

The Impact of CBDC on Bank Deposits and the Interbank Market*

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September 2022

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Abstract

This paper investigates how the introduction of a central bank digital currency (CBDC) impacts the banking sector. The deposit market is modeled as a Salop circle and deposits are subject to liquidity shocks. Absent a CBDC the interbank market can redistribute liquidity between banks. However, the central bank does not take part in the interbank market and CBDC leads to greater reliance of the banking sector on central bank standing facilities. The model shows adjusting the remuneration rate of CBDC has little pass-through to the deposit rate set by banks and may have implications for transmission of monetary policy.

Keywords: central bank digital currency, banking, money, interbank Market

JEL codes: E42, E52, E58, G21

*The views expressed in this paper are those of the author and do not necessarily reflect the position of the Bank of Lithuania or the Eurosystem.

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1 Introduction

An increasing number of central banks are entertaining the possibility of issuing a Central Bank Digital Currency (CBDC) as a modern alternative to the physical currency that they currently issue. From the perspective of a retail depositor, a CBDC is likely to have technical features that make it a closer substitute to bank deposits than physical currency would be and thus would likely be a greater source of competition for banks in the deposit market than physical currency. This is the starting position this paper adopts. Specifically, this paper adopts a rather narrow view of CBDC in order to analyze in detail the possible implications of introducing a retail CBDC on the structure of the banking market. In particular, this paper defines a CBDC as a liability of the central bank held by retail depositors and that is an imperfect substitute for deposits issued by private banks. The model also assumes imperfect substitutability between the deposits issued by the private banks. I model two features that makes a CBDC distinct from bank deposits. First, the remuneration rate, which could be fixed at zero, is determined exogenously by the central bank and not according to the profit maximization objective of a private institution. Second, in order to maintain convertibility between private bank deposits, there operates an interbank market which I assume the central bank does not take part in. Instead, CBDC requires banks to increase their use of the central bank standing facilities. While Barrdear and Kumhof (2022) suggest that there should be no guarantee of convertibility between CBDC and private bank deposits, they do so due to financial stability concerns. This paper focuses on the everyday impact of CBDC, that is in times of low financial stress, where we would expect convertibility to hold in practice even if convertibility could be suspended in times of extreme financial stress.

The key predictions of the model are that if the banks do not face liquidity risk from deposit financing then in the short-run the introduction of a CBDC will result in an increase in interest rates on bank deposits and a reduction of the market shares of banks in the deposit market and bank profitability. In the long-run, the model predicts that the number of banks active in the deposit market will fall following the introduction of CBDC. The interest rate on bank deposits may no longer be increasing in the remuneration rate of CBDC in the long-run as a more concentrated banking sector places downward pressure on the bank deposit rate. This paper also highlights the importance of the liquidity risk channel for monetary policy transmission more generally. Absent liquidity risk, the bank deposit rate increases one-for-one following an increase in the policy rate, even following the introduction of a CBDC. However, if banks face liquidity risk in the deposit market introducing a CBDC will now impact monetary policy transmission through the bank deposit rate. Furthermore, the impact of monetary policy will now impact the structure of the deposit market and thus monetary policy will have a different impact in the short-run and long-run.

This paper can be seen as complementary to the growing literature on the policy implica-

tions of CBDC. A large literature focuses on issues of financial stability, in particular both Böser and Gersbach (2020) and Fernández-Villaverde et al. (2021) consider the increased risk of bank runs that may occur if bank depositors had access to a CBDC that they could transfer their deposits to in times of financial stress. While both Brunnermeier and Niepelt (2019) and Niepelt (2020) discuss equivalence results where appropriate transfers from the central bank to the financial system neutralizes the impact of introducing a CBDC and mitigate the risk of CBDC induced bank runs. While this paper also introduces liquidity risk of deposits, the focus is not on bank runs but on the costs imposed on banks when they obtain liquidity from a central bank lending facility.

This paper is also related to the literature on how CBDC should be remunerated. Agur et al. (2022) consider the welfare trade-off for the central bank in choosing a non interest-bearing versus an interest-bearing CBDC. Barrdear and Kumhof (2022) find that a counter-cyclical remuneration rate rule for CBDC can contribute toward stabilizing the business cycle. Similarly Bordo (2021) suggests that an interest-bearing CBDC may improve the transmission mechanism of monetary policy. On the other hand, Chiu and Davoodalhosseini (2021) suggests a non interest-bearing CBDC increases bank intermediation and thus welfare while an interest-bearing CBDC results in bank disintermediation and lower welfare. Williamson (forthcoming) studies various implementations of CBDC and shows how an interest-bearing CBDC can increase welfare by competing with private means of payment. This paper casts doubt on the use of the CBDC remuneration rate in the monetary toolkit as the model predicts imperfect pass-through to the bank deposit rate as well as it affecting the structure of the banking sector.

Another strand of literature focuses on the implications of CBDC for monetary policy. A summary of the possible monetary policy implications of CBDC can be found in Bindseil (2019). For example Keister and Sanches (2019) suggests that while CBDC can promote efficient exchange, it may also raise funding costs. Meaning et al. (2021) provide a detailed discussion on the monetary transmission mechanism in general as well as other possible policy implications. Kumhof and Noone (2021) discuss the remuneration of CBDC in detail and its possible use for monetary policy. Kumhof and Noone (2021) propose a two-tier remuneration system while Barrdear and Kumhof (2022) propose both a quantity rule and a price rule for CBDC. This paper does not consider the impact of a quantity rule but does consider how in the presence of deposit liquidity risk a CBDC may impact the transmission of monetary policy through the bank deposit rate.

This paper is most closely related to the literature on the impact of CBDC on the banking sector. In a macroeconomic framework, Bacchetta and Perazzi (2021) assume a constant elasticity of substitution between a CBDC and a continuum of monopolistically competitive banks. While Andolfatto (2021) analyzes the case of a single monopoly bank where CBDC and bank deposits are perfect substitutes but there is a fixed cost for depositors to switch between the two. Chiu et al. (2019) study a model of Cournot oligopoly with a finite

number of banks where banks compete in the quantity rather than the remuneration of deposits. CBDC is assumed to be a perfect substitute for bank deposits and so imposes a minimum remuneration rate on bank deposits.

This paper is also related to the literature on spatial models of imperfect competition. Competition in the deposit market before the introduction of CBDC is modeled as in the classic paper by Salop (1979). The structure of competition following the introduction of CBDC is closely related to Salop Circle models with a center such as Bouckaert (2000) and Madden and Pezzino (2011).

Finally, this paper is also related to the literature on interbank markets. In particular, the theoretical treatment of the interbank market in this paper is closest to that of Hauck and Neyer (2014) and Bucher et al. (2020) who both study the operation of an interbank market within the framework of the euro area.

The rest of this paper is organized as follows. Section 2 presents the model. Section 3 goes into further detail on how the banking sector is modeled. In Section 4 the equilibrium is presented. Section 5 analyzes the impact of the CBDC remuneration rate on the bank deposit rate. Section 6 provides a discussion of the model's implications for monetary policy transmission and Section 7 concludes.

2 Model

I consider a three period model of the retail deposit market. The economy consists of three types of agents, risk-neutral banks, a central bank and a continuum of depositors. There are three discrete periods $t = 1, 2, 3$.

In the first period, $N \geq 2$ banks enter the market, paying a fixed cost $F > 0$. Banks have access to a technology which yields an exogenously given return R_L which they must obtain an exogenously given quantity of liquidity $L > 1$ in order to operate. Banks obtain liquidity in period $t = 2$, either from the central bank or from depositors. Bank i obtains liquidity B_i from the central bank at time $t = 2$ through open market operations at an interest rate R_{RO} . The market for retail deposits is subject to liquidity risk that is realized in $t = 3$.

At the end of $t = 3$ banks must return to a liquidity neutral position and in order to do so may have to access either through the interbank market or the central bank standing facilities. The central bank offers a deposit facility with an interest rate R_{DF} and a lending facility with an interest rate R_{LF} . The central bank charges penalty rates on these standing facilities such that $R_{DF} < R_{RO} < R_{LF}$. Banks are able to trade liquidity between themselves interbank market where banks are able to borrow at rate R_{IB} . The central bank interest rate corridor sets an upper- and lower-bound on the interbank rate.

The retail deposit market is modeled as a Salop circle as in Salop (1979). There is a continuum of depositors located around a circle with unit mass. Banks locate equidistant from each other around the circle. A depositor located at a distance $x \geq 0$ away from the bank must pay a linear transportation cost $t_B x \geq 0$ in order to deposit their funds at the bank. Banks compete in prices a la Bertrand with the interest rate paid on deposits by bank i denoted as $R_{D,i}$.

The central bank may also choose in $t = 1$ to enter the deposit market through issuing a Central Bank Digital Currency (CBDC). Should the central bank issue a CBDC, it chooses a remuneration rate R_{CB} and locates itself at the center of the Salop circle. Each depositor is assumed to pay a fixed transportation cost to obtain CBDC with this transport cost drawn uniformly from the interval $t_{CB} \in [0, t_B]$. The structure of CBDC transport costs serves two purposes. First, it captures the idea that CBDC may have specific features that differentiate it from retail deposits such as privacy issues or additional security of funds. Second, it allows for competition between neighbor banks and CBDC to occur simultaneously. This would not be the case if CBDC transport costs were homogeneous among agents.

The entry of CBDC into the deposit market is known to all participants and banks choose whether to enter the deposit market and set their deposit rates with full knowledge of whether they will be competing against a CBDC. I assume that the CBDC is only held by households and that banks cannot deposit into CBDC. This assumption allows the central bank to set R_{CB} larger than the interest rate on the deposit facility R_{DF} . In cases where $R_{CB} \leq R_{DF}$ this assumption is rendered unnecessary as from the bank's perspective, the return on CBDC is weakly dominated by the central bank's deposit facility.

Deposits are subject to liquidity shocks which are realized at $t = 3$. With probability λ , a fraction $\xi \in [0, 1]$ of bank deposits relocate to other locations evenly distributed around the circle while CBDC depositors do not relocate. While with probability $1 - \lambda$, CBDC depositors are subject to the same liquidity shocks as banks and a fraction ξ of all depositors relocate around the circle.

The liquidity shocks are such that absent CBDC, the law of large numbers ensures that each bank receives a liquidity inflow equal to its liquidity outflow. The introduction of CBDC introduces additional liquidity risk into the banking sector. While similar to papers such as Fernández-Villaverde et al. (2021) that focus on the possibility of CBDC generated bank runs, here there is no risk of bank runs. Instead, if CBDC depositors are not subject to the liquidity shock, the aggregate liquidity of the banking sector falls and banks will need to increase their use of the central bank standing facilities.

To summarize the model timing once more: in the first period, $t = 1$, both commercial banks and the central bank decide on whether to enter the deposit market and commercial banks obtain liquidity B_i from the central bank. Should the central bank decide to enter

the deposit market by issuing a CBDC, it will also set the remuneration rate R_{CB} . In the second period, $t = 2$, commercial banks compete in the deposit market by setting a deposit rate $R_{D,i}$. In the third period, the liquidity shock is realized and commercial banks use the central bank standing facilities as well as the interbank market in order to obtain a liquidity neutral position. I solve the game for its Subgame Perfect Nash Equilibrium in pure strategies using backward induction.

3 Banking Sector

3.1 Bank Liquidity

I begin the analysis of the banking sector with the final period, $t = 3$. At this point in time the $N \geq 2$ banks which are indexed by i have made their decisions regarding their liquidity structure. The bank's liquidity structure consists of a quantity of deposits $q_{B,i}$ and central bank liquidity B_i .

The bank's choice of central bank liquidity B_i and deposits $q_{B,i}$ implies that before the realization of the liquidity shocks the banks have the following ex ante liquidity deficit

$$\epsilon_i \equiv L - B_i - q_{B,i}. \quad (1)$$

With probability $1 - \lambda$, a fraction ξ of all depositors relocate to locations evenly distributed around the Salop circle. In this case, banks face the same liquidity inflows as liquidity outflows and their ex post liquidity deficit is simply equal to their ex ante liquidity deficit

$$\epsilon_i^0 = \epsilon_i. \quad (2)$$

With probability λ , a fraction ξ of bank depositors relocate while CBDC depositors do not. In this case, bank i receives a liquidity outflow equal to $q_{B,i}\xi$, while each bank receives an inflow of liquidity equal to $(1 - q_{CB})q_{B,i}\xi$. Thus each bank will receive a net outflow of liquidity and has an ex post liquidity deficit equal to

$$\epsilon_i^+ = \epsilon_i + q_{CB}q_{B,i}\xi. \quad (3)$$

Banks must return to a liquidity neutral position by the end of $t = 3$. This depends on their ex post liquidity deficit ϵ_i^s , where $s \in \{0, +\}$ denotes the realization of the liquidity shock. If $\epsilon_i^s > 0$, banks will need to obtain additional liquidity either through the interbank market or through the central bank liquidity facility, while if $\epsilon_i^s < 0$ banks will reduce their

liquidity either by lending in the interbank market or through the central bank deposit facility.

The interest rate in the interbank market depends on the aggregate liquidity deficit of the banking system $\sum_i \epsilon_i^s$, which in turn will depend on the realization of the liquidity shock. The interest rates on the central bank standing facilities acting as upper- and lower-bounds on the interbank rate and thus the interbank rate will be

$$R_{IB}^s \begin{cases} = R_{LF} & \text{if } \sum_i \epsilon_i^s > 0 \\ = R_{DF} & \text{if } \sum_i \epsilon_i^s < 0 \\ \in [R_{DF}, R_{LF}] & \text{otherwise.} \end{cases} \quad (4)$$

The expected liquidity cost of deposits is simply the expected cost of returning to a liquidity neutral position

$$E[C_{D,i}] = (1 - \lambda) R_{IB}^0 \epsilon_i^0 + \lambda R_{IB}^+ \epsilon_i^+. \quad (5)$$

As the central bank standing facilities are more costly for banks to access compared to the interbank market, this generates a greater liquidity cost of deposits that will be increasing in the size of the liquidity shock.

3.2 Bank's Problem

I first consider the banks problem in the intermediate period, $t = 2$, taking the number of banks N as given. In this period, the bank decides on its liquidity structure by obtaining liquidity from the central bank and sets the interest rate it offers to depositors $R_{D,i}$. Banks are risk neutral and maximize expected profits. The profit function of bank i is

$$\pi_i = \max_{B_i, R_{D,i}} \{R_L L - R_{RO} B_i - R_{D,i} q_{B,i} - E[C_{D,i}] - F\}, \quad (6)$$

where $E[C_{D,i}]$ is defined in equation (5) and $F > 0$ is the fixed cost that banks are assume to pay in order to enter the deposit market. Banks compete for depositors in prices à la Bertrand, taking as given the deposit rates set by other banks and the funding structure of other banks as given.

In the case where the central bank does not implement a CBDC, competition between banks in the deposit market is identical to Salop's circle model. If bank i offers a deposit rate equal to $R_{D,i}$, and the other banks offer a deposit rate equal to $R_{D,-i}$ then a depositor that is located at a distance x from bank i , where $x \in [0, \frac{1}{N}]$ will choose to deposit their funds at bank i rather than the bank neighboring bank so long as

$$R_{D,i} - t_B x \geq R_{D,-i} - t_B \left(\frac{1}{N} - x \right), \quad (7)$$

where t_B is the linear transport cost that is incurred by consumers. Bank i thus faces the following demand function

$$q_{B,i} = \frac{1}{N} + \frac{1}{t_B} (R_{D,i} - R_{D,-1}). \quad (8)$$

In the case where the central bank does implement a CBDC, bank i faces competition not just the two banks that neighbor it but also from the CBDC. I assume that the central bank sets a fixed interest rate R_{CB} and that depositors incur a transport cost t_{CB} if they deposit funds in the CBDC. The transport costs associated with CBDC are assumed to be drawn randomly from a uniform distribution from an interval $[0, t_B]$. Thus for a depositor located at distance x from bank i would prefer to deposit funds in bank i rather than in the CBDC so long as

$$R_{D,i} - t_B x \geq R_{CB} - t_{CB}. \quad (9)$$

In addition, in order for a depositor to deposit funds in bank i they must also satisfy equation (7) and prefer bank i to other banks.

To calculate the demand function bank i faces in the presence of CBDC first define the point $x_{B,i}^* \in [0, \frac{1}{N}]$ as the point where a depositor is indifferent between bank i and the neighboring bank $-i$. The equation for $x_{B,i}^*$ is as in the standard Salop model and is given by

$$x_{B,i}^* = \frac{1}{2} \left(\frac{1}{N} + \frac{1}{t_B} (R_{D,i} - R_{D,-i}) \right). \quad (10)$$

From equation (9) it follows that if the remuneration rate of CBDC, R_{CB} , is sufficiently low, no depositors will prefer CBDC to bank deposits and thus the model will collapse to a Salop model of bank deposits. In order for CBDC to have a positive market share, it is required that $R_{CB} \geq \underline{R}_{CB,i}$ for at least one i , where

$$\underline{R}_{CB,i} \equiv R_{D,i} - t_B x_{B,i}^*. \quad (11)$$

Similarly, if the remuneration of CBDC is sufficiently high banks will no longer compete directly with each other and instead would only compete with the CBDC. While banks will not be completely driven out of the deposit market at this point, banks will instead operate on a local monopoly on a smaller section of the market with CBDC acting as a random outside option. As the central bank is unlikely to want to avoid banks competing directly with each other, I assume that the central bank imposes an upper-bound on the remuneration rate such that $R_{CB} < \bar{R}_{CB,i}$ for all i where

$$\bar{R}_{CB,i} \equiv R_{D,i} + t_B (1 - x_{B,i}^*) \quad (12)$$

Given these limits on R_{CB} , there exists an $\hat{x}_{B,i} \leq x_{B,i}^*$ such that the following condition holds

$$\hat{x}_{B,i} \equiv \frac{1}{t_B} (R_{D,i} - R_{CB}), \quad (13)$$

where all depositors located at a distance $\hat{x}_{B,i}$ or closer to bank i will prefer to hold deposits at bank i over CBDC.

For the interval $x \in [\hat{x}_{B,i}, x_{B,i}^*] \cap [0, x_{B,i}^*]$ there exists a function $t_i^*(x) \in (0, t_B)$ such that the following condition holds

$$t_i^*(x) = t_B x + R_{CB} - R_{D,i}, \quad (14)$$

where the function $t_i^*(x)$ defines that smallest value of t_{CB} that depositors that are located at a distance x away from bank i must have in order to prefer depositing in bank i rather than depositing in the CBDC.

Given the above definitions and assumptions, the demand function that bank i faces is

$$q_{B,i} = \begin{cases} 2x_{B,i}^* & \text{if } \hat{x}_{B,i} \geq x_{B,i}^* \\ 2 \left(\int_{\hat{x}_{B,i}}^{x_{B,i}^*} \left(\frac{t_B - t^*(x)}{t_B} \right) dx + \hat{x}_{B,i} \right) & \text{if } x_{B,i}^* > \hat{x}_{B,i} \geq 0 \\ 2 \int_0^{x_{B,i}^*} \left(\frac{t_B - t^*(x)}{t_B} \right) dx & \text{otherwise.} \end{cases} \quad (15)$$

In the case where $\hat{x}_{B,i} \geq 0$ bank i receives deposits from all depositors located at a distance under $\hat{x}_{B,i}$ and a fraction $\left(\frac{t_B - t^*(x)}{t_B} \right)$ of depositors located at a distance $x \in [\hat{x}_{B,i}, x_{B,i}^*]$, while if $\hat{x}_{B,i} < 0$, banks receive a fraction of depositors located over the distance $x \in [0, x_{B,i}^*]$.

It will be easier to work with the definite integral form of equation (15), which can be written as

$$q_{B,i} = \begin{cases} 2x_{B,i}^* & \text{if } \hat{x}_{B,i} \geq x_{B,i}^* \\ 2x_{B,i}^* - (x_{B,i}^* - \hat{x}_{B,i})^2 & \text{if } x_{B,i}^* > \hat{x}_{B,i} \geq 0 \\ 2x_{B,i}^* - (x_{B,i}^{*2} - 2\hat{x}_{B,i}x_{B,i}^*) & \text{otherwise.} \end{cases} \quad (16)$$

One useful benchmark to consider is the case where $\hat{x}_{B,i} = x_{B,i}^*$, which occurs when R_{CB} is sufficiently low that the banks do not lose market share to CBDC. In this case equation (16) collapses to $q_{B,i} = 2x_{B,i}^*$ which, noting that in a symmetric equilibrium with $R_{D,i} = R_{D,-i}$, yields a market share for bank i of $1/N$ as in the standard Salop model.

As depositors are assumed not to have an outside option, there will be full coverage in the deposit market and all deposits will be deposited either at a retail bank or at the central

bank. As a result, the market share of CBDC can be written as

$$q_{CB} = 1 - \sum_i q_{B,i}. \quad (17)$$

3.3 Bank Entry

In $t = 2$, the number of banks competing in the deposit market can be taken to be fixed. I now consider the $t = 1$ entry problem for banks, given banks have to pay a fixed cost $F > 0$ in order to enter the deposit market. Banks will choose to enter so long as the expected profits, defined by equation (6) are weakly positive. The number of banks that enter N will adjust until expected profits are driven to zero.

4 Equilibrium

4.1 Interbank Market and Bank Liquidity Structure

I focus on a symmetric equilibrium where all banks make the same decision regarding their liquidity structure, B_i and set the same deposit rate $R_{D,i}$ in $t = 2$. As banks set the same rate on deposits, they will obtain the same market share of deposits $q_{B,i}$. I distinguish between a short-run equilibrium, where the number of banks N is fixed, and a long-run equilibrium where $N \geq 2$ adjusts according to a free entry condition such that all banks make zero profits.

I begin by characterizing the equilibrium liquidity structure of the bank and the equilibrium interest rates in the interbank market. In period $t = 2$, banks take the interest rates in the interbank market, the policy rate and the interest rates on standing facilities as given. In addition, banks are able to perfectly anticipate the market share of deposits they obtain, conditional on the deposit rate they set. Obtaining liquidity from the central bank in $t = 2$ has a marginal cost of R_{RO} but also reduces the bank's ex ante liquidity deficit ϵ_i . Thus in equilibrium, the bank will adjust B_i such that the marginal cost of increasing B_i equals the expected marginal cost of increasing its ex ante liquidity deficit ϵ_i and thus

$$\frac{\partial E[C_{D,i}]}{\partial \epsilon_i} = R_{RO}. \quad (18)$$

In equilibrium, the interbank rates are such that the bank liquidity decision in $t = 2$ is consistent. Given a bank's choice of B_i and its market share $q_{B,i}$, the ex post liquidity will be conditional on the realization of the liquidity shock. From equation (4), the interbank rate conditional on the liquidity shock can be found. The equilibrium in the interbank

market and the bank's equilibrium liquidity structure is summarized in proposition 1. Additional details can be found in the appendix.

Proposition 1. *If $\lambda \leq \left(\frac{R_{RO}-R_{DF}}{R_{LF}-R_{DF}}\right)$ then banks obtain liquidity from the central bank in $t = 2$ such that*

- i) $B_i = L - q_{B,i}$*
- ii) $R_{IB}^0 = R_{LF} - \left(\frac{1}{1-\lambda}\right)(R_{LF} - R_{RO})$ and*
- iii) $R_{IB}^+ = R_{LF}$.*

Otherwise if $\lambda > \left(\frac{R_{RO}-R_{DF}}{R_{LF}-R_{DF}}\right)$ then banks obtain liquidity from the central bank in $t = 2$ such that

- i) $B_i = L - (1 - q_{CB}\xi)q_{B,i}$*
- ii) $R_{IB}^0 = R_{DF}$ and*
- iii) $R_{IB}^+ = R_{DF} + \frac{1}{\lambda}(R_{RO} - R_{DF})$.*

Proof. See Appendix. □

One implication of proposition 1 is that the interest rates in the interbank market depends on λ , the probability the bank is hit by a net outflow of liquidity. A low λ implies $\epsilon_i^0 = 0$ and banks would have a neutral liquidity position if they are not hit by an outflow of liquidity while $\epsilon_i^+ > 0$ and/ thus banks would have a liquidity deficit should they be hit by a liquidity deficit. As λ increases, the probability that the banks are hit by a liquidity outflow increases and the interbank rates will weakly fall as banks have a greater incentive to accumulate liquidity. With a sufficiently high λ , banks accumulate enough liquidity such that $\epsilon_i^+ = 0$ and banks have a neutral liquidity position if they are hit by an outflow of liquidity while $\epsilon_i^0 < 0$ and the banks will have a liquidity surplus if they are not hit by an outflow of liquidity.

By combining the bank's equilibrium liquidity decision with equation (5), the bank's expected cost of deposits can be written as

$$E[C_{D,i}] = \epsilon_i R_{RO} + \lambda R_{IB}^+ q_{CB} q_{B,i} \xi. \quad (19)$$

An important property of equation (19) is that if $\lambda > 0$ the expected cost of deposits is strictly increasing in the market share of the central bank. This is an important feedback mechanism of the model where the introduction of a CBDC or an increase in the market share of CBDC will raise the liquidity risk of deposits and thus raises the expected cost of deposits for banks. To simplify the analysis, I assume in the remainder of the paper that $\lambda \leq \left(\frac{R_{RO}-R_{DF}}{R_{LF}-R_{DF}}\right)$ and thus banks obtain sufficient liquidity only to have a neutral liquidity position in the case where they are not hit by a liquidity outflow.

4.2 Deposit Market Equilibrium

Turning now to the equilibrium in the deposit market, the bank sets a deposit rate $R_{D,i}$ that in combination with its liquidity decision set out in Proposition 1 maximizes the bank's expected profit.

In general, the equilibrium deposit rate can be found by differentiating the bank's profit function given by equation (6) with respect to the deposit rate chosen by the bank, $R_{D,i}$ yielding

$$-q_{B,i} - \frac{\partial q_{B,i}}{\partial R_{D,i}} \left(R_{D,i} + \frac{\partial E[C_{D,i}]}{\partial q_{B,i}} \right) - \frac{\partial q_{CB}}{\partial R_{D,i}} \frac{\partial E[C_{D,i}]}{\partial q_{CB}} = 0. \quad (20)$$

I first focus on the case where there is no market share of CBDC. As discussed earlier, from equation (11), it follows that for a sufficiently low CBDC remuneration rate such that $R_{CB} \leq \underline{R}_{CB}$ that no depositor prefers CBDC to bank deposits. In this case, the model collapses to a standard Salop model without CBDC. In a symmetric equilibrium, all banks receive an equal market share. As depositors are assumed to have no outside option, absent CBDC they will always deposit their funds in a bank and thus bank i 's market share is simply $q_{B,i} = \frac{1}{N}$.

In the case where $q_{CB} = 0$, the appendix shows how the deposit rate first-order condition described in equation (20) can be simplified leading to a closed-form solution for the deposit rate as in a textbook Salop circle models. The short-run equilibrium without CBDC is fully characterized by proposition 2.

Proposition 2. *For any $N \geq 2$, if $R_{CB} \leq \underline{R}_{CB}$ where $\underline{R}_{CB} = R_{RO} - \frac{3}{2}t_B \frac{1}{N}$ then there exists a unique symmetric short-run equilibrium with $q_{CB} = 0$ and banks choose $R_{D,i}$ such that*

- i) $R_{D,i} = R_{RO} - \frac{1}{N}t_B \forall i$ and
- ii) $q_{B,i} = \frac{1}{N} \forall i$.

Proof. See Appendix. □

With $q_{CB} = 0$, the bank's equilibrium liquidity decision combined with equation (19) implies that $E[C_{D,i}] = 0$ and thus the expected liquidity cost of deposits is zero. This is a consequence of the structure of the liquidity shock where absent CBDC banks face net inflows of liquidity that exactly offset the net outflows of liquidity and banks accumulate sufficient liquidity that they will not need to make use of the central bank's standing facilities.

The profit bank i makes in the case where $R_{CB} \leq \underline{R}_{CB}$ can be found by substituting in the equilibrium deposit rate and market share into equation (6), yielding

$$\pi_{B,i} = (R_L - R_{RO})L - F + t_B \frac{1}{N^2}. \quad (21)$$

A necessary requirement for $N \geq 2$ banks to enter the market in an equilibrium with $q_{CB} = 0$ is that the fixed cost of entry is such that $F - (R_L - R_{RO})L \in [0, \frac{1}{4}t_B]$. Then, in the long-run the number of banks will adjust subject to a free entry condition such that banks make zero profit in expectation. Should R_{CB} be sufficiently low, a symmetric long-run equilibrium then a long-run equilibrium exists and is fully characterized by proposition 3.

Proposition 3. *If $N^* \equiv t_B^{\frac{1}{2}}(F - (R_L - R_{RO})L)^{-\frac{1}{2}} \geq 2$ and $R_{CB} \leq \underline{R}_{CB}$ where $\underline{R}_{CB} = R_{RO} - \frac{3}{2}t_B\frac{1}{N^*}$ then there exists a unique symmetric long-run equilibrium with $q_{CB} = 0$ where N^* banks enter in $t = 1$ and banks choose $R_{D,i}$ such that*

- i) $\pi_{B,i} = 0 \ \forall i$,
- ii) $R_{D,i} = R_{RO} - \frac{1}{N^*}t_B \ \forall i$ and
- iii) $q_{B,i} = \frac{1}{N^*} \ \forall i$.

Proof. See Appendix. □

The cutoff CBDC remuneration rate \underline{R}_{CB} is increasing in N , thus the more concentrated the banking sector, the lower the threshold for CBDC to obtain a positive market share as with a lower N banks offer lower deposit rates and thus CBDC poses greater competitive pressure to banks at a lower remuneration rate.

I now consider the bank's choice of deposit rate when $R_{CB} > \underline{R}_{CB}$ and thus the CBDC remuneration rate is sufficiently high that it poses meaningful competition to retail banks. In this case, with $q_{CB} > 0$, the market share of each bank in a symmetric equilibrium is no longer equal to $1/N$ and instead depends on the deposit rate offered by the bank. As a consequence, the short-run deposit rate is now determined by a system of two equations; the first-order condition for the deposit rate, equation (20), and the definition of $\hat{x}_{B,i}$ set out by equation (13). In addition, the long-run equilibrium will also require that the free entry condition of banks holds.

In a symmetric short-run equilibrium, it follows from equation (10) that $x_{B,i}^* = 1/N$. When $R_{CB} > \underline{R}_{CB}$, through a change of variables and combining equations (13) and (20) the short-run equilibrium can be found as the $\hat{x}_{B,i}$ that solves the following equation

$$\Gamma_{\hat{x}} \equiv t_B \hat{x}_{B,i} + R_{CB} - R_{RO} + \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} + \left(\frac{\partial q_{CB}}{\partial R_{D,i}} \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} + q_{CB} \right) \lambda R_{IB}^+ \xi = 0, \quad (22)$$

where $q_{B,i}$ and q_{CB} are functions of $x_{B,i}^*$ and $\hat{x}_{B,i}$ given by equations (16) and (17) respectively.

The bank chooses its deposit rate $R_{D,i}$ taking into account the effect a change in the deposit rate it has on both its own market share $q_{B,i}$ and on the market share of CBDC

q_{CB} , taking the deposit rates set by the other banks as well as the CBDC remuneration rate as given. From equation (15) the impact of an increase in $R_{D,i}$ on the bank's market share is

$$\frac{\partial q_{B,i}}{\partial R_{D,i}} = \begin{cases} \frac{1}{t_B} & \text{if } \hat{x}_{B,i} \geq x_{B,i}^* \\ \frac{1}{t_B} (1 + x_{B,i}^* - \hat{x}_{B,i}) & \text{if } x_{B,i}^* > \hat{x}_{B,i} \geq 0 \\ \frac{1}{t_B} (1 + x_{B,i}^* + \hat{x}_{B,i}) & \text{otherwise.} \end{cases} \quad (23)$$

To obtain the impact of an increase of $R_{D,i}$, holding the deposit rates of other banks fixed, on the market share of CBDC first consider the definition of q_{CB} set out by equation (17). As all depositors are assumed to deposit their funds somewhere, the market share of CBDC can be thought of as the mass of depositors that choose not to deposit funds at any bank. An increase in $R_{D,i}$ will affect the market share not only of bank i but also of the neighboring banks and thus can be calculated from

$$\frac{\partial q_{CB}}{\partial R_{D,i}} = -\frac{\partial q_{B,i}}{\partial R_{D,i}} - \frac{\partial q_{B,i+1}}{\partial R_{D,i}} - \frac{\partial q_{B,i-1}}{\partial R_{D,i}}, \quad (24)$$

where $q_{B,i+1}$ and $q_{B,i-1}$ denote the market shares of the two banks neighboring bank i . This can be rewritten as

$$\frac{\partial q_{CB}}{\partial R_{D,i}} = \begin{cases} 0 & \text{if } \hat{x}_{B,i} \geq x_{B,i}^* \\ -2\frac{1}{t_B} (x_{B,i}^* - \hat{x}_{B,i}) & \text{if } x_{B,i}^* > \hat{x}_{B,i} \geq 0 \\ -2\frac{1}{t_B} x_{B,i}^* & \text{otherwise.} \end{cases} \quad (25)$$

From equation (22), if $R_{CB} = \underline{R}_{CB}$, then $\hat{x}_{B,i} = x_{B,i}^*$ and the equilibrium will be such that $q_{CB} = 0$ as set out by Propositions 2 and 3. In cases where $R_{CB} > \underline{R}_{CB}$, should a short-run equilibrium exist, it follows from the properties of equation (22) that $\hat{x}_{B,i} < x_{B,i}^*$ and thus $q_{CB} > 0$. In a symmetric equilibrium, it follows from equation (12) there will be an upper-bound on the CBDC remuneration rate denoted by \bar{R}_{CB} above which banks will not directly compete with each other and instead would operate a local banking monopoly competing only against the CBDC. In the range $R_{CB} \in (\underline{R}_{CB}, \bar{R}_{CB}]$ a unique short-run equilibrium is guaranteed to exist in the case where the banks face no liquidity cost of deposits for example $\lambda = 0$. This result is summarized in the following proposition.

Proposition 4. *For any $N \geq 2$, if $\lambda = 0$ there exists some interval of the CBDC remuneration rate $R_{CB} \in (\underline{R}_{CB}, \bar{R}_{CB}]$ where $\underline{R}_{CB} \equiv R_{RO} - \frac{3}{2}t_B \frac{1}{N}$ and $\bar{R}_{CB} = R_{RO} + t_B (1 - \frac{1}{4N})$ such there exists a unique symmetric short-run equilibrium with $q_{CB} > 0$ where*

- i) $\Gamma_{\hat{x}} = 0$,
- ii) $x_{B,i}^* = \frac{1}{2N}$,
- iii) $\hat{x}_{B,i} \in [- (1 - \frac{1}{2N}), \frac{1}{2N})$
- iv) $R_{D,i} = t_B \hat{x}_{B,i} + R_{CB} \forall i$ and
- v) $q_{B,i}$ and q_{CB} are given by equations (16) and (17) respectively.

Proof. See Appendix. \square

It is unsurprising that the market share of CBDC is strictly increasing in R_{CB} over the interval $(\underline{R}_{CB}, \bar{R}_{CB}]$ as a higher remuneration rate of CBDC leads to more depositors choosing CBDC over bank deposits. In the long-run, the number of banks entering the market in $t = 1$ adjusts such that expected bank profits are zero.

In the case where $q_{CB} > 0$, the profit a bank makes by setting the deposit rate at the can be written as a function of $\hat{x}_{B,i}$ and $x_{B,i}^*$

$$\pi_{B,i} \equiv (R_L - R_{RO})L - F + \left(1 + \frac{\partial q_{CB}}{\partial R_{D,i}} \lambda R_{IB}^+ \xi\right) \left[\frac{\partial q_{B,i}}{\partial R_{D,i}}\right]^{-1} q_{B,i}^2 = 0. \quad (26)$$

The long-run equilibrium in the deposit market can be summarized as the $\{x_{B,i}^*, \hat{x}_{B,i}\}$ pair that satisfies equations (22) and (26).

With $\lambda = 0$ it is shown in the Appendix that bank profits are strictly increasing in $\hat{x}_{B,i}$ over the interval and thus $[-(1 - \frac{1}{2N}), \frac{1}{2N})$ decreasing in R_{CB} over the interval $(\underline{R}_{CB}, \bar{R}_{CB}]$ while bank profit is strictly increasing in $x_{B,i}^*$ and thus as the number of bank entrants falls, an individual bank's profit increases. As I focus on the equilibrium where $N \geq 2$ banks compete against each other and a CBDC, the remuneration rate on CBDC must be sufficiently low to allow two banks to make non-negative profits. I denote this threshold value by R_{CB}^* , the formal definition of which is set out in the following Lemma.

Lemma 1. *If $\lambda = 0$ and $t_B^{\frac{1}{2}}(F - (R_L - R_{RO})L)^{-\frac{1}{2}} > 2$ there exists some $R_{RO} - \frac{3}{4}t_B < R_{CB}^* \leq R_{RO} + \frac{7}{8}t_B$ such that if $N = 2$ banks enter in $t = 1$, both banks make weakly positive profit, $\pi_{B,i} \geq 0$ and that one of these inequalities holds strictly.*

Proof. See Appendix. \square

Absent liquidity shocks as in the case with $\lambda = 0$, a unique long-run equilibrium with $N^* \geq 2$ banks and $q_{CB} > 0$ exists if the remuneration rate of CBDC is such that $R_{CB} \in (\underline{R}_{CB}, R_{CB}^*]$. This result is set out in detail in the proposition below.

Proposition 5. *If $\lambda = 0$, $t_B^{\frac{1}{2}}(F - (R_L - R_{RO})L)^{-\frac{1}{2}} > 2$ and $R_{CB} \in (\underline{R}_{CB}, R_{CB}^*]$ then there exists a unique symmetric long-run equilibrium with $q_{CB} > 0$ where $N^* \geq 2$ banks enter in $t = 1$ and banks choose $R_{D,i}$ such that*

- i) $\pi_{B,i} = 0 \ \forall i$,
- ii) $\Gamma_{\hat{x}} = 0$,
- iii) $\hat{x}_{B,i} \in [-(1 - \frac{1}{2N}), \frac{1}{2N})$
- iv) $R_{D,i} = t_B \hat{x}_{B,i} + R_{CB} \ \forall i$ and
- v) $q_{B,i}$ and q_{CB} are given by equations (16) and (17) respectively.

Proof. See Appendix. □

In the case where banks face liquidity risk from CBDC such that $\lambda > 0$, the existence of a short-run equilibrium with $q_{CB} > 0$ cannot be guaranteed to hold over the entire interval $R_{CB} \in (\underline{R}_{CB}, \bar{R}_{CB}]$ as it could be if $\lambda = 0$. Instead, equilibrium existence only be guaranteed for some R_{CB} above but sufficiently close to \underline{R}_{CB} . To understand why this is the case, first note that if $\lambda = 0$, equation (22) is strictly increasing in $\hat{x}_{B,i}$ over the interval $\hat{x}_{B,i} \in \left[-\left(1 - x_{B,i}^*\right), x_{B,i}^*\right)$, which helps guarantee uniqueness. However, in the case where $\lambda > 0$, while equation (22) is strictly increasing in $\hat{x}_{B,i}$ for $\hat{x}_{B,i}$ sufficiently close to $x_{B,i}^*$, if the liquidity cost term, $\lambda R_{IB}^+ \xi$, is sufficiently large, equation (22) may be decreasing in $\hat{x}_{B,i}$ at sufficiently small values of $\hat{x}_{B,i}$. Intuitively, when $\lambda > 0$ banks face a disincentive in using deposits as a source of liquidity which is increasing in the market share of CBDC. If $\hat{x}_{B,i}$ is sufficiently high the market share of CBDC, and hence the liquidity cost of deposits will be low and banks will set a deposit rate such that they compete for deposits. However, if $\hat{x}_{B,i}$ is sufficiently low the market share of CBDC will be relatively large and thus banks face a high liquidity cost of deposits which may lead them to choose not to compete for bank deposits leading to the possibility of local monopolies forming.

Similarly, if $\lambda > 0$, the existence of a long-run equilibrium with $q_{CB} > 0$ cannot be guaranteed over as large an interval of R_{CB} as in the case where $\lambda = 0$ but can only be guaranteed for some R_{CB} above but sufficiently close to \underline{R}_{CB} . In the case where $\lambda = 0$ equilibrium bank profits, equation (26), are strictly increasing in $x_{B,i}^*$ and strictly increasing in $\hat{x}_{B,i}$ and thus bank profit will decrease as the number of banks increases and decrease in the market share of CBDC. When $\lambda > 0$, this property can only be guaranteed for $\hat{x}_{B,i}$ sufficiently close to $x_{B,i}^*$, that is when the market share of CBDC is sufficiently small. Similarly to the above discussion, when $\lambda > 0$ and the liquidity cost term, $\lambda R_{IB}^+ \xi$, is sufficiently large, as the market share of CBDC becomes large, so does the liquidity cost of deposits. Additionally, decreasing the number of active banks leads to an increase in the market share of the banks that remain, which from equation (5) will also lead to an increase in the liquidity cost of deposits.

As highlighted earlier, in the case where the short-run or long-run equilibrium do not exist, it is possible for local monopolies to form. If it is not profitable for banks to operate a local monopoly, then banks will leave the deposit market altogether, setting $q_{B,i} = 0$ and funding their liquidity solely through central bank open market operations. I consider either case a breakdown in the functioning of the deposit market. A key takeaway from above is that if $\lambda > 0$ and banks face additional liquidity risk following the introduction of CBDC, this increases the likelihood that the deposit market may suffer a breakdown should the central bank set too high a CBDC remuneration rate.

5 Impact of CBDC on deposit rates

I now present the impact of a change in the CBDC remuneration rate, R_{CB} , on the equilibrium deposit rate $R_{D,i}$ offered by the banks. The impact of the CBDC remuneration rate will depend on whether the bank faces liquidity costs in its use of deposits. In particular, I consider the impact of a change in R_{CB} when $\lambda = 0$ versus when $\lambda > 0$. The modeling framework I use also allows me to distinguish between the short-run impact of a change in R_{CB} , where the number of banks is fixed, with the long-run impact when the number of banks adjusts according to the free entry condition. The results presented in this section are especially important in regards to whether the remuneration rate of a CBDC can be used as an additional tool in the central bank's toolbox as has been suggested by some policymakers.

In the case where $R_{CB} \leq \underline{R}_{CB}$, $q_{CB} = 0$ and CBDC has no market share and the deposit rate is given by Proposition 4. An increase in the CBDC remuneration rate will have no impact on the bank deposit rate. This holds regardless of whether or not the bank faces liquidity risk of deposits.

If R_{CB} is sufficiently high that in equilibrium $q_{CB} > 0$ then the impact of an increase in R_{CB} on the deposit rate will depend on the size of the liquidity risk of deposits facing the bank. The short-run impact of an increase in R_{CB} on the deposit rate can be found through use of the Implicit Function Theorem and by rearranging equation (13) and differentiating with respect to R_{CB} which yields

$$\frac{\partial R_{D,i}}{\partial R_{CB}} = 1 - t_B \left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma_{\hat{x}}=0}. \quad (27)$$

The long-run impact of an increase in R_{CB} can be calculated in the same way, applying the Implicit Function Theorem to the two equation system of equation (22) and (26). In the case where $\lambda = 0$ and The properties of the response of $R_{D,i}$ to an increase in R_{CB} are summarized in the proposition below for both the short-run and the long-run.

Proposition 6. *If $\lambda = 0$ and $R_{CB} \in (\underline{R}_{CB}, \bar{R}_{CB}]$ then in the short-run equilibrium described by Proposition 4, $R_{D,i}$ will be strictly increasing in R_{CB} but at a rate less than 1.*

If $\lambda = 0$ and $R_{CB} \in (\underline{R}_{CB}, R_{CB}^]$ then in the long-run equilibrium, the derivative of $R_{D,i}$ with respect to R_{CB} will always be lower than in the short-run equilibrium, holding R_{CB} fixed, and may no longer be strictly positive.*

Proof. See Appendix. □

To better illustrate the response of the bank deposit rate $R_{D,i}$ as R_{CB} changes I present some numerical examples. The model is solve numerically assuming some fixed parameters.

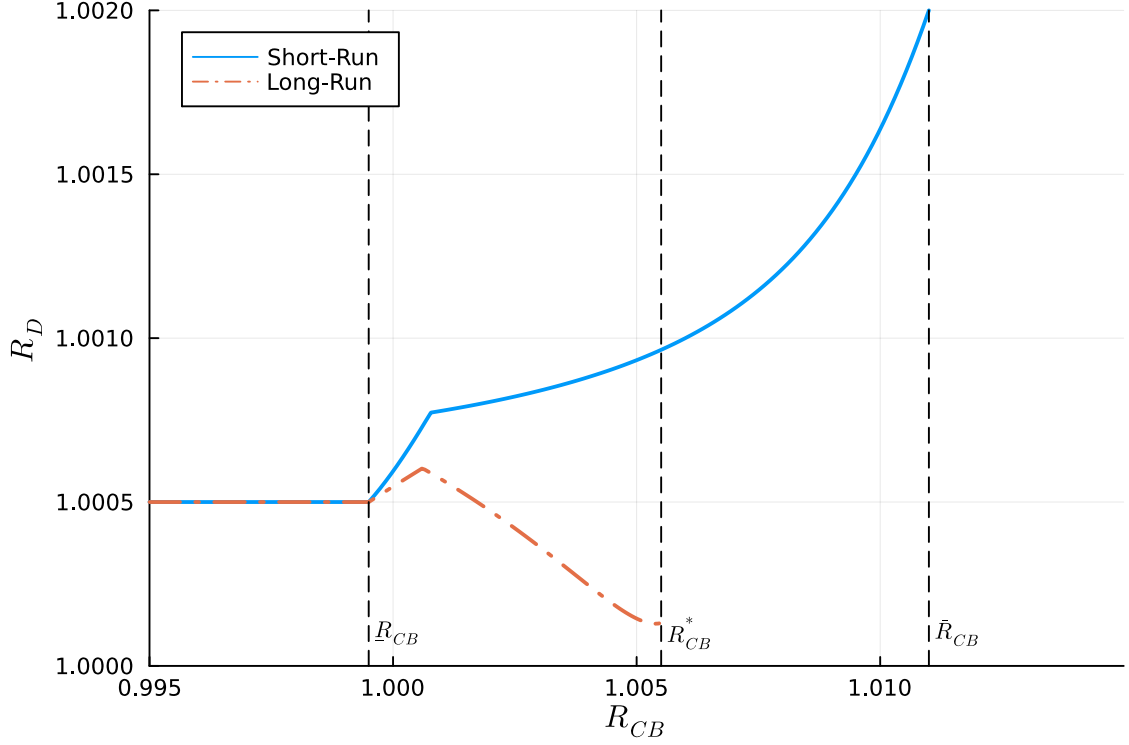


Figure 1: Impact of R_{CB} on deposit rate ($\lambda = 0$)

For the interest rates I assume that the policy rate R_{RO} is set at 25 basis points, the interest rate on the liquidity facility R_{LF} is set at 50 basis points and the interest rate on the deposit facility is set to zero. I set the linear transport cost $t_B = 0.01$ and the fraction of depositors that move subject to the liquidity shock $\xi = 0.1$. The probability of the liquidity shock hitting I allow to take two values, $\lambda \in \{0, 0.05\}$ to illustrate the two cases with and without deposit liquidity. I set the number of banks to $N = 5$ and set R_L and L such that the free entry condition holds with $N = 5$ and $R_{CB} = 0$. Thus in the numerical examples I assume the economy starts in a long-run equilibrium with $q_{CB} = 0$ and $N = 5$.

When $\lambda = 0$, the response of $R_{D,i}$ to a change in R_{CB} is plotted in figure 1 for some example set of parameters. For $R_{CB} \leq \underline{R}_{CB}$, there is no change in $R_{D,i}$ as R_{CB} changes because the market share of CBDC is zero and at these low remuneration rates CBDC does not pose meaningful competition to bank deposits. For higher values of CBDC, $R_{D,i}$ is strictly increasing in R_{CB} in the short-run while in the long-run the deposit rate is actually decreasing in R_{CB} at higher levels of R_{CB} . It should be noted that $R_{D,i}$ being decreasing in the long-run is a property of the numerical example only and need not hold for other parameterizations. What does always hold, as stated in Proposition 6 is that the long-run response of $R_{D,i}$ to an increase in R_{CB} will always be lower than in the short-run. The reason for this is that in the short-run, with the number of banks fixed, an increase in R_{CB} will lead to a fall in the market share of the banks with banks raising deposit rates in order to mitigate this loss of market share. The fall in market share and increase in cost

of deposits leads to a fall in bank profits in the short-run which results in a consolidation of the banking sector in the long-run. As the number of banks falls in the long-run in response to an increase in R_{CB} , banks face less competition from their neighboring banks and thus may be able to reduce deposit rates even in the face of greater competition from CBDC.

Figure 1 also highlights two kinks that exist in the response of $R_{D,i}$ to R_{CB} . The first of these occurs at the point where $\hat{x}_{B,i} = x_{B,i}^*$, that is the point at which CBDC starts putting competitive pressure on bank deposits. The second kink occurs at the point where $\hat{x}_{B,i} = 0$ which is the point at which some proportion of depositors will choose CBDC over bank deposit no matter how far away they are located from a bank. These kinks correspond to the intervals over which the piecewise continuous function for $q_{B,i}$ is defined by equation (16).

With $\lambda > 0$, the first part of Proposition 6 no longer holds. In the short-run, $R_{D,i}$ may no longer be monotonically increasing for $R_{CB} > \underline{R}_{CB}$. This result is summarized in the following proposition.

Proposition 7. *If $\lambda > 0$ and $R_{CB} \in (\underline{R}_{CB}, \bar{R}_{CB}]$ and where there exists a short-run equilibrium, $R_{D,i}$ will be strictly increasing in R_{CB} only if $\lambda R_{IB}^+ \xi$ is sufficiently small. If $\lambda R_{IB}^+ \xi$ is sufficiently large, $R_{D,i}$ will be decreasing in R_{CB} for R_{CB} sufficiently high.*

Proof. See Appendix. □

Setting $\lambda = 0.05$, the response of $R_{D,i}$ to a change in R_{CB} is plotted in figure 2. Apart from λ , all other parameters remain the same as in figure 1. Figure 2 illustrates the case where the expected liquidity cost of deposits, $\lambda R_{IB}^+ \xi$, is sufficiently large that even in the short-run, the deposit rate becomes decreasing in R_{CB} at sufficiently high levels of R_{CB} . In the previous case, with $\lambda = 0$, an increase in R_{CB} placed additional competitive pressure on the banking sector in the short-run and thus forced banks to raise the deposit rates they offer in order to compete for market share. In the case with $\lambda > 0$, increasing R_{CB} now has an additional effect which is to increase the cost of deposits for banks. This can be seen from equation (5) where the expected liquidity cost of deposits is increasing in the market share of CBDC and decreasing in the bank's own market share $q_{B,i}$. Thus if R_{CB} is sufficiently large, and the market share of CBDC is sufficiently large, banks may choose to lower their deposit rate in order to lower their own market share and thus lower the liquidity cost of deposits.

The results in this section have important policy implications. In particular regarding the use of the CBDC remuneration rate as an additional tool in the central bank's toolkit. Even in the most benign scenario where there is no liquidity risk and without considering the long-run impact on the banking sector, the pass-through of the CBDC remuneration

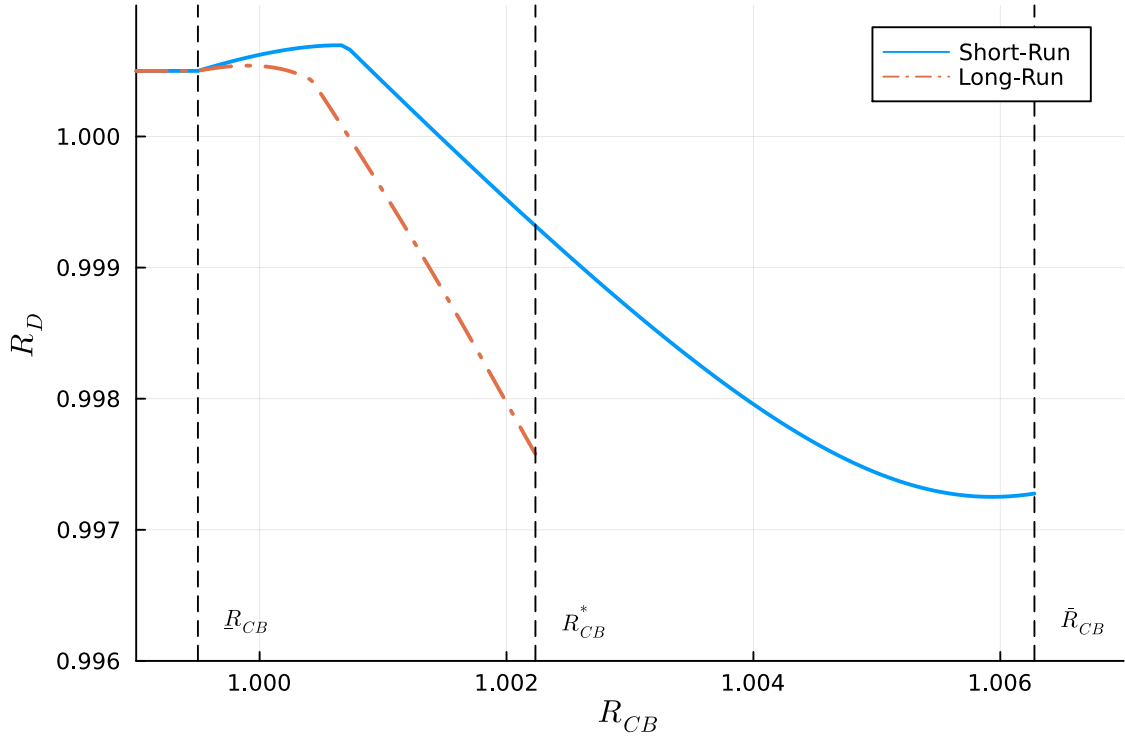


Figure 2: Impact of R_{CB} on deposit rate ($\lambda = 0.05$)

rate to the bank deposit rate is imperfect. In this scenario banks do raise their deposit rates in response to increased competition from CBDC but as competition is imperfect they do so less than one-for-one. This section also highlights that if the central bank chose to use the CBDC remuneration rate as a policy tool, there may be long-run consequences on the banking sector which would serve to dampen the pass-through to the bank deposit rate. Finally, in the case where there is risk of liquidity flowing from bank deposits to a CBDC, the additional cost this imposes on banks further weakens the pass-through of the CBDC remuneration rate to the bank deposit rate.

6 Implications for Monetary Policy Transmission

In this section, I consider the implication of CBDC for the transmission of monetary policy within the context of the model. To this end, I add some additional structure to the model in the following way. First, I assume that the spreads on the central bank standing facilities are held fixed and that the interest rate on the liquidity facility and on the deposit facility are of the form

$$R_{LF} = R_{RO} + \Delta_{LF}, \quad (28)$$

and

$$R_{DF} = R_{RO} - \Delta_{DF}, \quad (29)$$

with $\Delta_{LF} > 0$ and $\Delta_{DF} > 0$. Second, I assume that the interest rate on bank loans is equal to the policy rate plus a fixed mark-up such that

$$R_L = R_{RO} + \Delta_L, \quad (30)$$

with $\Delta_L > 0$. Finally, I assume that the central bank sets the remuneration rate of CBDC such that it is a fixed distance from the policy rate such that

$$R_{CB} = R_{RO} + \Delta_{CB}. \quad (31)$$

Here Δ_{CB} could be positive or negative depending on the central bank's CBDC policy. It should also be noted that this is just one possible remuneration policy that central banks could choose for CBDC. However, here I consider what I consider to be the most neutral implementation of CBDC remuneration. Other remuneration policies can be obtained through combining a change in the policy rate with a change in R_{CB} .

First, in the case where $q_{CB} = 0$, it follows from Proposition 2 and Proposition 3 that the deposit rate increases one-for-one with the policy rate. Turning now to the case where $q_{CB} > 0$, given the above assumptions on interest rates, the two key equations that determine the short-run and long-run equilibrium in the case where $q_{CB} > 0$, equations (22) and (26) can be rewritten respectively as

$$\tilde{\Gamma}_{\hat{x}} \equiv t_B \hat{x}_{B,i} + \Delta_{CB} + \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} + \left(\frac{\partial q_{CB}}{\partial R_{D,i}} \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} + q_{CB} \right) \lambda (R_{RO} + \Delta_{IB}^+) \xi = 0, \quad (32)$$

and

$$\tilde{\pi}_{B,i} \equiv \Delta_L L - F + \left(1 + \frac{\partial q_{CB}}{\partial R_{D,i}} \lambda (R_{RO} + \Delta_{IB}^+) \xi \right) \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i}^2 = 0, \quad (33)$$

where

$$\Delta_{IB}^+ = \begin{cases} \Delta_{LF} & \text{if } R_{IB}^+ = R_{LF} \\ -\Delta_{DF} & \text{if } R_{IB}^+ = R_{DF}. \end{cases}$$

Finally, the deposit rate can be written in terms of R_{RO} as $R_{D,i} = t_B \hat{x}_{B,i} + R_{RO} + \Delta_{CB}$.

The equilibrium with $q_{CB} > 0$ can be found as the solution to equations (32) and (33). In the case where $\lambda = 0$, both equations (32) and (33) do not respond to a change in the policy rate R_{RO} and thus the equilibrium value of $\hat{x}_{B,i}$ is also unchanged. Thus the deposit rate will increase one-for-one with the policy rate.

When $q_{CB} > 0$ and $\lambda > 0$, equations (32) and (33) now are impacted by changes in the policy rate R_{RO} . This in turn will impact the equilibrium value of $\hat{x}_{B,i}$ and thus the market share of CBDC will also be impacted by the policy rate. Thus the deposit rate will no longer increase one-for-one with the policy rate. Furthermore, as both equations are impacted by a change in the policy rate, the pass-through of the policy rate to the deposit

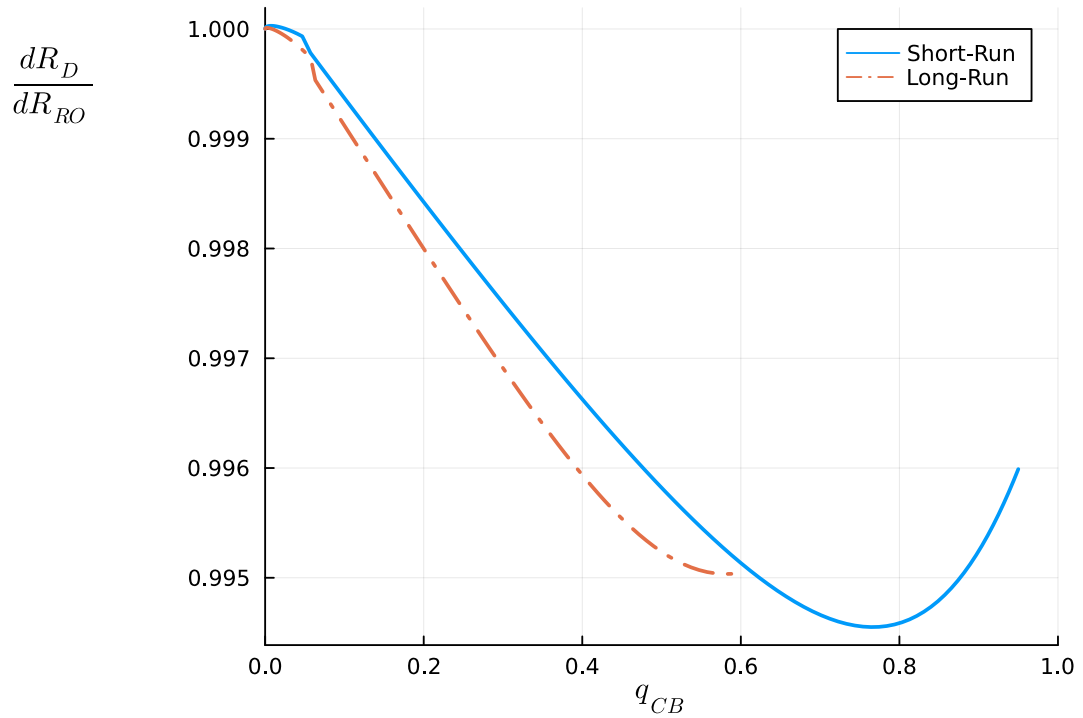


Figure 3: Impact of CBDC on Monetary Policy Transmission ($\lambda = 0.05$)

rate will be different in the short-run and long-run. Figure 3 provides a numerical example of the policy rate pass-through to the deposit rate, $dR_{D,i}/dR_{RO}$ in the case where $\lambda = 0.05$. The parameterization remains the same as that used earlier in figure 2.

This section highlights a possible risk the introduction of CBDC poses for the transmission of monetary policy to the economy. In the model, monetary transmission happens solely through pass-through of the policy rate to the deposit rate offered by banks. In the case without deposit liquidity risk, a CBDC can be introduced without impacting the normal workings of monetary policy. However, if the banks face a liquidity risk in obtaining liquidity from retail deposits, this cost will be increasing in the deposit rate and this in turn will affect the transmission of monetary policy through the deposit rate. This occurs because the cost of this liquidity risk that banks face depends on the cost of obtaining additional liquidity through the central bank lending facility. The cost of obtaining this liquidity increases with the policy rate.

7 Conclusion

As the policy debate surrounding the potential introduction of a retail CBDC grows, so does the need for further analysis of its potential implications. This paper focuses on the impact of CBDC on the structure of the market for retail bank deposits and on bank

liquidity. In this paper, CBDC is modeled as a source of direct competition for bank deposits. Competition in the deposit market is modeled using a Salop circle model and thus there is imperfect substitutability between deposits of different banks and the CBDC. This framework allows us to distinguish between the short-run impact of CBDC, where the number of banks is fixed from the long-run impact where the number of banks may adjust. In addition, the model suggests a liquidity risk channel through which CBDC may further raise the costs of banks operating in the deposit market.

Absent liquidity risk, the model suggests that in the short-run the introduction of CBDC will result in an increase in interest rates on bank deposits. This leads to a reduction of the market shares of banks in the deposit market. Banks substitute these deposits by obtaining additional liquidity from the central bank through open market operations and bank profitability falls. In the long-run, the model suggests that the introduction of CBDC will reduce the number of banks active in the deposit market and lead to greater concentration in the banking sector. In the long-run, the pass-through of the CBDC remuneration rate to the bank deposit rate is lower than in the short-run and the deposit rate may even be decreasing in the CBDC remuneration rate. This effect is amplified if banks face liquidity risk in holding deposits and in this case the bank deposit rate may be decreasing in the CBDC remuneration even in the short-run. Thus the paper casts doubt on the use of the remuneration rate of CBDC as an additional tool in the monetary policy toolkit of central banks.

The paper also highlights the importance of the liquidity risk channel for monetary policy transmission more generally. Absent liquidity risk, the bank deposit rate increases one-for-one following an increase in the policy rate, even following the introduction of a CBDC. However, if banks face liquidity risk in the deposit market introducing a CBDC will now impact monetary policy transmission through the bank deposit rate. Furthermore, the impact of monetary policy will now impact the structure of the deposit market and thus monetary policy will have a different impact in the short-run and long-run.

While this paper makes no claims regarding the welfare implications of the introduction of CBDC, it would be prudent for policymakers to take into account the welfare implications of a more concentrated banking sector that may follow the introduction of a CBDC as well as possible implications for the transmission of monetary policy.

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Appendix

Proof of Proposition 1

By combining (5) and (6) the single bank's problem can be written as follows

$$\pi_i = \max_{B_i, R_{D,i}} \{R_L L - R_{RO} B_i - R_{D,i} q_{B,i} - (1 - \lambda) R_{IB}^0 \epsilon_i^0 - \lambda R_{IB}^+ \epsilon_i^+ - F\} \quad (\text{A.34})$$

where ϵ_i^0 and ϵ_i^+ are defined by equations (2) and (3) respectively.

Differentiating with respect to B_i yields the following first-order condition

$$-R_{RO} + (1 - \lambda) R_{IB}^0 + \lambda R_{IB}^+ = 0. \quad (\text{A.35})$$

Given $\epsilon_i^0 < \epsilon_i^+$ it follows from equation (4) and that $R_{RO} \in (R_{DF}, R_{LF})$ that $R_{IB}^0 < R_{IB}^+$. There are two possible equilibria cases that are possible. Furthermore, as obtaining too much or too little liquidity from the central bank in $t = 2$ is costly, the following inequality constraints must hold, $\epsilon_i^0 \leq 0$ and $\epsilon_i^+ \geq 0$, with one of these inequality constraints holding with equality.

Thus there are two cases to consider. First, if $\epsilon_i^0 = 0$, then banks will hold exactly enough liquidity such that if they are in a neutral liquidity position if they do not receive a net outflow of liquidity. In this case, $R_{IB}^+ = R_{LF}$ and $R_{IB}^0 \in [R_{DF}, R_{LF})$. From equation (A.35) it follows that the value of R_{IB}^0 that ensures the first condition holds is

$$R_{IB}^0 = R_{LF} - \left(\frac{1}{1 - \lambda} \right) (R_{LF} - R_{RO}), \quad (\text{A.36})$$

and that for $R_{IB}^0 \geq R_{DF}$ it must be the case that

$$\lambda \leq \left(\frac{R_{RO} - R_{DF}}{R_{LF} - R_{DF}} \right). \quad (\text{A.37})$$

Finally, for $\epsilon_i^0 = 0$ it follows from equation (2) that

$$B_i = L - q_{B,i}. \quad (\text{A.38})$$

Thus the first part of the proposition has been obtained.

The second case to consider occurs if $\epsilon_i^+ = 0$ where banks hold exactly enough liquidity that they do not require any additional liquidity should they suffer a net outflow of liquidity.

In this case, $R_{IB}^0 = R_{DF}$ and $R_{IB}^+ \in (R_{DF}, R_{LF})$. From equation (A.35) it follows that the value of R_{IB}^+ that ensures the first condition holds is

$$R_{IB}^- = R_{DF} + \frac{1}{\lambda} (R_{RO} - R_{DF}), \quad (\text{A.39})$$

and that for $R_{IB}^+ < R_{LF}$ it follows that

$$\lambda > \left(\frac{R_{RO} - R_{DF}}{R_{LF} - R_{DF}} \right). \quad (\text{A.40})$$

Finally, for $\epsilon_i^+ = 0$ it follows from equation (3) that

$$B_i = L - (1 - q_{CB}\xi) q_{B,i}. \quad (\text{A.41})$$

Thus the whole proposition has now been obtained.

Proof of Proposition 2

First, differentiating the bank's profit function given in equation (A.34) with respect to $R_{D,i}$ and combining with equation (A.35) gives the following first-order condition for the bank given by equation (20).

In the case where $q_{CB} = 0$, the demand function that the bank faces is given by equation (8) and thus

$$\frac{\partial q_{B,i}}{\partial R_{D,i}} = \frac{1}{t_B}, \quad (\text{A.42})$$

while from equation (19) if $q_{CB} = 0$ then

$$\frac{\partial E[C_{D,i}]}{\partial q_{B,i}} = -R_{RO}, \quad (\text{A.43})$$

and

$$\frac{\partial E[C_{D,i}]}{\partial q_{CB}} = 0. \quad (\text{A.44})$$

In the short-run equilibrium with $q_{CB} = 0$, all banks have an equal market share and as there is full coverage, $q_{B,i} = 1/N$. Combining the above with the first-order condition yields the following equation for the deposit rate in the short-run

$$R_{D,i} = R_{RO} - t_B \frac{1}{N}. \quad (\text{A.45})$$

Finally, from equation (10), the distance from bank i where a depositor is indifferent between holding a bank i deposit and CBDC is $x_{B,i}^* = \frac{1}{2N}$. Thus, the largest possible

remuneration rate on CBDC such that all depositors prefer bank deposits to CBDC, given by equation (11) can be written as

$$\underline{R}_{CB} = R_{RO} - \frac{3}{2}t_B \frac{1}{N}. \quad (\text{A.46})$$

Proof of Proposition 3

In the long-run, N adjusts such that banks enter and make zero expected profits. The bank's profit function is given by equation (6). Substituting out the expected liquidity of deposits given by equation (19), the deposit rate given by equation (A.45) and the optimal liquidity decision as set out by proposition 1 yields the following equation for profit in the case where $q_{CB} = 0$

$$\pi_{B,i} = (R_L - R_{RO})L - F + t_B \frac{1}{N^2}. \quad (\text{A.47})$$

Denote the number of firms that drive bank profit to zero as N^* . Assuming that $F - (R_L - R_{RO})L > 0$, a positive N^* exists and can be written as

$$N^* = t_B^{\frac{1}{2}} (F - (R_L - R_{RO})L)^{-\frac{1}{2}}. \quad (\text{A.48})$$

Thus, if $N^* \geq 2$, and $R_{CB} \leq R_{RO} - \frac{3}{2}t_B \frac{1}{N^*}$ there exists a long-run symmetric equilibrium with $q_{CB} = 0$ where banks compete until profits are driven to zero. The rest of the long-run equilibrium follows from proposition 2.

Proof of Proposition 4

First, note that in the case of $\lambda = 0$, equation (22) can be written as

$$\Gamma_{\hat{x}} \equiv t_B \hat{x}_{B,i} + R_{CB} - R_{RO} + \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} = 0, \quad (\text{A.49})$$

where

$$\left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} = \begin{cases} t_B \left(\frac{2x_{B,i}^* - (x_{B,i}^* - \hat{x}_{B,i})^2}{1 + x_{B,i}^* - \hat{x}_{B,i}} \right) & \text{if } x_{B,i}^* \geq \hat{x}_{B,i} \geq 0 \\ t_B \left(\frac{2x_{B,i}^* - (x_{B,i}^{*2} - 2\hat{x}_{B,i}x_{B,i}^*)}{1 + x_{B,i}^* + \hat{x}_{B,i}} \right) & \text{if } \hat{x}_{B,i} < 0. \end{cases} \quad (\text{A.50})$$

Then note that in the limiting case when $R_{CB} \rightarrow \underline{R}_{CB} \equiv R_{RO} - \frac{3}{2}t_B \frac{1}{N}$, the solution to equation (A.49) is summarized by $\hat{x}_{B,i} = x_{B,i}^* = \frac{1}{2N}$ and the deposit rate follows immediately from equation (13). Next, note that by combining the largest possible value

of R_{CB} set out by equation (12) with equation (13) yields the following lower-bound on $\hat{x}_{B,i}$

$$\hat{x}_{B,i} \geq -(1 - x_{B,i}^*) = -\left(1 - \frac{1}{2N}\right). \quad (\text{A.51})$$

The solution to equation (A.49) at $\hat{x}_{B,i} = -(1 - \frac{1}{2N})$ yields the following definition of \bar{R}_{CB}

$$\bar{R}_{CB} = R_{RO} + t_B \left(1 - \frac{1}{4N}\right). \quad (\text{A.52})$$

For a unique short-run equilibrium for any $R_{CB} \in (\underline{R}_{CB}, \bar{R}_{CB}]$ it is sufficient to show that $\Gamma_{\hat{x}}$ is monotonically increasing in $\hat{x}_{B,i}$. As the derivative is simply

$$\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} = \begin{cases} t_B \left(1 + \frac{2(2x_{B,i}^* - \hat{x}_{B,i}) + (x_{B,i}^* - \hat{x}_{B,i})^2}{(1 + x_{B,i}^* - \hat{x}_{B,i})^2}\right) & \text{if } x_{B,i}^* \geq \hat{x}_{B,i} \geq 0 \\ t_B \left(1 + \frac{3x_{B,i}^{*2}}{(1 + x_{B,i}^* + \hat{x}_{B,i})^2}\right) & \text{if } \hat{x}_{B,i} < 0, \end{cases} \quad (\text{A.53})$$

it is straightforward to note that $\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} > 0$ and thus $\Gamma_{\hat{x}}$ is monotonically increasing in $\hat{x}_{B,i}$.

Given there exists an equilibrium value of $\hat{x}_{B,i}$ such that equation (A.49) is satisfied and in the short-run $x_{B,i}^* = \frac{1}{2N}$, it follows that the deposit rate is simply $R_{D,i} = t_B \hat{x}_{B,i} + R_{CB}$ and $q_{B,i}$ and q_{CB} are given by equations (16) and (17) respectively. Also note that for any $\hat{x}_{B,i} < x_{B,i}^*$, $q_{CB} > 0$.

Proof of Lemma 1

First note that with $\lambda = 0$, the free entry condition given by equation (26) can be written as

$$\pi_{B,i} \equiv (R_L - R_{RO})L - F + \left[\frac{\partial q_{B,i}}{\partial R_{D,i}}\right]^{-1} q_{B,i}^2 = 0. \quad (\text{A.54})$$

The derivative of equation (A.54) with respect to $x_{B,i}^*$ is

$$\frac{\partial \pi_{B,i}}{\partial x_{B,i}^*} = \begin{cases} t_B q_{B,i} \left(\frac{4 - 3(x_{B,i}^* - \hat{x}_{B,i})^2 - 2x_{B,i}^*}{(1 + x_{B,i}^* - \hat{x}_{B,i})^2}\right) & \text{if } x_{B,i}^* \geq \hat{x}_{B,i} \geq 0 \\ t_B q_{B,i} \left(\frac{(3 - 4(x_{B,i}^{*2} - 2\hat{x}_{B,i} - \hat{x}_{B,i}^2)) + (1 - q_{B,i})}{(1 + x_{B,i}^* + \hat{x}_{B,i})^2}\right) & \text{if } \hat{x}_{B,i} < 0, \end{cases}$$

It is clear that this derivative will be positive for any $\hat{x}_{B,i} \geq 0$. For the case where $\hat{x}_{B,i} < 0$, and noting that the lower-bound on $\hat{x}_{B,i}$ is $-(1 - x_{B,i}^*)$, it follows that the term $(x_{B,i}^{*2} - 2\hat{x}_{B,i} - \hat{x}_{B,i}^2)$ is decreasing in $\hat{x}_{B,i}$ and thus the largest value this term can take be is $x_{B,i}^{*2}$. Thus for any $N \geq 2$ with $\lambda = 0$ it follows that the derivative of equation $\frac{\partial \pi_{B,i}}{\partial x_{B,i}^*} > 0$ and thus $\frac{\partial \pi_{B,i}}{\partial N} < 0$.

Now note that the derivative of equation with respect to $\hat{x}_{B,i}$ is

$$\frac{\partial \pi_{B,i}}{\partial \hat{x}_{B,i}} = \begin{cases} t_B \left(\frac{q_{B,i} (3(x_{B,i}^* - \hat{x}_{B,i})^2 + 6x_{B,i}^* - 4\hat{x}_{B,i})}{(1+x_{B,i}^* - \hat{x}_{B,i})^2} \right) & \text{if } x_{B,i}^* \geq \hat{x}_{B,i} \geq 0 \\ t_B \left(\frac{x_{B,i}^* q_{B,i} (2\hat{x}_{B,i} + x_{B,i}^* + 2)}{(1+x_{B,i}^* + \hat{x}_{B,i})^2} \right) & \text{if } \hat{x}_{B,i} < 0. \end{cases}$$

Thus for any $N \geq 2$ with $\lambda = 0$, it follows that $\frac{\partial \pi_{B,i}}{\partial \hat{x}_{B,i}} > 0$ and thus $\frac{\partial \pi_{B,i}}{\partial R_{CB}} < 0$.

If $t_B^{\frac{1}{2}} (F - (R_L - R_{RO})L)^{-\frac{1}{2}} > 2$ it follows from Proposition 3 that at $\hat{x}_{B,i} = x_{B,i}^*$ with $N = 2$ bank profit will be strictly positive. As bank profit will be maximized at $N = 2$, if at $N = 2$ and $R_{CB} = R_{RO} + \frac{7}{8}t_B$ bank profit is positive, then there will exist an equilibrium over the entire range $R_{CB} \in [R_{RO} - \frac{3}{4}t_B, R_{RO} + \frac{7}{8}t_B]$. If on the other hand at $N = 2$ the banks make negative profit, then there exists some $R_{CB}^* \in (R_{RO} - \frac{3}{4}t_B, R_{RO} + \frac{7}{8}t_B)$ such that with $N = 2$ bank profit is zero.

Proof of Proposition 5

First note that assuming $t_B^{\frac{1}{2}} (F - (R_L - R_{RO})L)^{-\frac{1}{2}} > 2$, there exists an equilibrium at $\hat{x}_{B,i} = x_{B,i}^*$ with $N > 2$ which corresponds to the long-run equilibrium described in Proposition 3. Next, by Lemma 1 that there exists a $\hat{x}_{B,i} < x_{B,i}^*$ where there exists an equilibrium such that $R_{CB} = R_{CB}^*$ with $N^* \geq 2$. To show the existence of a short-run equilibrium for any $R_{CB} \in (R_{CB}^*, R_{CB}^*]$ it is sufficient to show that the equilibrium $\hat{x}_{B,i}$ is monotonically decreasing in R_{CB} . This can be shown by applying the Implicit Function Theorem to the system of equilibrium equations, equation (A.49) and (A.54).

In particular, note that we require

$$\frac{\partial \hat{x}_{B,i}}{\partial R_{CB}} = - \frac{\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial R_{CB}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial R_{CB}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix}}{\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix}} < 0, \quad (\text{A.55})$$

where

$$\frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} = \begin{cases} t_B \left(\frac{(1-2x_{B,i}^*) + (1-(x_{B,i}^* - \hat{x}_{B,i})^2)}{(1+x_{B,i}^* - \hat{x}_{B,i})^2} \right) & \text{if } x_{B,i}^* \geq \hat{x}_{B,i} \geq 0 \\ t_B \left(\frac{2 + (4\hat{x}_{B,i} - 2x_{B,i}^*) + (2\hat{x}_{B,i}^2 - 2\hat{x}_{B,i}x_{B,i}^* - x_{B,i}^{*2})}{(1+x_{B,i}^* + \hat{x}_{B,i})^2} \right) & \text{if } \hat{x}_{B,i} < 0, \end{cases} \quad (\text{A.56})$$

$$\frac{\partial \Gamma_{\hat{x}}}{\partial R_{CB}} = 1, \quad (\text{A.57})$$

$$\frac{\partial \pi_{i,B}}{\partial R_{CB}} = 0. \quad (\text{A.58})$$

and the other elements of equation (A.55) are given in the proof of Lemma 1 above. First note that

$$\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial R_{CB}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial R_{CB}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix} = \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*}, \quad (\text{A.59})$$

and thus it is sufficient to show that

$$\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix} = \frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} - \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} > 0. \quad (\text{A.60})$$

To simplify this note that the above equation can be rewritten as

$$\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix} = \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} \left(\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} \frac{\partial q_{i,B}}{\partial x_{B,i}^*} - \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \frac{\partial q_{i,B}}{\partial \hat{x}_{B,i}} \right). \quad (\text{A.61})$$

and given $\left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} > 0$ a sufficient condition for the determinant to be positive is that

$$\left(\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} \frac{\partial q_{i,B}}{\partial x_{B,i}^*} - \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \frac{\partial q_{i,B}}{\partial \hat{x}_{B,i}} \right) > 0. \quad (\text{A.62})$$

First note that in the case where $\hat{x}_{B,i} \geq 0$

$$\begin{aligned} \det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix} &= t_B \left(1 + \frac{2(2x_{B,i}^* - \hat{x}_{B,i}) + (x_{B,i}^* - \hat{x}_{B,i})^2}{(1 + x_{B,i}^* - \hat{x}_{B,i})^2} \right) 2(1 - x_{B,i}^* + \hat{x}_{B,i}) \\ &\quad - t_B \left(\frac{(1 - 2x_{B,i}^*) + (1 - (x_{B,i}^* - \hat{x}_{B,i})^2)}{(1 + x_{B,i}^* - \hat{x}_{B,i})^2} \right) 2(x_{B,i}^* - \hat{x}_{B,i}) \end{aligned} \quad (\text{A.63})$$

which can be rewritten as

$$\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} \frac{\partial q_{i,B}}{\partial x_{B,i}^*} - \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \frac{\partial q_{i,B}}{\partial \hat{x}_{B,i}} = \frac{2t_B}{(1 + \tilde{x})^2} \left[(1 + \tilde{x})^2 (1 - \tilde{x}) + q_{i,B} \right], \quad (\text{A.64})$$

where $\tilde{x} \equiv x_{B,i}^* - \hat{x}_{B,i}$ and for $N \geq 2$, $\tilde{x} \in [0, \frac{1}{4}]$ and this is strictly positive over the entire range of \tilde{x} .

Next note that in the case where $\hat{x}_{B,i} \in \left[-\left(1 - x_{B,i}^*\right), 0\right)$

$$\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix} = \frac{2t_B \left(1 + x_{B,i}^*\right)^2 \left(1 - x_{B,i}^* + \hat{x}_{B,i}\right)}{\left(1 + x_{B,i}^* + \hat{x}_{B,i}\right)^2} + \frac{2t_B \left[x_{B,i}^{*2} \left(4 - 3x_{B,i}^*\right) - \hat{x}_{B,i} x_{B,i}^* \left(2 - 4x_{B,i}^*\right)\right]}{\left(1 + x_{B,i}^* + \hat{x}_{B,i}\right)^2}, \quad (\text{A.65})$$

which again is strictly positive given $x_{B,i}^* \in \left[0, \frac{1}{4}\right]$ and we have shown that the determinant of the system of equations is always strictly positive.

Proof of Proposition 6

In the short-run with $\lambda = 0$ and $R_{CB} \in (\underline{R}_{CB}, \bar{R}_{CB}]$ there exists a short-run equilibrium described by Proposition 4. As described by the derivative of $R_{D,i}$ with respect to R_{CB} can be written as

$$\left. \frac{\partial R_{D,i}}{\partial R_{CB}} \right|_{\Gamma_{\hat{x}}=0} = 1 - t_B \left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma_{\hat{x}}=0}. \quad (\text{A.66})$$

Through the Implicit Function Theorem, the latter term can be solved as

$$\left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma_{\hat{x}}=0} = - \frac{\partial \Gamma_{\hat{x}} / \partial R_{CB}}{\partial \Gamma_{\hat{x}} / \partial \hat{x}_{B,i}} \quad (\text{A.67})$$

which can be written as

$$\left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma_{\hat{x}}=0} = \begin{cases} -\frac{1}{t_B} \left(\frac{(1+x_{B,i}^*-\hat{x}_{B,i})^2}{(1+x_{B,i}^*-\hat{x}_{B,i})^2 + 2(2x_{B,i}^*-\hat{x}_{B,i}) + (x_{B,i}^*-\hat{x}_{B,i})^2} \right) & \text{if } x_{B,i}^* \geq \hat{x}_{B,i} \geq 0 \\ -\frac{1}{t_B} \left(\frac{(1+x_{B,i}^*+\hat{x}_{B,i})^2}{(1+x_{B,i}^*+\hat{x}_{B,i})^2 + 3x_{B,i}^{*2}} \right) & \text{if } \hat{x}_{B,i} < 0, \end{cases} \quad (\text{A.68})$$

where we note that $-\frac{1}{t_B} < \left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma_{\hat{x}}=0} < 0$ and thus combining this with equation (27) yields the following property

$$0 < \frac{\partial R_{D,i}}{\partial R_{CB}} < 1. \quad (\text{A.69})$$

Thus in the short-run, with $\lambda = 0$ and increase in R_{CB} will increase $R_{D,i}$ but by less than the increase in R_{CB} .

In the long-run with $\lambda = 0$ and $R_{CB} \in (\underline{R}_{CB}, R_{CB}^*]$ there exists a long-run equilibrium described by Proposition 5. In a similar way to above, the derivative of $R_{D,i}$ with respect to R_{CB} can be written as

$$\left. \frac{\partial R_{D,i}}{\partial R_{CB}} \right|_{\Gamma=0} = 1 - t_B \left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma=0}, \quad (\text{A.70})$$

where through the Implicit Function Theorem,

$$\left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma=0} = - \frac{\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial R_{CB}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial R_{CB}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix}}{\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix}}. \quad (\text{A.71})$$

Using equations (A.59) the above equation can be written as

$$\left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma=0} = - \left(\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} - \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} \left[\frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \right]^{-1} \right)^{-1}. \quad (\text{A.72})$$

It follows from the property that $\det \begin{pmatrix} \frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} & \frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} \\ \frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} & \frac{\partial \pi_{i,B}}{\partial x_{B,i}^*} \end{pmatrix} > 0$, which was shown in the previous section of this Appendix, and that $\frac{\partial \Gamma_{\hat{x}}}{\partial x_{B,i}^*} > 0$ and $\frac{\partial \pi_{i,B}}{\partial \hat{x}_{B,i}} > 0$ that

$$\left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma=0} < \left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma_{\hat{x}}=0}, \quad (\text{A.73})$$

and thus

$$\left. \frac{\partial R_{D,i}}{\partial R_{CB}} \right|_{\Gamma_{\hat{x}}=0} > \left. \frac{\partial R_{D,i}}{\partial R_{CB}} \right|_{\Gamma=0}. \quad (\text{A.74})$$

Furthermore, $\left. \frac{d\hat{x}_{B,i}}{dR_{CB}} \right|_{\Gamma=0}$ may now be smaller than $-\frac{1}{t_B}$, thus $\left. \frac{\partial R_{D,i}}{\partial R_{CB}} \right|_{\Gamma=0}$ may no longer be strictly positive.

Proof of Proposition 7

First, note that with $\lambda > 0$, equation (22) can be written as

$$\Gamma_{\hat{x}} \equiv t_B \hat{x}_{B,i} + R_{CB} - R_{RO} + \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} + \Upsilon_{\hat{x}} \lambda R_{IB}^+ \xi = 0, \quad (\text{A.75})$$

where

$$\Upsilon_{\hat{x}} = \begin{cases} \frac{1}{2x_{B,i}^*} \left(x_{B,i}^* - \hat{x}_{B,i} \right)^2 - 2 \left(\frac{x_{B,i}^* - \hat{x}_{B,i}}{1+x_{B,i}^* - \hat{x}_{B,i}} \right) \left(2x_{B,i}^* - \left(x_{B,i}^* - \hat{x}_{B,i} \right)^2 \right) & \text{if } x_{B,i}^* \geq \hat{x}_{B,i} \geq 0 \\ \frac{1}{2} x_{B,i}^* - \hat{x}_{B,i} - 2x_{B,i}^* \frac{(2x_{B,i}^* - x_{B,i}^{*2} + 2\hat{x}_{B,i} x_{B,i}^*)}{1+x_{B,i}^* + \hat{x}_{B,i}} & \text{if } \hat{x}_{B,i} < 0. \end{cases} \quad (\text{A.76})$$

In the case of $\lambda > 0$, as $R_{CB} \rightarrow \underline{R}_{CB}$, in the equilibrium $\hat{x}_{B,i} \rightarrow x_{B,i}^*$ and $\Upsilon_{\hat{x}} \rightarrow 0$, thus the derivative properties from the previous section of the Appendix will hold. In general,

the derivative in the short-run will depend on

$$\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} = \frac{\partial}{\partial \hat{x}_{B,i}} \left\{ \left[\frac{\partial q_{B,i}}{\partial R_{D,i}} \right]^{-1} q_{B,i} \right\} + \frac{\partial \Upsilon_{\hat{x}}}{\partial \hat{x}_{B,i}} \lambda R_{IB}^+ \xi. \quad (\text{A.77})$$

The first term is greater than t_B and it can be noted from before that

$$\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}} > t_B \iff \frac{\partial R_{D,i}}{\partial R_{CB}} \Big|_{\Gamma_{\hat{x}}=0} > 0. \quad (\text{A.78})$$

Thus if $\frac{\partial \Upsilon_{\hat{x}}}{\partial \hat{x}_{B,i}} \lambda R_{IB}^+ \xi$ is positive or if it is negative but sufficiently small in absolute magnitude, then the short-run response of $R_{D,i}$ to an increase in R_{CB} will remain positive. However, this will depend in a large part on the properties of $\frac{\partial \Upsilon_{\hat{x}}}{\partial \hat{x}_{B,i}}$ as well as the magnitude of $\lambda R_{IB}^+ \xi$.

First, note that

$$\frac{\partial \Upsilon_{\hat{x}}}{\partial x_{B,i}^*} = \begin{cases} \frac{1}{2} \left(8 \left(x_{B,i}^* - \hat{x}_{B,i} \right) - 11 - \left(\frac{\hat{x}_{B,i}}{x_{B,i}^*} \right)^2 + \frac{12 - 8\hat{x}_{B,i}}{(1 + x_{B,i}^* - \hat{x}_{B,i})^2} \right) & \text{if } x_{B,i}^* \geq \hat{x}_{B,i} \geq 0 \\ \frac{4 + \hat{x}_{B,i}(\hat{x}_{B,i}(6\hat{x}_{B,i} + 14) + 12)}{(1 + x_{B,i}^* + \hat{x}_{B,i})^2} - 4\hat{x}_{B,i} - 3.5 & \text{if } \hat{x}_{B,i} < 0, \end{cases} \quad (\text{A.79})$$

where it should be noted that

$$\lim_{\hat{x}_{B,i} \rightarrow 0^+} \frac{\partial \Upsilon_{\hat{x}}}{\partial \hat{x}_{B,i}} < 0 \quad (\text{A.80})$$

and

$$\frac{\partial \Upsilon_{\hat{x}}}{\partial \hat{x}_{B,i}} < 0 \quad \forall \hat{x}_{B,i} < 0. \quad (\text{A.81})$$

Finally, note that

$$\frac{\partial^2 \Upsilon_{\hat{x}}}{\partial \hat{x}_{B,i}^2} = \begin{cases} 4 + \frac{1}{x_{B,i}^*} + 4 \frac{1 - 2x_{B,i}^*}{(1 + x_{B,i}^* - \hat{x}_{B,i})^3} > 0 & \text{if } \hat{x}_B \geq 0 \\ \frac{4x_{B,i}^*(3x_{B,i}^{*2} + 2x_{B,i}^* + 1)}{(1 + x_{B,i}^* - \hat{x}_{B,i})^3} > 0 & \text{otherwise.} \end{cases} \quad (\text{A.82})$$

Given $\frac{\partial \Upsilon_{\hat{x}}}{\partial \hat{x}_{B,i}}$ is increasing in $\hat{x}_{B,i}$ and negative for sufficiently small values of $\hat{x}_{B,i}$, if $\lambda R_{IB}^+ \xi$ is sufficiently large, then at high levels of R_{CB} , when $\hat{x}_{B,i}$ is small, $\frac{\partial \Gamma_{\hat{x}}}{\partial \hat{x}_{B,i}}$ will be less than t_B and thus $\frac{\partial R_{D,i}}{\partial R_{CB}} \Big|_{\Gamma_{\hat{x}}=0} < 0$.