can lower real interest rates, taxes, and transaction costs, boosting GDP. Assenmacher et al. (2023) show that interest-bearing CBDC may smooth monetary policy responses to macroeconomic shocks.

Agent-based models also study CBDC with a focus on adoption. Ramadiah et al. (2021) and León et al. (2024) analyze CBDC's impact on consumer wealth and payment behaviors but focus less on broader economic implications. The model which comes closest to this research is the one by Gross and Letizia (2023). They investigate the demand for CBDC for the US and the EU in an agent-based stock-flow consistency model containing households, banks and one central bank. Thereby also the implications for the stocks and flow of the banking system are shown such as reduced bank profitability and increased seigniorage earnings for the central bank.

Overall, many economic papers share a common problem: the banking sector is often modeled unrealistically using a loanable funds approach, where loans are created by lending deposits. In Agur et al. (2022), banks make loans directly from deposits. Keister and Sanches (2022) and Chiu et al. (2023) assume that deposit interest rates directly influence loan supply. These models neglect the role of the policy rate in banks' interest-setting behavior and the central bank's influence, contrary to empirical evidence (Gregor et al., 2021). Moreover, many studies in the trade-off category assume that bank deposits and CBDC carry the same default risk. As a result, these studies

are inherently designed in a way that prevents CBDC from offering any potential benefits to risk-averse deposit holders. Consequently, their findings are difficult to apply in the context of CBDC introduced into the current banking system. Conversely, papers in the equivalence category, while modeling a more realistic banking sector, often operate at such high levels of abstraction that they cannot clearly determine whether CBDC is beneficial in specific scenarios. Furthermore, studies of limited designs cannot show whether CBDC is any beneficial if those limitations do not apply. The model developed in this paper distinguishes itself by implementing realistic endogenous money creation with stock-flow consistency. It draws on assumptions from the equivalence studies, including lender-of-last-resort guarantees and the absence of collateral requirements for central bank lending. Additionally, it incorporates imperfect market conditions in the deposit market, assuming limited competition with sticky deposits. The paper's key contribution is its detailed investigation of CBDC under different monetary policy and bank bankruptcy regimes—an area not previously explored in this depth. Earlier studies have primarily focused on positive interest corridor regimes and relied on bailout or deposit insurance mechanisms without explicitly modeling them. In contrast, this paper examines multiple monetary policy regimes and explicitly models various bank bankruptcy regimes under a situation of financial instability. Compared to Gross and Letizia (2023), this study introduces a production sector, treats CBDC demand as exogenous, and models bank lending rates as endogenous.

3 Model

I build on an agent-based stock-flow consistent model for a closed economy JMAB 2.0, which was developed by Hess (2025) and is an update of the model by Caiani et al. (2016).³ This model uses agents with different behaviors to model a dynamic macro economy. Furthermore, the stocks and flows of the agents are explicitly modeled to guarantee a stock-flow consistency, meaning that every flow implies the change in one or more stocks, and every financial asset has a corresponding liability. This section briefly summarizes the main aspects of the model.

The agents, their stocks, and financial flows between them are depicted in Figure 2. Overall, the model economy embraces six different types of agents: households H , consumption firms C , capital firms K , banks B , a government g and a central bank cb . Additionally, every agent may

³ The model developed in this paper is openly accessible under <https://github.com/simonhess/cbdc>

own specific stocks. There are deposits, reserves (CBDC), governments bonds, capital goods and consumption goods, loans, central bank loans (advances) and interbank loans.

The model processes forward in multiple periods with discrete timesteps $t_{0,1,...,T}$. Each period in the model represents one quarter of a year. In each period agents perform their activities along a predefined order. Agents follow certain strategies when performing activities and interact with other agents on markets. After each period selected aggregated and micro-agent data is collected in reports.

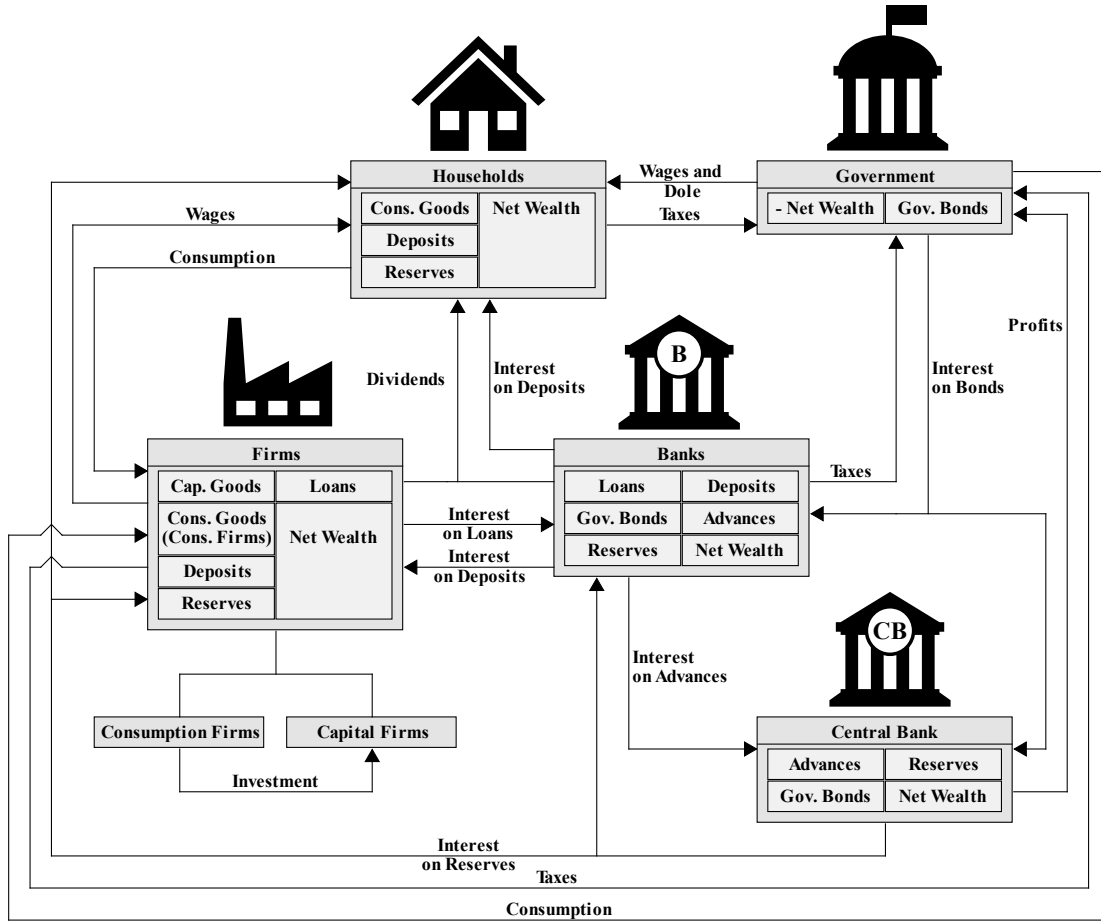


Figure 2: JMAB 2.0 with Extensions

The agents interact in seven markets: consumption and capital goods markets, loan market, deposit market, bond market, central bank advances market and the interbank market. Each market has its own matching mechanism. All markets are buyer markets where the buyer chooses its supplier. Each buyer is randomly chosen and randomly assigned a number of matching partners of suppliers ξ_x . The buyer preselects the supplier with the cheapest price (consumption good, capital good,

labor and loan) or highest price (deposits). If the preselected supplier offers a lower price than the past supplier (or higher price for deposits) the buyer switches its supplier to the preselected one with a fixed probability PS . If the past supplier is out of stock the buyers always switches. Buyers are matched with seller as long as there is at least one active buyer and one supplier. In each period events take place in the following order:

1. Expectations, Production planning: All agents formulate their expectations. Firms plan their desired production based on the expectations which creates the supply of consumption goods.
2. External Shock: The economy is hit with shocks. In this paper a digital bank run and bank asset value shock.
3. Labor demand, labor supply and labor market interaction: Firms determine their demand for labor while households determine their wage. Firms pick households at the market.
4. C and K Good Price determination: Consumption and capital firms set the prices of their goods.
5. CB policy: The central bank sets the rate on advances and reserves.
6. Interbank interest: banks determine the interest rate for interbank loans.
7. Capital market brochure: Consumption firms receive “brochures” from capital firms containing the prices of their goods. Based on this information consumption firms choose their supplier at the capital market. The pricing information is used later in credit demand planning.
8. Investment demand: Consumption firms determine their desired investment in capital goods.
9. Deposits and Reserve Interest payment: Banks pay interest on deposits of their depositors. The central bank pays interest to reserve holders.
10. Deposit and Loan interest rate: Banks set their interest on deposits and loans.
11. Credit supply, Credit demand and credit market interaction: Banks determine their maximum supply of credit. Firms determine their demand for credit. Firms choose their credit supplying bank and banks provide credit after assessing the credit worthiness.
12. Production: Firms produce consumption goods.
13. Wages and dole: Firms pay wages to their employees. The government pays wages to public servants and dole to unemployed households.

14. Consumption demand and market interaction: Households determine their demand for consumption goods and interact on the market by choosing the supplying firm and buying the goods. The government determines its demand and buys consumption goods as well.
15. Capital market: Consumption firms interact in the capital market and buying capital goods from the previously chosen supplier.
16. Interest and principal payment of credit, advances, interbank and bonds: Firms make interest and principal payments on their credits. Banks make interest and principal payments on advances and interbank credits. The government pays interest on its bonds and repays them.
17. Taxes: Firms, banks and households make tax payments.
18. Dividends: Firms and banks pay out dividends.
19. Deposit demand and market interaction: Firms and households determine their demand for deposits (if there is also cash available) and interact on the deposit market by choosing their deposit supplier and transferring their deposits to that bank.
20. Bond interest, supply, demand, and market interaction: Government determines its interest and supply of bonds and issues them. Banks determine their demand for bonds and interact on the bond market by buying them from the government. The central bank buys leftover bonds which were not purchased by banks.
21. Interbank credit supply, demand, and market interaction: Banks determine their supply and demand for interbank credit. Demanding banks choose their supplier. Supplying banks grant credit.
22. Reserve demand and market interaction: Banks determine their demand for reserves. The central bank grants advances to all requesting banks.
23. Bankruptcy: Firms and banks with negative net wealth are recapitalized.

This paper also relies on the denotation by Caiani et al. (2016). Thus, capital firms are denoted with k , consumptions firms with c , household with h and banks with b . Terms that apply to both consumption and capital firms are denoted with x .

3.1 Firms

Firms produce and sell goods. While capital firms produce capital goods consumptions firms produce consumption goods. Consequently, firms hire workers and borrow from banks. Consumption firms additionally invest in capital goods.

3.1.1 Expectation of Sales and price determination

Firms predict their future sales using rule-based (RB) adaptive expectations. Thereby, the expectation $s_{x,t}^{eRB}$ is increased when sales from the last period are greater than expected and vice versa:

$$s_{x,t}^{eRB} = \begin{cases} s_{x,t-1}^{eRB} + \alpha_x^S LN & \text{if } s_{x,t-1} > s_{x,t-1}^{eRB} \\ s_{x,t-1}^{eRB} - \alpha_x^S LN & \text{if } s_{x,t-1} < s_{x,t-1}^{eRB} \end{cases} \quad (3.1)$$

where LN is a random number drawn from a lognormal distribution with the parameters mean μ_{LN} and standard deviation σ_{LN}^2 . α_x^S is the fixed adaptive parameter which determines the step size of the increase/decrease.

The markup of a firm is adjusted analogously. If sales were higher than expected, the firm increases its markup to make its goods less attractive. Conversely, if sales were lower, the firm decreases its markup to make their goods more attractive.

$$mu_{x,t} = \begin{cases} \overline{mu}_{x,t-1} + \alpha_x^{mu} LN & \text{if } s_{x,t-1} > s_{x,t-1}^{eRB} \\ \overline{mu}_{x,t-1} - \alpha_x^{mu} LN & \text{if } s_{x,t-1} < s_{x,t-1}^{eRB} \end{cases} \quad (3.2)$$

With $\overline{mu}_{x,t-1}$ being the average markup of all firms in the last periods which is approximated by the firm with its own unit cost.

Firms set the prices of their goods by charging a non-negative markup $mu_{x,t}$ on their unit costs:

$$p_{k,t} = (1 + mu_{x,t})uc_{x,t} \quad (3.3)$$

The unit costs for capital firms are defined as the expected labor costs multiplied by the labor demand, plus the interest paid on loans in the last period (current loans are granted after price determination), divided by the desired output:

$$uc_{k,t} = \frac{\sum_{n \in N_{k,t}} W_{n,t} + i_{k,t-1}^L L_{k,t-1}}{y_{k,t}^d} \quad (3.4)$$

where $W_{n,t}$ is the wage of employee n of firm k and $y_{k,t}^d$ is the desired output.

Consumption firms on the other hand rely on the normal-cost pricing method, as described by Godley and Lavoie (2007), and set their prices with a non-negative markup on their normal unit costs:

$$p_{c,t} = (1 + mu_{x,t})nuc_{x,t} \quad (3.5)$$

Normal unit costs are defined as the costs a consumption firm incurs when operating at full capacity at its target level of capacity utilization and are calculated by dividing labor costs, interest paid, and amortization by the normal output:

$$nuc_{c,t} = \frac{\sum_{n \in N_{c,t}} W_{n,t} + i_{c,t-1}^L L_{c,t-1} + \sum_{k \in K_{c,t-1}} (k^k p^k) \frac{1}{\kappa}}{y_{c,t}^n} \quad (3.6)$$

Normal output is the output at full capacity and is defined as $y_{c,t}^n = K_{c,t} cu_c^T$. This way consumption firms set their prices independently of their capacity utilization and stay competitive.

3.1.2 Production planning

Every firm x computes their desired output $y_{x,t}^d$ based on the firms' sales expectations $s_{x,t}^{eRB}$, the current inventories $inv_{x,t}$ and the target inventories-to-sales ratio v :

$$y_{x,t}^d = s_{x,t}^{eRB} (1 + v) - inv_{x,t} \text{ with } x = \{c, k\} \quad (3.7)$$

3.1.3 Labor Demand

Capital firms produce their output using labor only. Their demand for labor is determined by the desired output and labor productivity μ_N :

$$N_{k,t}^d = y_{k,t}^d / \mu_N \quad (3.8)$$

The labor productivity is assumed to be constant and exogenous. Labor demand by consumption firm is:

$$N_{c,t}^d = cu_{c,t}^d \frac{k_{c,t}}{l_k} \quad (3.9)$$

where $k_{c,t}$ is the real stock of capital, l_k is the constant capital-labor ratio, and $cu_{c,t}^d$ is the rate of capacity utilization needed to produce $y_{c,t}^d$. $cu_{c,t}^d$ is defined as:

$$cu_{c,t}^d = \min \left\{ 1, \frac{y_{c,t}^d}{k_{c,t} \mu_K} \right\} \quad (3.10)$$

where μ_K is capital productivity, which is fixed and determined exogenously.

3.1.4 Firm's profits and dividends

The pre-tax profit of a consumption firm is defined by considering revenues from sales, interest received, the nominal variation of inventories (priced in unit costs), wages, interest paid on loans, and capital amortization:

$$\begin{aligned} \Pi_{c,t} = & s_{c,t} p_{c,t} + i_{b,t-1}^D D_{c,t-1} + i_{cb,t-1}^R R_{c,t-1} + (inv_{c,t} uc_{c,t} - inv_{c,t-1} uc_{c,t-1}) \\ & - \sum_{n \in N_{c,t}} W_{n,t} - \sum_{j=t-\eta}^{t-1} i_{c,j}^L L_{c,j} \frac{\eta - [(t-1) - j]}{\eta} - \sum_{k \in K_{c,t-1}} (k^k p^k) \frac{1}{k} \end{aligned} \quad (3.11)$$

where $i_{b,t-1}^D D_{c,t-1}$ and $i_{cb,t-1}^R R_{c,t-1}$ is the interest received on deposits and reserves from the previous period, uc_{ct} are unit costs of production, $W_{n,t}$ is the wage paid to worker n , $i_{c,j}^L$ is the interest rate on loan $L_{c,j}$ obtained in period $j = t - \eta, \dots, t - 1$, p^k is the price paid for the batch of capital goods k^k belonging to the firm's collection of capital goods $K_{c,t-1}$, and $\eta = k$ are the durations of loans and capital. Pre-tax profits of capital firms are defined similarly, except that there is no capital amortization. Based on pre-tax profits the dividends can be determined as follows:

$$Div_{x,t} = \rho_x (1 - \tau_x) \max\{0, \Pi_{x,t}\} \quad (3.12)$$

where τ_x is the firm's tax rate and ρ_x is its dividend payout ratio which are both fixed and endogenously given.

3.1.5 Firm's loan demand

To ensure sufficient liquid assets for their operations, firms take out loans. It is assumed that firms do not issue new shares, relying instead on retained profits and bank loans. The loan demand of a consumption firm is determined by its investment, expected dividends, wages, principal payments, minus the expected operating cash flow and deposits:

$$L_{c,t}^d = \max \left\{ I_{c,t}^d + Div_{c,t}^e + \sigma \sum_{n \in N_{c,t}} W_{n,t} + \sum_{j=t-\eta}^{t-1} L_{c,j} \frac{1}{\eta} - OCF_{c,t}^e - D_{c,t} - R_{c,t}, 0 \right\} \quad (3.13)$$

where $Div_{c,t}^e = \rho_x(1 - \tau_x)\Pi_{x,t}^e$ are the expected dividend disbursements. Firms consider their wage disbursements with the factor σ to maintain a liquidity buffer. Expected profits $\Pi_{x,t}^e$ are calculated analogously to Equation 3.10, with the exception that revenue and change in inventories are calculated using expected sales $s_{c,t}^{eRB}$ instead of actual sales $s_{x,t}$. Expected operating cash flow is calculated as:

$$OCF_{x,t}^e = s_{x,t}^{eRB} p_{x,t} + i_{x,t-1}^D D_{x,t-1} + i_{x,t-1}^R R_{x,t-1} - \sum_{n \in N_{c,t}} W_{n,t} - i_{x,t-1}^L L_{x,t-1} - T_{x,t}^e \quad (3.14)$$

where expected taxes are defined as $T_{x,t}^e = \tau_x \Pi_{x,t}^e$. The loan demand for capital firms is determined similarly, except that investment in capital goods is excluded.

3.1.6 Investment demand

Consumption firms increase their investment by a random number if the desired capacity is above current capacity and the net present value of the current capital is greater than 0.

$$i_{c,t} = \begin{cases} i_{c,t-1} + \alpha_c^i LN & \text{if } k_{c,t}^d > k_{c,t-1} \text{ and } NPV_{c,t} > 0 \\ i_{c,t-1} - \alpha_c^i LN & \text{if } k_{c,t}^d < k_{c,t-1} \end{cases} \quad (3.1)$$

Net present value is calculated by summing up discounted future cashflows of one capital unit and subtracting the investment cost the price of one capital unit:

$$NPV_{c,t} = \sum_{n=1}^m \frac{ROR K_{c,t+n}^{eDES}}{(1 + WACC_{c,t})^n} - p_k \quad (3.2)$$

The future cash flow is calculated by considering the expected return on real capital $RORK_{c,t}^{eDES}$ which is the double exponentially smoothed expectation of unlevered free cash flow divided by capital stock $RORK_{c,t} = UFCF_{c,t}/k_{c,t}$. Unlevered free cash flow in turn is defined as profits minus interest payment minus amortization minus investment. The expectation of return on real capital is computed with double exponential smoothing to account for the nominal increasing trend. For a generic variable z_t , the double exponentially smoothed expectation z_t^{eDES} is calculated as follows:

$$lvl_t = \beta^{lvl} z_{t-1} + (1 - \beta^{lvl})(lvl_{t-1} + trd_{t-1}) \quad (3.3)$$

$$trd_t = \beta^{trd}(lvl_t - lvl_{t-1}) + (1 - \beta^{trd})trd_{t-1} \quad (3.4)$$

$$z_t^{eDES} = lvl_t + trd_t \quad (3.5)$$

$$z_{t+n}^{eDES} = lvl_t + n trd_t \quad (3.6)$$

with lvl_t and trd_t being the level and trend while β^{lvl} and β^{trd} being the respective smoothing parameters for the level and trend.

The discount factor used to calculate the NPV is the weighted average cost of capital (WACC), calculated as follows:

$$WACC_{c,t} = \overline{ROE}_{c,t-1} \overline{ER}_{c,t-1} + \bar{i}_{b,t-1}^L (1 - \overline{ER}_{c,t-1}) \quad (3.7)$$

where $\overline{ROE}_{c,t-1}$ is the average return on equity, $\overline{ER}_{c,t-1}$ is the average equity ratio of all consumption firms in the previous period, and $\bar{i}_{b,t-1}^L$ is the average interest rate on loans of all banks in previous period. Average values are used so that firms can compare themselves to the market.

3.1.7 Demand for liquid assets

Firms maintain their liquid assets in a financial portfolio containing deposits and reserves. The portfolio weights ω_x^D for deposits and ω_x^R for reserves with the constrain $\omega_x^D + \omega_x^R = 1$ determine the share of liquid assets a firm wants to hold in deposits and cash. The demand for deposits is therefore $D_{x,t}^d = \omega_x^D (D_{x,t} + R_{x,t})$ while the demand for reserves is $R_{x,t}^d = \omega_x^R (D_{x,t} + R_{x,t})$.

3.2 Households

Households work, purchase consumption goods and keep deposits with banks. Additionally, they own firms and banks and receive dividends from both.

3.2.1 Wage determination

A worker (an employed household) determines their desired wage based on an adaptive heuristic. If the worker has been unemployed for more than four periods, they decrease their demanded wage. Otherwise, the worker increases it:

$$W_{h,t}^d = \begin{cases} W_{h,t-1}^d (1 + LN) & \text{if } \sum_{n=1}^4 \varepsilon_{h,t-n} > 0 \\ W_{h,t-1}^d (1 - LN) & \text{else} \end{cases} \quad (3.15)$$

where $\varepsilon_{h,t} = 1$ if h is employed in t , and 0 otherwise. Unemployed workers receive a share θ of average wages as dole.

There is also a turnover ratio ϑ , which describes the portion of the workforce in consumption firms, capital firms, and the government that is fired and replaced each period by random households from the unemployed population, which includes the fired workers.

3.2.2 Consumption

A household's consumption is determined by fixed propensities to consume out of net income pc_h^{NI} and net wealth pc_h^{NW} . Real consumption demand can be derived by dividing net consumption by the current price:

$$c_{h,t}^d = \frac{pc_h^{NI} NI_{h,t} + pc_h^{NW} (NW_{h,t-1} - Div_{h,t-1})}{p_{c,t}} \quad (3.16)$$

where $NI_{h,t}$ is the net income, $NW_{h,t-1}$ is the previous net wealth, and $p_{h,t}$ is the current price for consumption goods. Dividends are paid at the end of each period as the order of agent activities suggests and are consumed in the next period. To prevent them from being consumed twice (as part of net income and previous net wealth) they are excluded from previous net wealth.

3.2.3 Demand for liquid assets

Households maintain their net wealth in a financial portfolio containing deposits and reserves same as firms described in chapter 3.1.7.

3.3 Banks

Banks grant loans to firms and accept deposits from households and firms. Another source of funding are central bank loans, which are called advances. Whenever banks grant loans or buy government bonds they create deposits at the same time, which is in line with the endogenous money model and current practice (Jakab and Kumhof, 2018; Werner, 2014). Every bank has a reserve account with the central bank.

3.3.1 Loan supply

The loan supply of a bank is constrained by its expected capital adequacy ratio and its target. The capital adequacy ratio is defined as the ratio of equity to risky assets $CAR_{b,t} = NW/L$ while the target capital adequacy ratio CAR_b^T is given exogenously. Bonds and interbank credit are considered risk-free. The maximum credit supply is determined by the expected net wealth divided by the target capital adequacy ratio, minus current loans plus the principal payments:

$$L_{b,t}^s = \frac{NW_{b,t-1} + \Pi_{b,t}^e}{CAR_b^T} - L_{b,t} + \sum_{j=t-\eta}^{t-1} L_{b,j} \frac{1}{\eta} \quad (3.17)$$

where $\Pi_{b,t}^e$ represents expected after-tax profits, calculated by subtracting the interest costs of all liabilities from the interest revenue of all assets and applying the tax rate.

3.3.2 Bank's Dividends

Banks pay dividends based on their capital adequacy ratio. A bank compares its past net worth $NW_{b,t-1}$ with its target net worth defined as $NW_{b,t}^T = CAR_b^T L_{b,t}$. If past net worth is lower than the target the banks only pays dividends if profits are higher than the missing capital gap. If past net worth is higher than the target, the bank pays out its full profit as dividends, plus a portion λ of the excess capital to gradually reduce it:

$$\begin{aligned}
& Div_{b,t} \\
&= \begin{cases} \max\{0, (1 - \tau_b)\Pi_{b,t}\} + (NW_{b,t-1} - NW_{b,t}^T)\lambda & \text{if } NW_{b,t-1} \geq NW_{b,t}^T, \\ \max\{0, \max\{0, (1 - \tau_b)\Pi_{b,t}\} + (NW_{b,t-1} - NW_{b,t}^T)\} & \text{otherwise} \end{cases} \quad (3.18)
\end{aligned}$$

3.3.3 Loan Interest Rate

A bank determines its loan rate as a non-negative markup $mu_{b,t}$ over the interbank loan rate as a reference rate:

$$i_{b,t}^L = i_{b,t}^{LBL} + mu_{b,t} \quad (3.19)$$

The markup is adjusted using an adaptive heuristic, similar to the one used for firms' real sales expectations. Instead of real sales, banks rely on the real new loans granted in the previous period $\hat{l}_{b,t-1} = \hat{L}_{b,t-1}/\pi_{t-1}$ and its expectation $\hat{l}_{b,t-1}^{eRB}$. If real new loans from the previous period exceed expectations, the bank increases its markup and expectation. Otherwise, both are decreased:

$$mu_{b,t} = \begin{cases} \overline{mu}_{b,t-1} + \alpha_b^{mu} LN & \text{if } \hat{l}_{b,t-1} > \hat{l}_{b,t-1}^{eRB}, \\ \overline{mu}_{b,t-1} - \alpha_b^{mu} LN & \text{if } \hat{l}_{b,t-1} < \hat{l}_{b,t-1}^{eRB} \end{cases} \quad (3.20)$$

$$\hat{l}_{b,t}^{eRB} = \begin{cases} \hat{l}_{b,t-1}^{eRB} + \alpha_b^{\hat{l}} LN & \text{if } \hat{l}_{b,t-1} > \hat{l}_{b,t-1}^{eRB}, \\ \hat{l}_{b,t-1}^{eRB} - \alpha_b^{\hat{l}} LN & \text{if } \hat{l}_{b,t-1} < \hat{l}_{b,t-1}^{eRB} \end{cases} \quad (3.21)$$

where $\overline{mu}_{b,t-1}$ is the average markup of all banks in the previous period.

3.3.4 Loan Approval Decision

A bank makes the loan approval decision for a requested loan L^d based on a recursive function. If the expected return r^e on the initial amount $L_0 = L^d$ is greater than zero the bank supplies the full amount. Otherwise, the loan amount is reduced by one percent of the initial amount $L_0 = L^d$ till the expected return of that amount is greater than zero or the loan amount cannot be reduced further:

$$L_{b,t}^s(L_n) = \begin{cases} 0 & \text{if } L_n = 0, \\ L_n & \text{if } r^e(L_n, i_{b,t}^L, PD_{x,t}(L_n), \delta_x) > 0, \\ L_{b,t}^s(L_n - L_0/100) & \text{otherwise} \end{cases} \quad (3.8)$$

The expected profit is calculated with consideration of the discounted expected cashflow and discounted expected loss:

$$r^e = \sum_{j=1}^{\eta} \left((1 - PD_{x,t}) \frac{ds_j^{L^d}}{(1 + i_{b,t}^{IBL})^n} - PD_{x,t} \frac{L_j^d (1 - \delta_x)}{(1 + i_{b,t}^{IBL})^n} \right) - L^d \quad (3.9)$$

where $L_j^d = L^d \frac{\eta-j+1}{\eta}$ is the remaining loan value at time j , $ds_j^{L^d} = L^d \frac{1}{\eta} + L_j^d i_{b,t}^L$ the debt service at time n , and δ_x is the recovery rate defined as the ratio between the discounted value of the firm's capital to total debt. The debt service from the loan and the potential defaulted loan amount are thereby discounted using the interbank rate $i_{b,t}^{IBL}$ as a proxy for the financing costs. When the initial loan amount is subtracted, the bank receives the expected return on the loan.

The probability of default in turn is calculated with the debt service coverage ratio:

$$PD_{xt} = \frac{1}{1 + \exp \left(\zeta \frac{EBITDA_{x,t}^{eDES}}{ds_{x,t+1}^{L^{tot}}} - 5 \right)} \quad (3.10)$$

where ζ is the bank's risk aversion parameter towards firms. Capital firms use a double-exponential smoothed expectation of earnings before interest, taxes, depreciation, and amortization $EBITDA_{x,t}$, defined as pre-tax profits plus interest payments:

$$EBITDA_{k,t} = \Pi_{k,t} + \sum_{j=t-\eta}^{t-1} i_{k,j}^L L_{k,j} \frac{\eta - [(t-1) - j]}{\eta} \quad (3.11)$$

Consumption firms in contrast, use a double exponential smoothed expectation of EBITDA minus CAPEX $EMC_{c,t}$, which adds capital amortization and subtracts capital expenditure (CAPEX):

$$EMC_{c,t} = \Pi_{c,t} + \sum_{j=t-\eta}^{t-1} i_{c,j}^L L_{c,j} \frac{\eta - [(t-1) - j]}{\eta} + \sum_{k \in K_{c,t-1}} (k^k p^k) \frac{1}{k} - I_{c,t}^d \quad (3.12)$$

The total debt service is defined as the sum of the future debt services for all existing loans and the first debt service of the demanded loan:

$$ds_{x,t+1}^{L^{tot}} = \sum_{j=t-\eta+1}^{t-1} \left(L_{x,j} \frac{1}{\eta} + i_j^L L_{x,j} \frac{\eta - 1 - [(t-1) - j]}{\eta} \right) + \left(i_{b,t}^L + \frac{1}{\eta} \right) L^d \quad (3.13)$$

3.3.5 Deposit Interest Rate

A bank determines its deposit interest rate based on its excess liquidity, opportunity costs, and the profit from reserves, which is inspired by Schasfoort et al. (2017). A bank will aim to attract customers (by increasing the deposit rate) when it has a liquidity deficit (excess liquidity is zero or negative), deposit funding is cheaper than interbank market funding (the current deposit rate is lower than or equal to the upper bound), and the profit on reserves exceeds the cost of deposits. Conversely, a bank will seek to repel customers (by lowering the deposit rate) when it holds excess reserves, alternate funding is cheaper than deposits, or no profits are earned from reserves. The liquidity deficit aspect is covered by χ^{LD} , the opportunity cost aspect by χ^{OC} and the profit on reserves aspect by χ^{PR} :

$$\chi^{LD} = \begin{cases} 1 & \text{if } EL_{b,t} \leq 0 \\ -1 & \text{otherwise} \end{cases} \quad (3.14)$$

$$\chi^{OC} = \begin{cases} 1 & \text{if } i_{b,t-1}^D \leq i_{b,t}^{DUB} \\ -1 & \text{otherwise} \end{cases} \quad (3.15)$$

$$\chi^{PR} = \begin{cases} 1 & \text{if } i_{b,t-1}^D \leq i_{cb,t}^R \\ -1 & \text{otherwise} \end{cases} \quad (3.16)$$

Excess liquidity is defined as:

$$EL_{b,t} = R_{b,t-1} - A_{b,t-1} + IBL_{b,t-1} - IBB_{b,t-1} - D_{b,t-1}LR_b^T \quad (3.17)$$

where $IBL_{b,t-1}$ are interbank loans, $IBB_{b,t-1}$ is interbank borrowing (interbank loans on the liability side), and LR_b^T is the target liquidity ratio set exogenously by the central bank.

The deposit upper bound $i_{b,t}^{DUB}$ represents the maximum rate the bank is willing to pay before deposit funding becomes more expensive than funding through the interbank market. This upper bound considers the cost of minimum reserves, as banks must pay for central bank advances to maintain minimum reserves. Additionally, it accounts for the cost of excess reserves. If excess reserves earn a lower interest rate than the interbank rate, the bank incurs losses. Therefore, the upper bound is defined as:

$$i_{b,t}^{DUB} = i_{b,t}^{IBL} - \max\{LR_b^T - \max\{\overline{NLR}_{b,t}, 0\}, 0\}(i_{cb,t}^A - i_{cb,t}^R) \\ - \max\{\overline{NLR}_{b,t}, 0\}(i_{b,t}^{IBL} - i_{cb,t}^R) \quad (3.18)$$

The cost of minimum reserves is determined by the first subtrahend, where the portion (relative to deposits) of minimum reserves financed with advances is multiplied by the spread between the advances rate and reserves rate. The second subtrahend accounts for the cost of excess reserves. The proportion of excess reserves is multiplied by the spread between the interbank rate and the central bank reserves rate. The interbank rate is used here as a proxy for the funding cost of excess reserves. $\overline{NLR}_{b,t}$ is the average net liquidity ratio of all banks, defined as:

$$\overline{NLR}_{b,t} = \frac{\sum_{bSize} (R_{b,t-1} - A_{b,t-1})}{\sum_{bSize} D_{b,t}} \quad (3.19)$$

Additionally, banks also consider the upward stickiness of deposits. Thus, banks adjust their deposit rate only with a delay if the policy rate increases while instantaneously adjust their rate if the policy rate is decreased. This is realized in this model by the stickiness parameter χ^{ST} . The parameter is 1 if the policy rate is above the deposit rate ($i_{b,t}^{DUB} > i_{b,t-1}^D$) with a probability of fifty percent (cumulative distribution function CDF of a log normally generated random number LN_2 is smaller than 0.5) and -1 otherwise:

$$\chi^{ST} = \begin{cases} 1 & \text{if } i_{b,t}^{DUB} > i_{b,t-1}^D \text{ and } CDF(LN_2) < 0.5, \\ -1 & \text{otherwise} \end{cases} \quad (3.20)$$

Based on these values, an adaptive heuristic is applied. If the sum of the values is greater than 0 and stickiness parameter is negative meaning no stickiness, the bank raises its rate above the previous average deposit interest rate of all banks. Otherwise, the rate is decreased below the previous average rate. If the stickiness parameter is 1 the deposit rate stays the same:

$$i_{b,t}^D = \begin{cases} \min \{ \bar{i}_{b,t-1}^D + \alpha_b^D LN, i_{b,t}^{DUB} \} & \text{if } \chi^{LR} + \chi^{OC} + \chi^{RP} > 0 \text{ and } \chi^{ST} = -1, \\ \max \{ \bar{i}_{b,t-1}^D - \alpha_b^D LN, 0 \} & \text{if } \chi^{LR} + \chi^{OC} + \chi^{RP} \leq 0 \text{ and } \chi^{ST} = -1, \\ \bar{i}_{b,t-1}^D & \text{otherwise} \end{cases} \quad (3.21)$$

where $\bar{i}_{b,t-1}^D$ is the average deposit interest rate of all banks in the past period.

3.3.6 Interbank Market

Competition in the deposit market leads to reserve imbalances between banks which can be balanced through the interbank market. A bank's supply of interbank loans is determined by its excess reserves as described in Equation (3.17):

$$IBL_{b,t}^S = ER_{b,t} \quad (3.22)$$

The demand for reserves of banks with a liquidity deficit is determined analogously:

$$IBL_{b,t}^d = \min\{0, ER_{b,t}\}(-1) \quad (3.23)$$

I assume that there is perfect competition and information on the interbank market. Therefore, the interbank interest rate is based on the total amount of excess reserves in the banking system and is determined with a linear function which is the percentage deviation of excess reserves to required reserves:

$$i_{b,t}^{IBL} = i_{cb,t}^A - (i_{cb,t}^A - i_{cb,t}^R) \min\left\{\frac{\sum_{bSize} NL_b}{LR_b^T \sum_{bSize} D_b}, 1\right\} \quad (3.24)$$

Banks are always willing to lend if they have excess liquidity because this would be more profitable than holding reserves at the central bank and interbank loans are considered risk free.

3.3.7 Demand for Reserves

If the demand for reserves cannot be satisfied on the interbank market, banks apply for advances from the central bank. A bank determines its demand for reserves from the central bank by comparing its reserves with its target liquidity given by the target liquidity ratio, which is assumed to be defined exogenously by regulatory requirements, multiplied with its current deposits:

$$R_{b,t}^d = \max\{LR_t D_{b,t} - R_{b,t}, 0\} \quad (3.25)$$

Banks can borrow from the central bank without collateral and the central bank is always willing to lend to banks as the lender of last resort.

3.3.8 Demand for Bonds

The demand for bonds $b_{b,t}^d$ of a bank is determined by two factors: first, the bank's deposit amount relative to the total non-bank money supply, since this portion can be financed by cheap deposits. Second, the relation between the non-bank money supply other than bank deposits and the total non-bank money supply divided by the number of banks. This portion is financed with central bank funding:

$$b_{b,t}^d = b_{g,t}^s \left(\frac{D_{b,t}}{M_{nonbs}} + \frac{\left(1 - \frac{D_{nonbs}}{M_{nonbs}}\right)}{size_B} \right) \quad (3.26)$$

where M_{nonbs} is the money supply of all non-bank agents and D_{nonbs} the deposit amount of all non-bank agents.

3.4 Central bank

The central bank lends at the rate for advances and buys bonds which have not been purchased by banks. It determines its lending rate, the advances rate, following a Taylor rule with inflation targeting, an unemployment gap and smoothing:

$$i_{cb,t}^A = \beta^{tay} i_{cb,t-1}^A + (1 - \beta^{tay}) \left(\pi_{t-1} + i^{nat} + (\pi_{t-1} - \pi_{cb}^T) + (u_{t-1} - u_{cb,t}^{eSES}) \right) \quad (3.27)$$

where π_t is the inflation rate on consumption goods, π_{cb}^T is the exogenously given inflation target, i^{nat} is the natural rate of interest and β^{tay} is the smoothing parameter. The expected unemployment rate $u_{cb,t}^{eSES}$ is an approximation of the natural rate of unemployment (NROU) and is based on the simple exponentially smoothed past unemployment rates. The simple exponentially smoothed expectation e^{SES} for a variable z is defined as:

$$z_t^{eSES} = z_{t-1}^{eSES} + \beta^{SES} (z_{t-1} - z_{t-1}^{eSES}) \quad (3.28)$$

Where β^{SES} is the smoothing parameter. SES is employed in this case since there is no trend in the data.

The profit of the central bank is transferred to the government and can be derived from interest on government bonds plus interest on central bank advances.

$$\Pi_{cb,t} = i_{g,t-1}^B B_{cb,t-1} + i_{cb,t-1}^A A_{cb,t-1} - i_{cb,t-1}^R R_{cb,t-1} \quad (3.29)$$

The central bank buys governments which have not been purchased by banks:

$$b_{cb,t}^d = b_{g,t}^s - b_{b,t}^d \quad (3.30)$$

3.5 Government

The government employs workers, pays dole to unemployed workers and buys consumption goods. The deficit of the government is financed through the issuance of bonds and is determined based on taxes, wages to government employees, dole and interest payments on bonds:

$$\bar{p}^b \Delta b_t = T_t - \sum_{n \in N_{g,t}} W_n - U_t d_t - i_{g,t}^B \bar{p}^b b_{t-1} \quad (3.31)$$

where T_t is the sum of $T_{H,t} + T_{C,t} + T_{K,t} + T_{B,t}$, d_t are the unemployment benefits defined as $\theta \bar{W}_n$, U_t is the number of unemployed households, $i_{g,t}^B$ the interest on bonds, \bar{p}^b is the fixed price of bonds and N_{gt} the collection of public workers. The interest rate of bonds follows the rate for interbank loans:

$$i_{g,t}^B = i_{b,t}^{LBL} \quad (3.32)$$

All bonds are bought by either the banks or the central bank depending on the monetary regime (ceiling or floor). In this paper the model is calibrated with a ceiling regime. Furthermore, the government has a reserve account at the central bank by default and handles all transactions with this account.

The government spends all its central bank profits on consumption goods to keep the Debt-GDP ratio constant in the baseline and the CBDC model:

$$c_{g,t}^d = \frac{\max\{0, \Pi_{cb,t}\}}{\bar{p}_{c,t}} \quad (3.33)$$

Where $\bar{p}_{c,t}$ is the average price for consumption goods on the market. This prevents the debt-GDP ratio from falling and decreasing economic output. The same procedure is applied by Barrdear and Kumhof (2016). The central bank profits could also be used to reduce taxes as in the model of Barrdear and Kumhof (2016) (lower average cost of government financing). Furthermore, the government buys consumption goods from all consumption firms proportionally to their market share to minimize the influence on the competition in the market.

3.6 Firm Bankruptcy

If a firm goes bankrupt meaning that it cannot repay its loans or wages it undergoes a bankruptcy procedure. Thereby the firm's liquid assets are distributed to its creditors and its capital goods are symbolically sold to households to raise additional funds. The capital goods do not leave the firm because it is assumed that households transfer the bought capital goods directly back to the respective firm. After that the firm is recapitalized with the net wealth of households if it has insufficient capital.

3.7 Bank Bankruptcy Regimes

When a bank exhibits negative net wealth, it undergoes a bankruptcy process. Generally, without CBDC there are three possibilities how bank bankruptcies can be handled in the model: Bail-out by the state, bail-in by depositors and rescue by the deposit insurance scheme. The three regimes differ in how the negative net wealth is paid off. With CBDC there is an additional bank bankruptcy regime. For simplicity after the payoff in all regimes banks are recapitalized by all households proportionally to their wealth (Deposits + CBDC). The recapitalization payment by each household can be defined as:

$$RECAP_{h,b,t} = \frac{NW_{h,t} L_{b,t} CAR_b^T}{NW_{H,t}} \quad (3.34)$$

3.7.1 Bail-out by the Government

In a bail-out regime the negative net wealth is paid off by the government. To keep Debt-GDP ratio fixed this bailout is financed through a one-time wealth dependent tax raised on households. The bank rescue payment RP each households makes is defined as follows:

$$RP_{x,b,t} = \frac{NW_{h,t} (-NW_{b,t})}{NW_{H,t}} \quad (3.35)$$

3.7.2 Bail-In by Depositors

In a bail-in regime the negative net wealth is paid off by the depositors and interbank creditors of the bankrupt bank. If there are not enough deposits, the bailout strategy applies. Each depositor x bails in the amount proportionally to the amount of his/her deposit held with bank b :

$$RP_{h,b,t} = \frac{D_{x,b,t}(-NW_{b,t})}{D_{b,t}} \quad (3.36)$$

3.7.3 Bank bankruptcy with CBDC

In a system with CBDC and a digital bank run, the bank bankruptcy process works analogously to a bailout by the government. Due to the bank run and liquidity demand the central bank granted uncollateralized loans to the bankrupt bank and became its only creditor. Before the central bank writes off these bad loans and runs into negative net wealth the bankrupt bank receives a bailout by the government in this model. Another option would be the bailout of the central bank but for simplicity the former is applied. It should be noted that CBDC cannot be considered as completely risk free since households would lose an amount of their wealth through the bailout.

3.7.4 Deposit Insurance Scheme

In a deposit insurance scheme, the negative net wealth of the failed bank is paid off by the deposit insurance fund which is financed by all banks and their customers. The scheme may be set up as ex-ante or ex-post. In an ex-ante scheme, the bank rescue payments are made before the bankruptcy has taken place, which usually includes a fund. In an ex-post scheme, the bank rescue payments are made after the bankruptcy has taken place. This paper implements an ex-ante scheme. All banks make contributions to the deposit insurance fund proportionally to their deposit stock. The contribution is made from the banks net wealth and therefore their interest spread earning from their customers. The fund is held by the government. If the deposit insurance fund does not have sufficient deposit insurance reserves, as in the case of a systemic bank failure, the bailout strategy (Chapter 3.7.1) applies. Contrary to most deposit insurance schemes in practice there is no upper limit on the deposit amount that is insured.

Each bank has a deposit insurance fund target which is determined by the amount of deposits and the deposit coverage target ratio $DIF_{b,t}^T = D_{b,t}DIRR^T$. The dividend of a bank is determined depending on both the differences in its net wealth and its deposit insurance fund from their targets. Thereby four cases arise:

$$\chi^{Div} = \begin{cases} 1 & \text{if } NW_{b,t-1} \geq NW_{b,t}^T \text{ and } DIF_{b,t-1} \geq DIF_{b,t}^T, \\ 2 & \text{if } NW_{b,t-1} \geq NW_{b,t}^T \text{ and } DIF_{b,t-1} < DIF_{b,t}^T, \\ 3 & \text{if } NW_{b,t-1} < NW_{b,t}^T \text{ and } DIF_{b,t-1} \geq DIF_{b,t}^T, \\ 4 & \text{if } NW_{b,t-1} < NW_{b,t}^T \text{ and } DIF_{b,t-1} < DIF_{b,t}^T \end{cases} \quad (3.37)$$

Based on the four cases the dividend of a bank can be determined:

$$Div_{b,t} = \begin{cases} \max\{0, (1 - \tau_b)\Pi_{b,t}\} + \Delta NW_{b,t}\lambda + \Delta DIF_{b,t}\lambda & \text{if } \chi^{Div} = 1, \\ \max\{0, \max\{0, (1 - \tau_b)\Pi_{b,t}\} + \Delta NW_{b,t}\lambda + \Delta DIF_{b,t}\lambda\} & \text{if } \chi^{Div} = 2, \\ \max\{0, \max\{0, (1 - \tau_b)\Pi_{b,t}\} + \Delta NW_{b,t} + \Delta DIF_{b,t}\lambda\} & \text{if } \chi^{Div} = 3, \\ \max\{0, \max\{0, (1 - \tau_b)\Pi_{b,t}\} + \Delta NW_{b,t} + \Delta DIF_{b,t}\} & \text{if } \chi^{Div} = 4 \end{cases} \quad (3.38)$$

where $\Delta DIF_{b,t}$ is the difference of actual funds in the deposit insurance fund and its target $\Delta DIF_{b,t} = DIF_{b,t-1} - DIF_{b,t}^T$ while $\Delta NW_{b,t}$ being the difference between actual net wealth of the bank and its target $\Delta NW_{b,t} = NW_{b,t-1} - NW_{b,t}^T$.

Similarly, the contribution $DIC_{b,t}$ each bank makes in each period to the deposit insurance fund can be defined as follows:

$$DIC_{b,t} = \begin{cases} -\Delta DIF_{b,t}\lambda & \text{if } \chi^{Div} = 1, \\ \min\{\max\{0, (1 - \tau_b)\Pi_{b,t}\} + \Delta NW_{b,t}\lambda, -\Delta DIF_{b,t}\lambda\} & \text{if } \chi^{Div} = 2, \\ -\Delta DIF_{b,t}\lambda & \text{if } \chi^{Div} = 3, \\ \min\{\max\{0, \max\{0, (1 - \tau_b)\Pi_{b,t}\} + \Delta NW_{b,t}\}, -\Delta DIF_{b,t}\} & \text{if } \chi^{Div} = 4 \end{cases} \quad (3.39)$$

4 Experiment setup and Calibration

In this section the different scenarios, the baseline configuration, the digital bank run and the calibration are described.

4.1 Scenarios

Overall, there are six scenarios. The first three scenarios investigate the effects of CBDC under different monetary policy regimes. Thereby 400 periods are simulated with the digital bank run at period 200. In the first, the central bank maintains a corridor system. The initial rate for central bank advances is set at 0.015, while the rate for central bank reserves is set to 0. The central bank follows the Taylor Rule described in Chapter 3.3.8, and there is a liquidity deficit in the banking system, meaning there are no excess reserves, and a minimum reserve requirement is in place. In

the second scenario, there is a zero-interest environment, with both the rate for central bank advances and reserves fixed at 0. In the third scenario, the central bank maintains a floor system. The initial rate for central bank advances and reserves is set at 0.015, and the central bank follows a Taylor Rule which is applied to both advances and reserves. Additionally, the central bank buys all government bonds, creating a liquidity surplus in the banking system.

The fourth, fifth, and sixth scenarios explore the effects of CBDC under different bank bankruptcy regimes. These experiments are conducted in a zero-interest environment to isolate the effects of the bankruptcy regime and minimize any influence from interest payments. These experiments simulate 600 periods in each run. In period 400, an idiosyncratic bank failure is simulated, where one bank is randomly drawn and the value of all its loans is reduced by 75 percent. This reduces the banks net wealth so that it goes bankrupt. Additionally, this increases the profits and the net wealth of firms whose loans are reduced. It is assumed that these firm profits are not paid out as dividends to isolate the negative effect of the bankruptcy. In the fourth scenario, a bailout regime is investigated, where the negative net wealth of banks is covered by a wealth tax on households, as described in chapter 3.7.1. The fifth scenario explores a bail-in regime, where the bank's negative net wealth is absorbed by its depositors. Finally, the sixth scenario examines a deposit insurance system, in which the bank is rescued by the deposit insurance fund.

4.2 *Baseline Configuration*

In the baseline run the preferred portfolio weight for deposits is 1 and the weight for reserves is 0, i.e. households and firms only want to hold deposits:

$$\omega_h^D = \omega_c^D = \omega_k^D = 1; \omega_h^R = \omega_c^R = \omega_k^R = 0$$

4.3 *Digital Bank Run*

The digital bank run happens at period 200. Thereby, the portfolio weight for reserves of households and firms is set to 1 while the weight for deposits is set to 0 so that all their deposits are converted to reserves.

$$\omega_h^D = \omega_c^D = \omega_k^D = 0; \omega_h^R = \omega_c^R = \omega_k^R = 1$$

4.4 Calibration

The calibration is performed, and initial parameters are set following the six-step process described by Caiani et al. (2016), with minor modifications. First, an aggregated model is derived. Second, it is constrained by a nominal growth rate. Third, the model is solved numerically using exogenous values to determine the endogenous unknown stocks and parameters. Fourth, the stocks in the aggregated model are evenly distributed among all agents. Fifth, the outstanding and original amounts of loans and capital are determined. Finally, in the sixth step, each agent is assigned a previous supplier for each market in which they participate. The aggregated model in the first step was adjusted using the equations described in Appendix A to align with the model developed in this paper. Appendix A also provides the exogenous values and calculated steady-state values used in the third step of the calibration. As a result of this process, all agents begin under the same conditions. The stock-flow consistency of the model in the steady state was verified and found to be valid.

5 Results

This section contains the results of the six scenarios. For each scenario a Monte Carlo simulation of 100 periods was performed for both the baseline and CBDC run. The following plots contain the average values of the 100 runs. The plots start at period 200 since the model requires a “burn-in” period with higher volatility till it reaches a steady state at period 200.

5.1 Scenario I: Unremunerated CBDC in a Corridor System

The digital bank run from deposits to CBDC has implications for the balance sheets and assets of the banking system, as demonstrated by Figure 3. Banks replace their deposits with newly issued central bank advances, which includes the creation of reserves. As a result, advances for banks and reserves for non-banks increase, while deposits decrease, leading to changes in financial flows. Figure 4 shows selected macroeconomic variables.

Deposit interest payments to households are replaced by advances interest payments to the central bank. This has two effects. First the interest payments going to the central bank increases the central bank profit and thus the government’s seigniorage income. This, in turn, leads to higher government spending (Real Gov Consumption) and a reduction in household consumption due to lower deposit interest income. Since the government fully spends its seigniorage income (100

percent), while households consume their deposit interest income with a specific propensity (90 percent), aggregate demand increases, resulting in a rise in GDP. In response to this increased demand, firms require more loans, suggesting that the digital bank run would, in the long run, lead to higher GDP and increased bank lending. In this experiment government consumption increases GDP in a one-to-one relation since the government buys consumption goods. In reality the effect on GDP might even be larger if the government buys investment goods which increases GDP multiple times due to the multiplier effect. As a second effect overall bank funding becomes more expensive since cheap deposits being replaced by advances remunerated at the current policy rate.

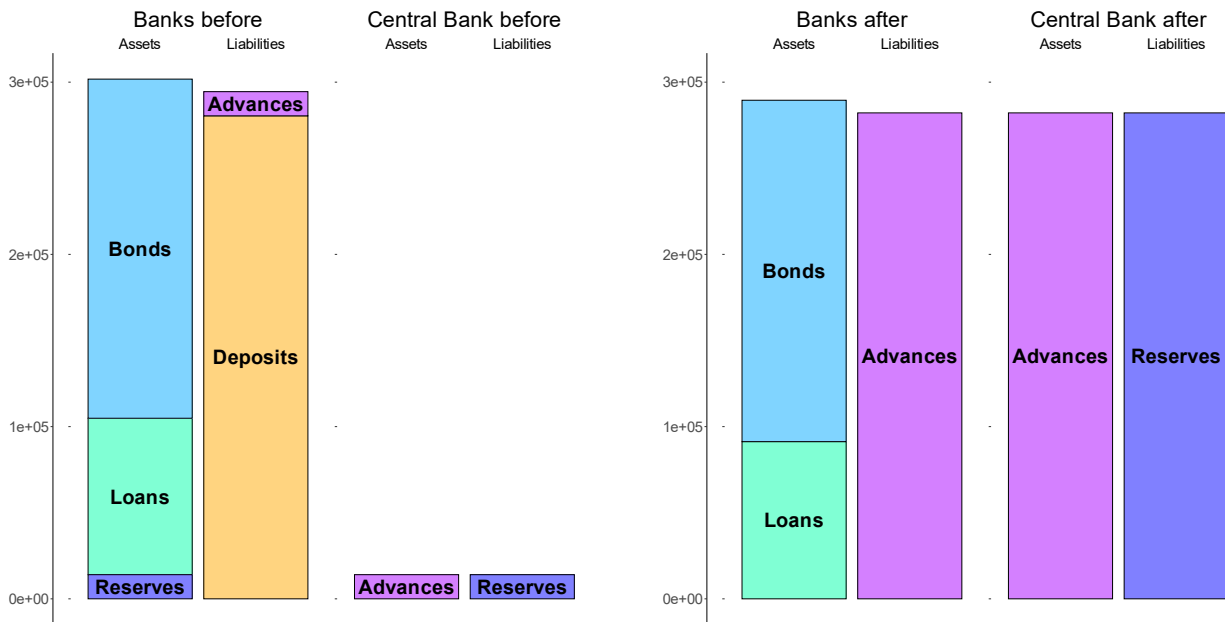


Figure 3: Balance Sheets before and after the digital bank run in corridor system

This leads to decreasing profits. However, the loss in profits from sticky deposits is compensated for by the profit gains from the increased loans due to increased GDP rendering the effect of CBDC on bank's profit situation as almost neutral.⁴ This loss of profit also flows to the government and increases GDP since the government has higher propensity to consume than bank owners.

⁴ There is also an increase in the Gini index, which can be explained by labor turnover. As GDP increases, firms hire more households, widening the gap between the income of employed and unemployed households. After about 50 periods, this gap closes as employed households face layoffs, and unemployed households take over their positions.

From a monetary policy perspective, the digital bank run makes monetary policy through interest rates less effective. Households are no longer affected by interest rate changes in their investment and saving decisions, as they hold all their wealth in unremunerated CBDC.

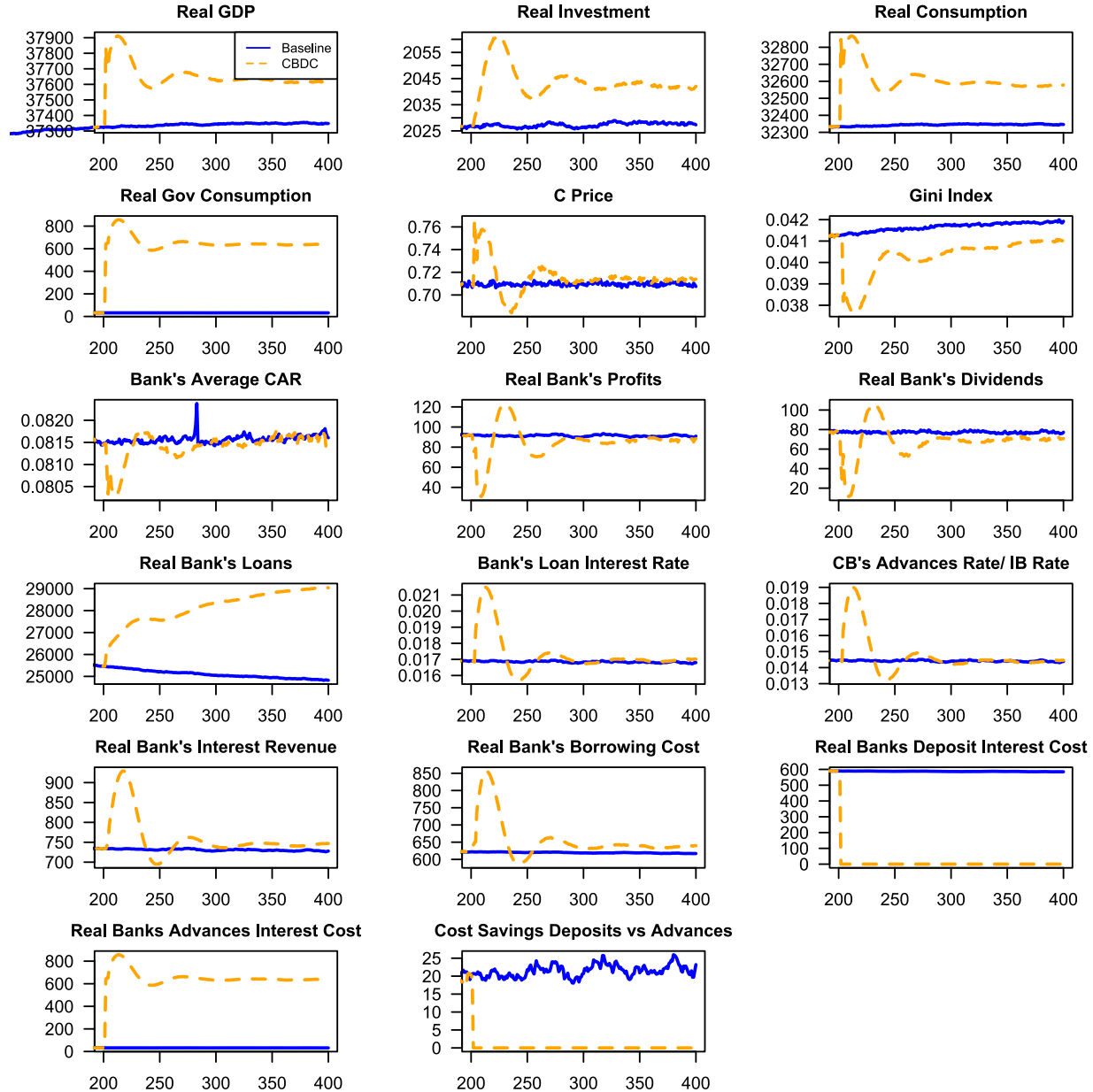


Figure 4: Results Corridor System

5.2 Scenario II: Unremunerated CBDC in a Zero-Interest Environment

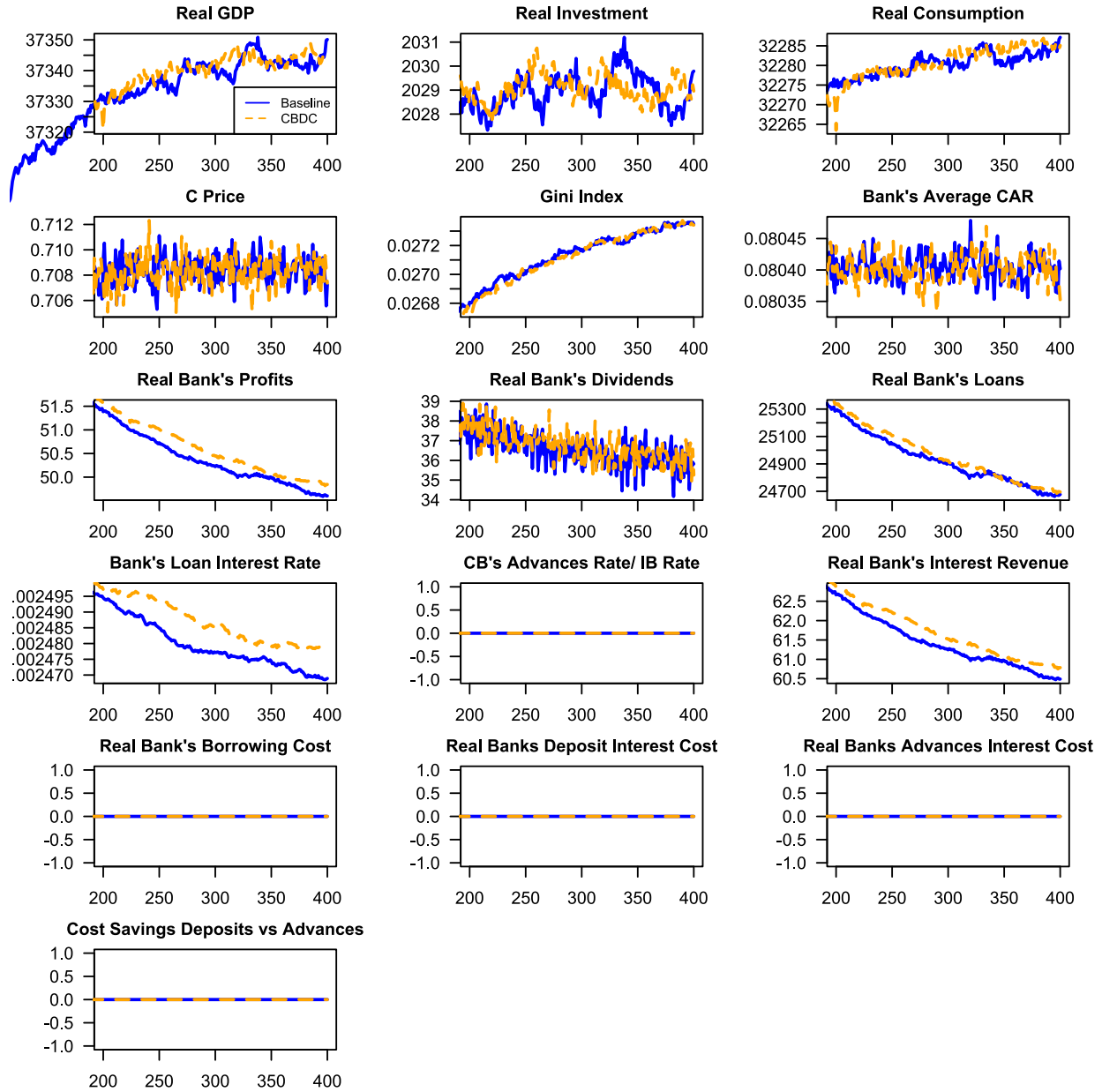


Figure 5: Results Zero-Interest Environment

In a zero-interest environment, the balance sheets are affected similarly to the corridor system. Banks replace their deposit funding with central bank advances. However, since the interest rate is zero, the interest payment flow is not redirected, and the digital bank run has no overall effect on the economy. As Figure 5 shows, all economic variables are on the same level as the baseline. There are only small differences due to the random number generator. Both the baseline and CBDC runs use the same random seed but with CBDC the interactions on the deposit market are missing,

which includes the random allocation of buyers to sellers. Therefore, the agents in the CBDC run use the same numbers generated but draw less numbers.

5.3 Scenario III: Remunerated CBDC in a Floor System

In a floor system, the changes in the balance sheets of the banking system differ from the previous scenarios. As Figure 6 shows, the majority of reserves needed by banks was already created through asset purchases by the central bank. However, since the withdrawn deposit amount exceeds the amount of purchased bonds, the shortfall in reserves must be made up through central bank advances. From a monetary policy perspective this means that the floor system changes to a corridor system since banks lose all their excess reserves.

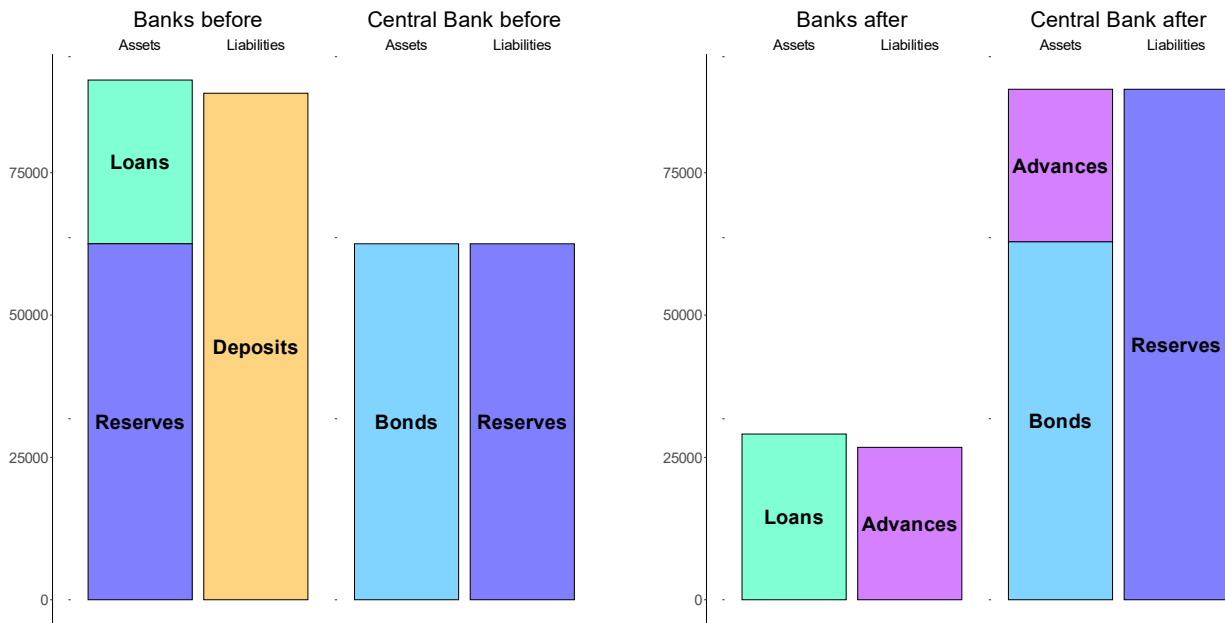


Figure 6: Balance Sheet Changes of Digital Bank Run in Floor System

As Figure 7 suggests, the balance sheet changes have no effect on GDP. Instead, banks' profits and dividends fall as a result of the prevention of sticky deposits. CBDC held by households and firms is remunerated at the current policy rate, unlike deposits, where the policy rate is passed through with a delay. This leads to a redistribution of dividends to CBDC holders. However, this has no effect on GDP in the model since bank shareholders and CBDC holders are the same agents. In countries where they are not the same, there would be a redistribution of wealth. Whether this has any economic impact depends on whether deposit holders have different propensities to consume out of their income than shareholders, as pointed out by Driscoll and Judson (2013). Overall, the

pass-through of monetary policy is improved, as changes in the central bank's policy rate are instantly passed on to households and firms.

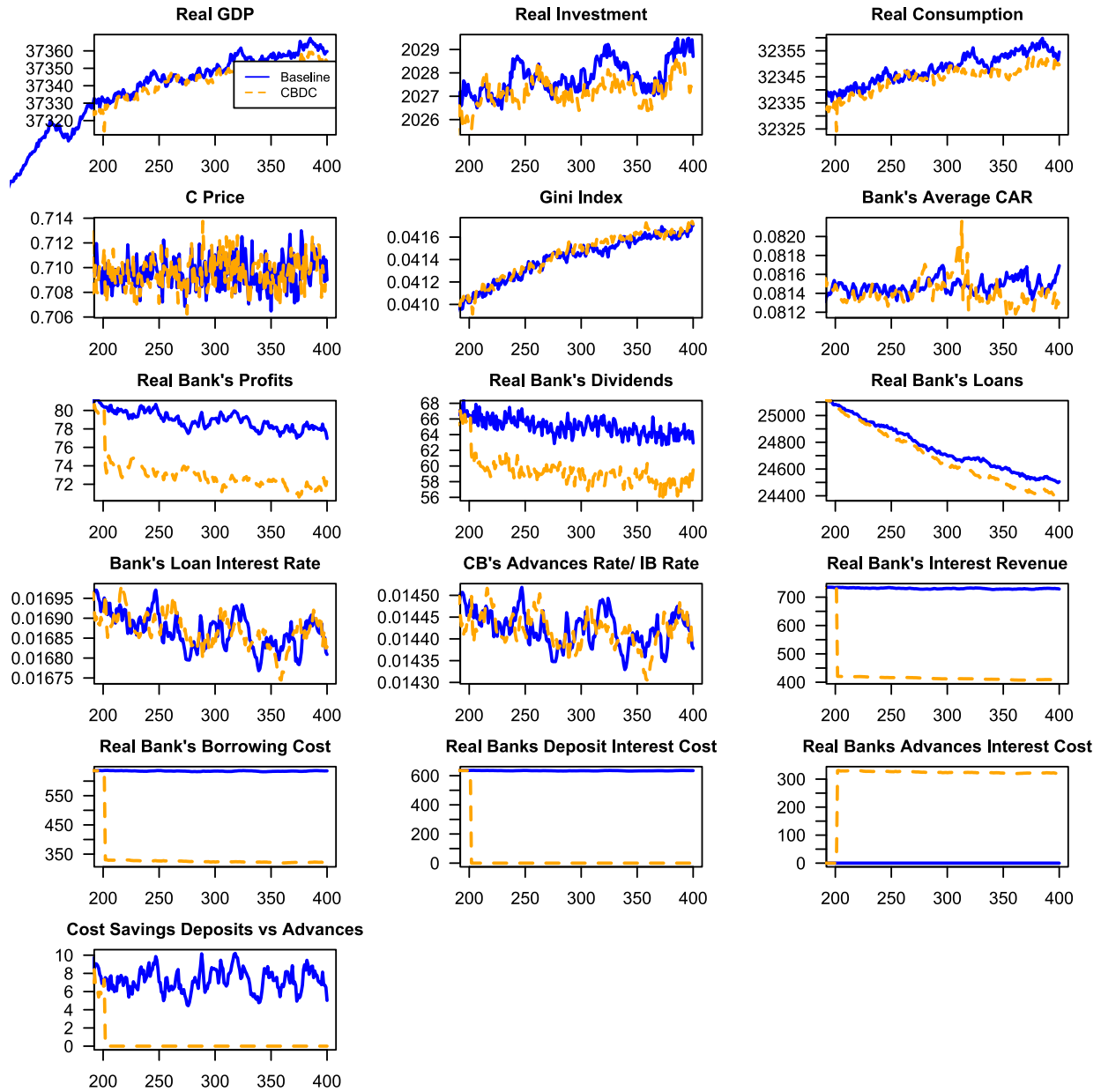


Figure 7: Results Floor-System

5.4 Scenario IV: Bail-out Regime

Scenarios IV to VI include the bank asset value shock at period 400 where a portion of the assets of a randomly chosen bank are transferred to its competitors. On one side this makes the one bank go bankrupt so that it undergoes a bankruptcy process with corresponding economic effects. On

the other side the loss increases profits and net wealth of firms. Although, this has no effects since it is assumed that firms do not pay out these profits. Figure 8 shows the effects of the asset shock in a bail-out regime with bank deposits and CBDC. As can be seen, the digital bank run into CBDC has the same effect on the economy as bank deposits in a bail-out regime except for small differences produced by the random number generator. With both CBDC and bank deposits the bank rescue costs are born by taxpayers. This decreases output since households have less to consume out of wealth. In the model, the rescue payments go directly to the failed bank. Alternatively, the central bank could be rescued by these payments if the failed bank materializes its losses through its central bank advances, bringing the central bank's net wealth into negative territory. However, this would only change the route the rescue payments take.

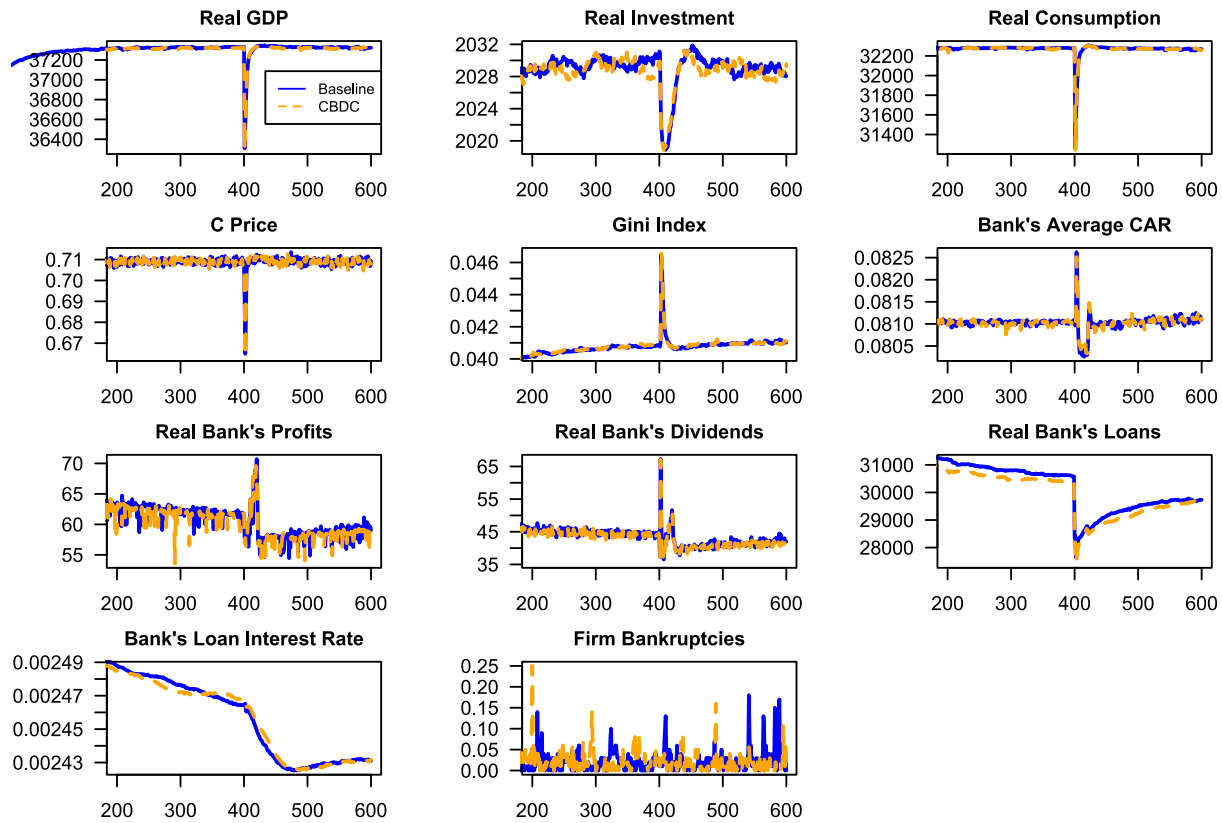


Figure 8: Results: Bail-out Regime

5.5 Scenario V: Bail-In Regime

The effects of a digital bank run into CBDC in a bail-in regime are shown in Figure 9. As can be seen after the bank asset shock there is a decline in loans in the baseline. This can be explained by the distribution of bank rescue costs which differ between the regimes. In the bail-in regime

without CBDC, the rescue costs are borne solely by the depositors of the failed banks, including the firm. The loss in deposits constitutes a liquidity shock for firms which cannot pay their wages and make them go bankrupt as consequence, which also the average firm bankruptcies show. The creditors of the bankrupt firms have to write down their loans, which increases their bankruptcy risk and threatening financial stability. With CBDC, the rescue costs are distributed equally among all households, promoting equality which translates to a lower Gini index. This prevents firms from going bankrupt, keeps the loan level steady and maintains financial stability.

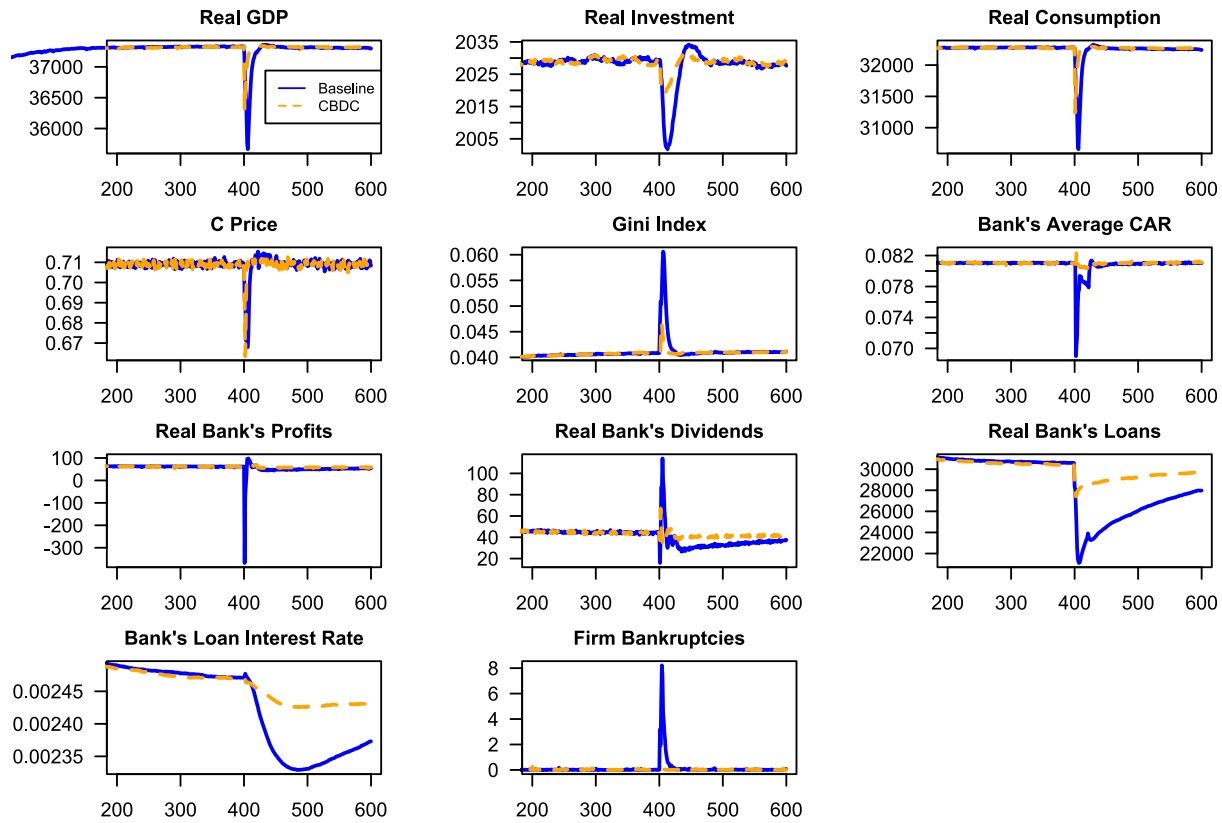


Figure 9: Results Bail-In Regime

Also, the GDP is at a higher level than the baseline run since bankrupted firms cannot pay their workers the full wages, thereby reducing their consumption. Furthermore, the written down loans in the baseline run may also affect solvent banks and thus affect the whole financial system. In the model banks loans of the bankrupt firms are evenly distributed among banks which prevents such contagion effects. Overall, CBDC transforms the bail-in regime into a quasi-bailout regime and improves financial stability.

5.6 Scenario VI: Deposit Insurance Regime

The results of CBDC issued in a deposit insurance system is depicted in Figure 10. In theory, CBDC should have the same effects as the deposit insurance fund since with both systems bank rescue costs are borne by households. While with CBDC households are taxed with deposit insurance system the fund is built up by the profit margin of banks which originates from their loan interest income received from firms which in turn pass-through their interest costs to households with their product prices.

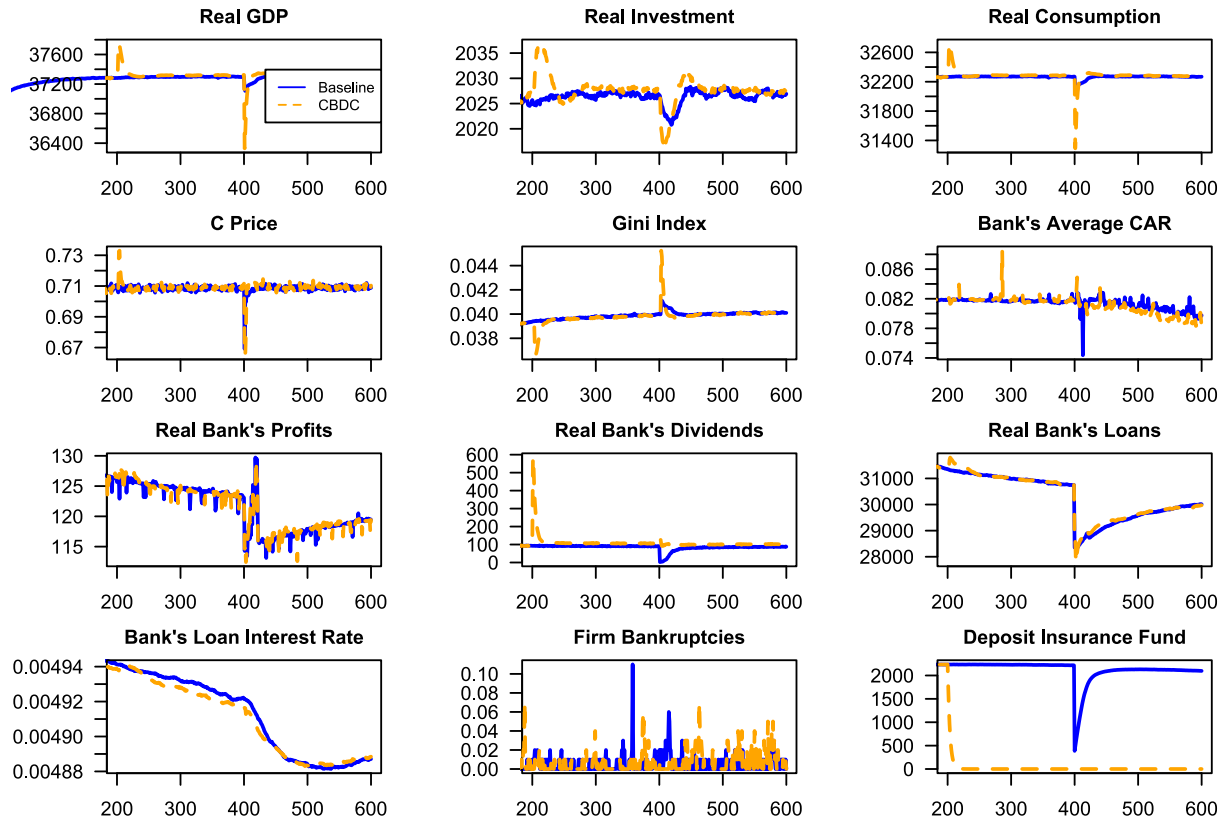


Figure 10: Results Deposit Insurance System

The plots, however, show a difference between the baseline and CBDC. At period 200, the deposit insurance fund is distributed among bank owners, who consume it, leading to an increase in aggregate demand and GDP. At the time of the bank bankruptcy in period 400 the GDP increase reverses since households bear all bank rescue costs which decreases their consumption. In the baseline the economy stays stable since the bank rescue costs are paid by the insurance fund. There is only a small GDP decrease since banks pay out less dividends to rebuild the deposit insurance fund. Overall, CBDC and insured deposits have roughly the same outcome. CBDC only creates an

additional dynamic in GDP because the model is calibrated with a deposit insurance fund. If the model was calibrated with no deposit insurance fund in the steady state the dynamic would reverse and the buildup of the insurance fund in the baseline run would decrease GDP first and later at period 400 increase GDP compared to CBDC. It also should be noted that the GDP increase with CBDC in the beginning is smoother than the sharp decrease at period 400 since banks pay out only a portion of excess capital per period while the bank rescue costs at period 400 are deducted only once.

6 Discussion

There are theoretical and practical implications arising from this research. These include economic output, financial stability, disintermediation, equivalence between private and public money, policy makers and agent-based modelling.

6.1 *Economic Output*

A shift from remunerated bank deposits to unremunerated CBDC increases economic output in the first scenario which is in line with the findings of Gross and Letizia (2023) and Burlon et al. (2024). Additionally, this research has demonstrated that the disbursement of the deposit insurance fund can create a dynamic in economic output which no other major research paper has covered yet.

6.2 *Financial stability*

This research has shown that the effects of CBDC on financial stability vary under different bank bankruptcy regimes. It was demonstrated that CBDC has only an effect in a bail-in regime while it has no effect in a bail-out or deposit insurance system. This is because with CBDC, the bail-in and deposit insurance, the bank rescue costs are borne by a larger community. In a bail-in regime bank rescue costs are only borne by the depositors of the bank and a CBDC would distribute the bank rescue costs more equally. The bankruptcy of a single bank is less likely to impact the economy and cause bankruptcies of their depositors due to liquidity shocks. At the same time other solvent banks are less probable to default since their borrowers stay solvent. Previous research on CBDC and financial stability was limited to the probability of bank runs. This research was focused on the effects of a bank bankruptcy on financial instability when CBDC was introduced.

The socialization of risk with CBDC also has implications for moral hazard. In a bailout regime, moral hazard exists because banks are incentivized to grant risky loans, knowing they will be bailed out by the government in case of bankruptcy. The same applies to the deposit insurance system. Since all banks contribute to the insurance fund, regardless of their individual risk, banks are incentivized to grant risky loans. With CBDC, moral hazard is similar to that in a bailout regime. If banks receive unlimited funding from the central bank, they remain incentivized to grant risky loans. In contrast, in a bail-in regime with bank deposits, there is no moral hazard under normal conditions since banks grant loans based on the risk preference of their depositors. However, during a digital bank run, depositors seeking a safer alternative to their deposits have no option since cash is too costly to hold and handle. Consequently, banks may receive more funding than they would with CBDC. Thus, moral hazard is present in all regimes, including bail-in, and there is no indication that moral hazard with CBDC would be worse than in a bail-in regime. On the contrary, if the demand for CBDC is in line with the supply of government bonds and these are pledged as collateral there would be no moral hazard since the central bank is not required to take any risks. Thus, CBDC may reduce moral hazard in these situations.

6.3 Disintermediation

This paper has shown that CBDC has effects on disintermediation and bank lending, but only if introduced in specific environments. In a positive interest rate environment CBDC counteracts the market imperfections in the deposit market by preventing the sticky deposit effect and thereby prevents banks from making extra profits. This is in line with previous research belonging to the literature strand that studies CBDC under imperfect market conditions intermediation (Andolfatto, 2018; Gross and Letizia, 2023; Niepelt, 2024). In a zero-interest environment no effect on disintermediation can be observed and both types of money CBDC and deposits are quasi-equivalent which is in line with the equivalence theorem by Brunnermeier and Niepelt (2019). Overall, no trade-off can be observed. CBDC has either no or only positive effects from the perspective of non-bank owners. In current economies with positive-interest rates the effects of the first or third scenario may be realized. According to Guo and Prezas (2019), between 1986 and 2013 in the US insured deposits made up 76 percent and uninsured deposits around 14 percent of total bank funding. While banks paid a positive spread on the uninsured deposits of 0.04 relative to the risk-free T-Bill rate the spread on insured deposits was strongly negative with -0.74, which indicates market imperfection due to the sticky deposits described earlier, as well as deposit

insurance and too-big-to-fail guarantees. Consequently, banks fail to effectively intermediate between insured depositors and loan demanders. This issue is even more pronounced with risk-free remunerated excess reserves, where pass-through obviously fails (see Ricks et al. (2021)). If CBDC is introduced and heavily demanded, the spread would be eliminated, and banks would pay a competitive interest rate on their funding. Therefore, it can be argued that CBDC improves intermediation by addressing the market failures of banks. On the other hand, the positive interest spread or risk premium on uninsured deposits implies some form of intermediation. This was not explicitly modelled in the bail-in scenario. However, during the digital bank run non-banks only demand money with lower credit risk in the form of CBDC. Thus, banks cannot intermediate between borrowers of loans and depositors since they cannot offer risk free deposits. The central bank is the only institution that can offer an adequate supply of CBDC to match that demand for money with lower credit risk. Overall, CBDC enables the intermediation between the central bank and non-banks while transferring moral hazard problem from the depositors to the central bank.

One potential issue in the model arises with a bail-in regime after a digital bank run when CBDC holders want to switch to riskier deposits, but banks only offer the policy rate because central bank funding is cheaper for them than more expensive deposits (as described by Niepelt (2020)). In such a scenario, the central bank needs to introduce a penalty rate into its monetary policy framework to penalize additional funding from the central bank. In a bank run situation with high liquidity demand, the central bank charges the regular policy rate for all granted loans. In contrast, during normal times, the central bank needs to estimate the demand for remunerated and non-remunerated CBDC and offer loans to match that amount at the regular policy rate. For any additional central bank loans, a penalty rate, set above the regular policy rate, can be charged.

Furthermore, I made assumptions in this paper regarding bank behavior and the conditions at which the central bank grant loans that may be violated in reality. In the model banks reduce their dividends to maintain sufficient capital so that their loan supply is not affected by the CBDC introduction. If this is not possible and banks want to retain their levels of dividend CBDC may impact bank equity and loan supply. However, if loans are granted only due to extra profits and resulting extra capital, this indicates a distortion in credit allocation, and CBDC would return credit allocation to a “normal” level. Furthermore, authorities could lower capital requirements so that banks can provide the same loan supply as before the CBDC introduction.

In the model, banks receive central bank loans under the same conditions despite no collateral requirements. This could be modified by allowing the central bank to charge risk-adequate interest rates for different banks. In the model banks are relatively homogenous since their loan portfolios are similar. But in reality, the risk between banks portfolios varies. The central bank may charge a risk-adequate premium above the risk-free rate on central bank loans to account for that risk similar to the risk premium paid on uninsured deposits in a bail-in regime (which is not modelled in this paper). This could affect the allocation since the central bank may not be capable of monitoring the risk of each bank in the same way as many depositors do. However, even if the central bank had perfect information about the banks from the perspective of intermediation, this would make no difference compared to charging only the risk-free rate from banks. During the digital bank run there is always a mismatch between the risk of the bank's assets and the risk preferences of households and firms (Demand for risk-free means of payment). If the central bank charges the premium, banks would maintain a riskier loan portfolio than households and firms are willing to accept. If the central bank charges only the risk-free rate, banks would still hold risky loans but with cheaper funding. The central bank could require banks to restructure their assets to the risk profile of the CBDC holders but this would neither be possible due to the lack of risk-free assets. Thus, whether there are specific loan conditions, moral hazard remains as discussed in chapter 6.2. The risk premiums on central bank loans would only transfer the moral hazard gains from commercial banks to the central bank. These gains would eventually increase central bank profits, government spending and GDP if the government spends the whole amount, similar to scenario I. Furthermore, in the model, banks are not required to pledge any collateral to the central bank in exchange for receiving a loan. However, collateral requirements could significantly alter the model's outcomes. If banks are required to pledge loans as collateral along with government bonds, the outcome would not change since the amount of collateral required would match the amount of central bank loans. This situation differs if the central bank requires only government bonds. In the digital bank run scenario, the demand for CBDC would exceed the amount of government bonds, potentially leaving banks unable to receive the required reserves, becoming illiquid, being forced to fire sale their assets and becoming insolvent. This might also affect the one-to-one parity between bank deposits and central bank money, as deposits are only convertible to a fraction of central bank money. However, this can be prevented by a collateral policy which allows the central bank to take risks. Historically, central banks have regularly accepted collateral of lower quality

to keep banks liquid and have purchased private debt to reduce business funding costs (Bank for International Settlements, 2023, 2015). Furthermore, the regulation of CBDC issuance could also alter the collateral framework so that central bank loans related to CBDC require only low quality collateral or no at all.

According to Bindseil (2020) CBDC would require the central bank to adjust its collateral framework which shifts credit allocation toward the central bank and ultimately affects collateral prices and may have negative effects on the efficiency of the economy. However, this argument is one sided since if the demand for risk-free assets exceeds the supply of government bonds (Digital bank run) in both economies with and without CBDC there is moral hazard and misallocation as described before.

6.4 *The possibility of equivalence*

Brunnermeier and Niepelt (2019) argue that equivalence between private money (deposits) and public money (CBDC) can be established with transfer payments between agents, so that CBDC would have no economic effect at all. They also contend that this is not the case in the real world due to the heterogeneity of households. This can be validated in the presented model. The results of the different scenarios suggest that equivalence is established without any transfers in the scenario where the interest rate is zero and a bailout regime is prevailing. In every other scenario, equivalence cannot be established due to the heterogeneity of households and banks and the lack of information on deposits and depositors.

With the different monetary policy regimes, the interest payment flows need to be redirected to establish equivalence. In a corridor system the central bank's profit from interest needs to be redirected to households, firms and banks. In the floor system the extra interest gains of households and firms need to be redirected to banks and their owners. With the different bank bankruptcy regimes, the bank rescue cost flows need to be redirected. In the bail-in regime some theoretical depositors of the bankrupt bank need to make transfer payments to all households while in the deposit insurance system banks need to make payments to the deposit insurance fund. For all those transfers deposit information is required. Households and firms need to choose a deposit supplying bank despite not having any demand for deposits so that their theoretical deposit amount, and the corresponding deposit interest rates of each bank can be determined.

6.5 *Implications for policy makers*

There are implications for policymakers derived from the results of this paper. It was demonstrated that CBDC has various effects depending under which circumstances a digital bank run takes place. In the described environments, CBDC has shown to be a measure that can increase GDP, reduce banks' extra profits, and enhance financial stability. When policymakers consider the potential introduction of CBDC, these factors should be taken into account. However, this research did not investigate whether CBDC is a more suitable measure for achieving these specific goals compared to other measures. To reduce banks' extra profits, the government might also consider introducing a tax on bank profits. To increase financial stability, the government might implement an unlimited ex-post deposit insurance system or a bail-out regime, which may have similar effects to CBDC. Furthermore, this research investigated the extreme case of a digital bank run where all deposits are converted to CBDC. The demand will not necessarily be that high. Unremunerated CBDC will most likely attract only bank depositors which are not safeguarded by the deposit insurance system. In the US for example, they make up only 15 percent of deposits. In such an environment, the GDP gains will be less than those modeled in this paper. However, remunerated CBDC will very likely attract a big portion of bank depositors if the interest rate is higher than those of bank deposits which would lead to the digital bank run and the described effects concerning this scenario.

6.6 *Implications for agent-based modelling*

Lastly, this research extended the JMAB 2.0 model by incorporating reserves for non-banks, government spending, sticky deposits, and different monetary policy and bank bankruptcy regimes. Up to now it is the only large-scale macroeconomic AB-SFC model with CBDC since the model of Gross and Letizia (2023) is limited to the banking system and households. Due to the model's modularity and free availability, other researchers can reuse its components or the entire model for their own studies.

7 Conclusion

This paper studied the macroeconomic effects of introducing a Central Bank Digital Currency (CBDC) in a closed economy using an Agent-based Stock Flow Consistent (AB-SFC) Model. Compared to previous studies, a digital bank run was investigated across various economic

environments with different monetary policy and bank bankruptcy regimes. It was shown that non-remunerated CBDC issued in a positive-interest environment with a ceiling system may increase GDP when the government debt level is fixed, and central bank profits are allocated to government spending. This occurs because the government spends all its interest earnings, whereas households spend only a fraction of their interest earnings with a specific propensity. Non-remunerated CBDC issued in a zero-interest environment has no impact since there is no distributional effect of the interest payments. In a floor system where the interest rate on CBDC matches the policy rate, CBDC counteracts deposit stickiness and redistributes bank profits from shareholders to depositors. This improves the transmission of the policy rate to households and firms. The bank bankruptcy regime also affects the outcome. While CBDC makes no difference in a bailout regime, it does in a bail-in regime, where it decreases inequality and bank rescue costs for deposit holders, potentially enhancing financial stability. Introducing CBDC within a deposit insurance system postpones bank rescue payments, which creates an additional dynamic in GDP. It has been demonstrated that the two major threats associated with CBDC—namely digital bank runs and disintermediation—are unproblematic as long as the central bank acts as a lender of last resort. Moreover, CBDC may improve intermediation in terms of balancing risks between banks' assets and liabilities, as well as providing risk-averse depositors with a risk-free option.

There are also opportunities for future research arising from this paper. The same model could be applied to the Chicago Plan or Sovereign Money as well. The only adjustment for the Chicago Plan would be that the central bank lends only against sufficient collateral in the form of government bonds. Future research might calibrate the model with empirical data to forecast the effects of CBDC for a specific economy or extend the portfolio choice of households so that the CBDC demand is dynamic. Additionally, CBDCs might be compared to measures that have similar effects on the economy, such as taxes on bank extra profits and ex-post deposit insurance systems.

References

- Agur, I., Ari, A., Dell'Ariccia, G., 2022. Designing central bank digital currencies. *J Monet Econ* 125, 62–79. <https://doi.org/https://doi.org/10.1016/j.jmoneco.2021.05.002>
- Ahnert, T., Hoffmann, P., Leonello, A., Porcellacchia, D., 2023. Central Bank Digital Currency and financial stability, Working Paper Series, Working Paper Series. European Central Bank.
- Andolfatto, D., 2018. Assessing the Impact of Central Bank Digital Currency on Private Banks. Federal Reserve Bank of St. Louis, Working Papers 2018. <https://doi.org/10.20955/wp.2018.026>

- Assenmacher, K., Bitter, L., Ristiniemi, A., 2023. CBDC and Business Cycle Dynamics in a New Monetarist New Keynesian Model. SSRN Electronic Journal. <https://doi.org/10.2139/SSRN.4442377>
- Auer, R., Böhme, R., 2020. The technology of retail central bank digital currency. *BIS Quarterly Review* 85–100.
- Bank for International Settlements, 2023. Central bank asset purchases in response to the Covid-19 crisis. CGFS Papers.
- Bank for International Settlements, 2015. Central bank operating frameworks and collateral markets. CGFS Papers.
- Barrdear, J., Kumhof, M., 2016. The macroeconomics of central bank issued digital currencies. <https://doi.org/10.2139/SSRN.2811111>
- Bindseil, U., 2020. Tiered CBDC and the financial system, Working Paper Series 2351, European Central Bank.
- Bindseil, U., Senner, R., 2025. Modeling Central Bank Digital Currencies. *J Econ Surv.* <https://doi.org/10.1111/JOES.12686>
- BIS, 2018. Central bank digital currencies.
- Brunnermeier, M.K., Niepelt, D., 2019. On the equivalence of private and public money. *J Monet Econ* 106, 27–41. <https://doi.org/10.1016/j.jmoneco.2019.07.004>
- Burlon, L., Muñoz, M.A., Smets, F., 2024. The Optimal Quantity of CBDC in a Bank-Based Economy. *American Economic Journal: Macroeconomics* 16, 172–217. <https://doi.org/10.1257/mac.20220152>
- Caiani, A., Godin, A., Caverzasi, E., Gallegati, M., Kinsella, S., Stiglitz, J.E., 2016. Agent based-stock flow consistent macroeconomics: Towards a benchmark model. *J Econ Dyn Control* 69, 375–408. <https://doi.org/10.1016/j.jedc.2016.06.001>
- Chiu, J., Davoodalhosseini, S.M., Jiang, J., Zhu, Y., 2023. Bank Market Power and Central Bank Digital Currency: Theory and Quantitative Assessment. <https://doi.org/10.1086/722517> 131, 1213–1248. <https://doi.org/10.1086/722517>
- Driscoll, J.C., Judson, R., 2013. Sticky Deposit Rates. SSRN Electronic Journal. <https://doi.org/10.2139/ssrn.2357993>
- Dyson, B., Hodgson, G., 2016. Digital cash: Why Central Banks Should Start Issuing Electronic Money. *Positive Money*.
- Federal Reserve, 2023. Joint Statement by Treasury, Federal Reserve, and FDIC [WWW Document]. URL <https://www.federalreserve.gov/newsevents/pressreleases/monetary20230312b.htm> (accessed 9.4.24).
- Fernández-Villaverde, J., Sanches, D., Schilling, L., Uhlig, H., 2021. Central bank digital currency: Central banking for all? *Rev Econ Dyn* 41, 225–242. <https://doi.org/10.1016/J.RED.2020.12.004>
- Fraschini, M., Somoza, L., Terracciano, T., 2024. The Monetary Entanglement between CBDC and Central Bank Policies. SSRN Electronic Journal. <https://doi.org/10.2139/SSRN.3804966>

- FSB, 2022. Assessment of Risks to Financial Stability from Crypto-assets.
- Gregor, J., Melecký, A., Melecký, M., 2021. Interest Rate Pass-Through: A Meta-Analysis Of The Literature. *J Econ Surv* 35, 141–191. <https://doi.org/10.1111/JOES.12393>
- Gross, J., Schiller, J., 2021. A Model for Central Bank Digital Currencies: Implications for Bank Funding and Monetary Policy. *SSRN Electronic Journal*. <https://doi.org/10.2139/SSRN.3721965>
- Gross, M., Letizia, E., 2023. To Demand or Not to Demand: On Quantifying the Future Appetite for CBDC. *IMF Working Papers* 2023, 1. <https://doi.org/10.5089/9798400228780.001>
- Guo, L., Prezas, A.P., 2019. Market monitoring and influence: evidence from deposit pricing and liability composition from 1986 to 2013. *Journal of Financial Stability* 43, 146–166. <https://doi.org/10.1016/J.JFS.2019.06.003>
- Hess, S., 2025. JMAB 2.0: A Fix for the Fundamental Problems with the Agent-based Model JMAB, Forthcoming, Unpublished doctoral dissertation.
- Iorio, A. Di, Kosse, A., Mattei, I., 2024. Embracing diversity, advancing together - results of the 2023 BIS survey on central bank digital currencies and crypto. *BIS Papers*.
- Jakab, Z., Kumhof, M., 2018. Banks are Not Intermediaries of Loanable Funds — Facts, Theory and Evidence. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.3274706>
- Kahn, C.M., Rivadeneyra, F., Wong, R., 2018. Should the Central Bank Issue E-Money?, Working Papers 2019-3, Federal Reserve Bank of St. Louis. <https://doi.org/10.2139/ssrn.3271654>
- Keeley, M.C., 1990. Deposit Insurance, Risk, and Market Power in Banking. *American Economic Review* 80, 1183–1200.
- Keister, T., Sanches, D., 2022. Should Central Banks Issue Digital Currency? *Rev Econ Stud* rdac017. <https://doi.org/10.1093/restud/rdac017>
- Kumhof, M., Noone, C., 2018. Central Bank Digital Currencies - Design Principles and Balance Sheet Implications, Bank of England working papers 725, Bank of England. <https://doi.org/10.2139/ssrn.3180713>
- León, C., Moreno, J.F., Soramäki, K., 2024. Simulating the Adoption of a Retail CBDC. *Jahrb Natl Okon Stat*. https://doi.org/10.1515/JBNST-2024-0002/ASSET/GRAPHIC/J_JBNST-2024-0002_FIG_003.JPG
- Mancini-Griffoli, T., Soledad Martinez Peria, M., Agur, I., Ari, A., Kiff, J., Popescu, A., Rochon, C., 2018. Casting Light on Central Bank Digital Currency. *IMF Staff Discussion Note* (2018) 08.
- Niepelt, D., 2024. Money and Banking with Reserves and CBDC. *J Finance* 79, 2505–2552. <https://doi.org/10.1111/JOFI.13357>
- Niepelt, D., 2020. Reserves for all? Central bank digital currency, deposits, and their (non)-equivalence. *Int J Cent Bank* 16, 211–238.
- Norges Bank, 2022. Costs in the Norwegian payment system 2020.
- Ramadah, A., Galbiati, M., Soramäki, K., 2021. Agent-Based Simulation of Central Bank Digital Currencies. *SSRN Electronic Journal*. <https://doi.org/10.2139/SSRN.3959759>

- Ricks, M., Crawford, J., Menand, L., 2021. FedAccounts: Digital Dollars. *George Washington Law Review* 89.
- Schasfoort, J., Godin, A., Bezemer, D., Caiani, A., Kinsella, S., 2017. Monetary Policy Transmission in a Macroeconomic Agent-Based Model. *SOM Research Reports* 17010-GEM, 1–48. <https://doi.org/10.1142/S0219525918500030>
- Schilling, L., Fernández-Villaverde, J., Uhlig, H., 2024. Central bank digital currency: When price and bank stability collide. *J Monet Econ* 145, 103554. <https://doi.org/10.1016/J.JMONECO.2024.01.007>
- Werner, R.A., 2014. Can banks individually create money out of nothing? - The theories and the empirical evidence. *International Review of Financial Analysis* 36, 1–19. <https://doi.org/10.1016/j.irfa.2014.07.015>
- World Bank, 2025a. Broad money (% of GDP) [WWW Document]. World Development Indicators, The World Bank Group. URL <https://databank.worldbank.org/reports.aspx?source=2&series=FM.LBL.BMNY.GD.ZS&country=#> (accessed 2.15.25).
- World Bank, 2025b. Bank deposits to GDP (%) [WWW Document]. Global Financial Development, The World Bank Group. URL <https://databank.worldbank.org/source/global-financial-development/Series/GFDD.OI.02#> (accessed 2.15.25).

8 Appendix A

Symbol	Description	Scenario I	Other Scenario
Exogenous parameters:			
g_{SS}	Nominal rate of growth in the SS	0.0075	
$size_{\phi_H}$	Number of households	8000	
$size_{\phi_C}$	Number of consumption firms	100	
$size_{\phi_K}$	Number of capital firms	10	
$size_{\phi_B}$	Number of banks	10	
N_g	Number of public servants (constant)	1360	
$N_{c,0}$	Consumption firms' initial workers	5000	
$N_{k,0}$	Capital firms' initial workers	1000	
u_0	Initial unemployment	0.08	
μ_K	Productivity of Capital	1	
$\xi^k = \xi^c$	Number of potential partners on C and K goods markets	5	
$\xi^d = \xi^l$	Number of potential partners on deposit and credit markets	10	
ξ^n	Number of potential partners on labor mkt (for each vacant job)	10	

$PS^k = PS^c = PS^d = PS^l$	Probability to switch K good supplier, C good supplier, deposit demander and loan supplier	0.05	
ν	Firms' target inventories to sales ratio	0.1	
ϑ	Labor turnover ratio	0.05	
$mu_{c,0}$	Initial mark-up on NUC for C firms	0.165	
$mu_{k,0}$	Initial mark-up on ULC for K firms	0.075	
$mu_{b,0}$	Initial mark-up for banks	0.0025	
$(\mu_{LN}, \sigma_{LN}^2)$	Log-normal Distribution parameters	(0,0.0094)	
$\tau_k = \tau_c = \tau_b = \tau_h$	Profit and Income tax rates	0.18	
η	Loans duration	20	
κ	Capital goods duration	20	
cu_c^T	Target capacity utilization	0.8	
σ	Firms' precautionary deposits as share of wage cost	1.25	
$\rho_k = \rho_c$	Firms' profits' share distributed as dividends	0.9	
λ	Banks' decay parameter for excess capital	0.25	
CAR_b^T	Banks' target capital adequacy ratio	0.08	
LR_b^T	Banks' target liquidity ratio	0.05	
$DIRR_b^T$	Banks' deposit insurance reserve target ratio	0	0.05 (VI)
ψ	Central bank's share of bond holdings	0	1.0 (III)
$i_{cb,0}^A$	Initial CB interest rates on advances	0.015	0 (II, IV, V, VI)
$i_{cb,0}^R$	Initial CB interest rates on reserves	0	0.015 (III)
ι	Haircut on defaulted firms' capital value	0.5	
$W_{h,0}$	Initial wages	5	
pc_h^{NI}	Propensity to consume out of net income	0.9	
pc_h^{NW}	Propensity to consume out of net wealth	0.5	
ω_x^D	Portfolio weight of deposits	1	
ω_x^C	Portfolio weight of reserves	0	
p^b	Bonds price	1	
π_{cb}^T	Inflation target of the central bank	0.0075	
i^{nat}	Natural rate of interest	0.0075	
β^{tay}	Smoothing parameter in Taylor rule	0.7	
α_c^s	Adaptive parameters for firm sales expectation	320	
α_k^s	Adaptive parameters for firm sales expectation	500	
$\alpha_k^{mu} = \alpha_c^{mu}$	Adaptive parameter for firm markup	0.1	
α_c^i	Adaptive parameter for C firm investment	20	
α_b^D	Adaptive parameter for banks deposit interest rate	0.01	

α_b^{mu}	Adaptive parameter for banks markup for loans	0.001
β^{lvl}	Smoothing parameter for level	0.05
β^{trd}	Smoothing parameter for trend	0.05
β^{SES}	Smoothing parameter for simple exponential smoothing	0.05
<hr/>		
Endogenous parameters:		
<hr/>		
μ_N	Productivity of labor in K sector	2
l_K	Capital/labor ratio	6.4
$i_{b,0}^{IBL}$	Initial interest rate on loans	0.015
$i_{b,0}^L$	Initial interest rate on loans	0.0175
$i_{b,0}^D$	Initial interest rate on deposits	0.01425
$i_{g,0}^b$	Bonds interest rate	0.015
ζ	Banks' risk aversion towards C and K firms	7.1972
$NLR_{b,0}$	Banks' initial net liquidity ratio	0
ρ_b	Banks' initial profit share distributed as dividends	0.80224
θ	Ratio of dole to average wage	0.49459

Table 1: Model baseline exogenous and calibrated endogenous parameters

To be in line with the model developed in this paper the original model calibration for JMAB 2.0 by Hess (2025) needed the following minor adjustments. Endogenous variables are bold in the equations while exogenous are not. In the calibrations of each scenario the real consumption of households (A.1) also considers central bank profits and central bank profits are excluded in the derivation of bonds (A.2). In the calibration of the deposit insurance scenario the contribution to the insurance system is subtracted from the profits in the calculation of bank dividends (A.3). Additionally, the deposit insurance fund in the steady state is calculated with the deposit insurance reserve ratio target multiplied by the bank's deposits (A.4).

$$c_h = y_c - \frac{\Pi_{cb}}{p_c} \quad (A.1)$$

$$\frac{g_{SS}}{g_{SS} + 1} \mathbf{B}_g = N_g W + \theta W (size_{\phi_H} - N_{tot}) - T_b - T_c - T_h - T_k + \frac{\mathbf{B}_g i^B}{g_{SS} + 1} \quad (A.2)$$

$$\mathbf{Div}_b = \rho_b \mathbf{\Pi}_b (\tau_b - 1) - \frac{g_{ss}}{g_{ss} + 1} \mathbf{R}_g \quad (\text{A.3})$$

$$\mathbf{R}_g = \mathbf{DIRR}^T (\mathbf{D}_c + \mathbf{D}_h + \mathbf{D}_k) \quad (\text{A.4})$$