Central Bank Digital Currency and Financial Stability*

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Abstract

We examine the implications of central bank digital currency (CBDC) for financial stability using a monetary general equilibrium model in which commercial bank deposits compete with the central bank deposits in CBDC account. CBDC is a national currency-denominated, interest-bearing and account-based claim on the central bank. Claims on specific agents cannot be traded across locations due to limited commnication and hence in the event of relocation an agent needs to withdraw deposits in the form of universally verified paper currency. Claims on interest-bearing CBDC is not subject to limited communication problem in the sense that it is also universally verified across locations as an account-based legal tender. The introduction of deposits in CBDC account essentially decreases supply of private credit by commercial banks, which raises the nominal interest rate and hence lowers a commercial bank's reserve-deposit ratio. This has negative effects on financial stability by increasing the likelihood of bank panic in which commercial banks are short of cash reserves to pay out to depositors. However, once the central bank can lend all the deposits in CBDC account to commercial banks, an increase in the quantity of CBDC which does not require reserve holdings can enhance financial stability by essentially increasing supply of private credit and hence lowering nominal interest rate. Except for a sufficiently large quantity of CBDC, overall welfare increases in CBDC with central bank lending due to the positive interest-rate effect on borrowers as well as the positive financial-stability effect on lenders which dominate the negative interest-rate effect on lenders.

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1 Introduction

Central banks around the world have been actively exploring the possibility of introducing sovereign digital currencies.[1] Central bank digital currency (CBDC) is a national currency-denominated, possibly interest-bearing, and account-based claim on the central bank. It is universally accessible to the general public via commercial banks or direct deposit at the central bank, and hence it can compete with bank deposits as medium of exchange and a store of value. A major potential concern is the financial stability issue associated with the risk of an economy-wide run from bank deposits to CBDC that would leave the banking system "short of funds".

Specifically, in many countries around the world, highly levered banks are at the core of the financial system. They play a key role in operating the payment system by conducting liquidity and maturity transformation. Their liabilities (i.e., bank deposits) serve as "inside money" in the sense that they are backed by private credit and become both a store of value and means of payment. In the presence of fractional reserve on bank deposits, however, this banking arrangement is exposed to a risk that banks cannot meet withdrawal demand (i.e., bank panic). As a result, the supply of inside money can decrease substantially with adverse effects on the economy. This then necessitates bank regulation, deposit insurance, and other policy interventions.

Noting that CBDC is an essentially risk-free "outside money" acting as both a means of payment and a store of value, it can enhance stability in the financial system.[2] However, a shift from bank deposits to CBDC could have a negative impact on bank funding and credit

[1] For example, the Sveriges Riksbank has an accelerated timeframe for deciding whether to launch a CBDC (Boel 2016 and Skingsley 2016), the Peoples Bank of China is experimenting with technical specifications (Fan 2016), and the Bank of England is conducting a multiyear investigation (Broadbent 2016). See also recent perspectives from officials at the European Central Bank (Mersch 2017), National Bank of Belgium (Smets 2016), and Norges Bank (Nicolaisen 2017). Also, there have been increasing discussions on motivations, designs, and policy implications of CBDC such as Bech and Garratt (2017), Bordo and Levin (2017), Engert and Fung (2017), Fung and Halaburda (2016).

[2] For discussions on the financial stability issues related to CBDC, see Barrdear and Kumhof (2016), Dyson and Hodgson (2016), Raskin and Yermack (2016), Stevens (2017), Cecchetti and Schoenholtz (2017), and Ricks, Crawford and Menand (2018).

provision, causing financial instability as well. In particular, if a central bank launches CBDC with a positive interest rate, both individuals and firms can find it attractive to convert their account balances in the commercial banks into CBDC with the central bank. As pointed out properly by Skingsley (2016), the banking system could then be drained of the funding for its lending and become unstable, which could damage the supply of credit in the economy.

The goal of this paper is to set up a monetary general equilibrium model in which commercial bank deposits compete with the central bank deposits in CBDC account. CBDC is introduced in the model economy as a national currency-denominated, interest-bearing and account-based claim on the central bank. People have access to CBDC via direct deposit at the central bank itself.[3] The model is then used to investigate the effects of the introduction of a CBDC on financial stability. We show that an increase in the quantity of CBDC can increase the likelihood of bank panic by reducing the supply of private credit, which raises nominal interest rate and lowers a commercial bank's reserve-deposit ratio. However, once the central bank can lend all the deposits in CBDC account to commercial banks, an increase in the quantity of CBDC can improve financial stability by reducing the likelihood of bank panic via an increase in the supply of private credit.

The model is a version of Champ, Smith, and Williamson (1996). They constructed a general equilibrium model of bank liquidity provision as in Diamond and Dybvig (1983) where banks provide liquidity in the form of fiat currency. Their model is extended here by introducing CBDC which is a new central bank currency of an electronic form, fixed in nominal terms, account-based legal tender for all transactions, and universally accessible for all agents.

Specifically, agents are initially assigned to a location and face relocation risk. Claims on specific agents cannot be traded across locations due to limited communication and only paper currency can be transported between locations. This generates a transactions role

[3]These are the desirable properties of CBDC as identified by Bordo and Levin (2017) based on the criteria of an efficient medium of exchange, a secure store of value, and the stable unit of account for transactions.

for paper currency in the sense that an agent needs paper currency as a means of payment in the event of relocation. However, claims on interest-bearing CBDC is not subject to limited communication problem in the sense that it is universally verified across locations as an account-based legal tender. Agents in each location receive endowment and savers deposit either at a commercial bank or at the central bank in the form of account-based CBDC. In an equilibrium where both commercial bank deposit and CBDC deposit exist for a given quantity of CBDC, the central bank sets interest rate on CBDC such that agents are indifferent between commercial bank deposit and deposit in CBDC account at the central bank.

Banks can be regarded as being differentiated by geographical location and savers deposit in particular banks nearby they locate initially. Then, depending on the realization of relocation risk, the withdrawal demand for liquidity in particular banks will be affected considerably. Under a fractional reserve system and the “inelastic currency” regime where commercial banks are prohibited from issuing their own notes, the equilibrium nominal interest rate is positive and a bank panic occurs with a positive probability in which case some banks will have to suspend reserve payout following the exhaustion of its cash reserves. The possibility of bank panics also implies that return on deposits made by agents in need of liquidity is lower than that made by those not in need.

Our main results are as follows. First, in a general equilibrium with CBDC, an increase in the CBDC deposit account means a decrease in the deposits at commercial banks. For a given reserve-deposit ratio, this implies a decrease in the supply of private credit relative to the demand for private credit by borrowers, leading to an increase in the equilibrium nominal interest rate at which borrowers take out loans from commercial banks. A decrease in a commercial bank’s reserve-deposit ratio follows, increasing the probability of bank panic in which commercial banks are short of cash reserves to pay out to depositors. Further, even in the presence of minimum reserve requirement, the introduction of CBDC can have negative effects on financial stability by increasing the likelihood of bank panic due to a higher nominal interest rate.

Second, once the central bank is allowed to lend all the deposits in CBDC account to commercial banks, the introduction of CBDC can improve financial stability by reducing the likelihood of bank panic. An increase in the quantity of CBDC implies a greater increase in the supply of private credit compared to the traditional case where all the deposits are made in commercial banks. Unlike commercial bank deposits, the deposits in CBDC account do not require reserve holdings, which allows more resources available for supply of private loans. Therefore, reserve-deposit ratio falls and nominal interest rate falls as well in equilibrium. The probability of bank panic also decreases due to the direct effect of an increase in CBDC despite a decrease in reserve-deposit ratio which has the effect of increasing the probability of bank panic.

Finally, the welfare implications of CBDC depend on both its positive financial-stability effect and negative interest-rate effect on lenders (or depositors) as well as its positive interest-rate effect on borrowers. Except for a sufficiently large quantity of CBDC, the positive financial-stability effect on lenders slightly dominates the negative interest-rate effect on lenders. Therefore, together with the positive interest-rate effect on borrowers, overall welfare increases in the quantity of CBDC as long as the size of borrowers is sufficiently large relative to that of lenders.

Our model's implications of the introduction of CBDC for the banking sector conform to the arguments put forward by Smets (2016). He notes that the adoption of a CBDC would bring about draining deposits from commercial banks and hence a tightening of the credit market or at least an increase in lending rates. As a result, investment and economic activity are likely to suffer as well. If the central bank can step in as "a provider of alternative bank funding", it would have more discretion over financial conditions so that it can better safeguard macroeconomic stability.

The literature on theoretical accounts for CBDC, including its implications for financial stability, is relatively small. Using a rich dynamic general equilibrium model, Barrdear and Kumhof (2016) show that the use of CBDC in the purchase of government bonds leads to a decline in lending and deposit rates, but by less than the decline in the policy rate. The lower real policy rate has the effect of stimulating macroeconomic activity and with it bank lending volumes and deposit levels, which could actually benefit incumbent banks. Andolfatto (2018) develops a model of a monopolistic banking sector and shows that the introduction of interest-bearing CBDC not only promotes financial inclusion (decreasing the demand for cash), but also may lead to an expansion of bank deposits if CBDC competition forces banks to raise their deposit rates. Keister and Sanches (2018) develop a New Monetarist model where a credit constraint prevents banks from financing an efficient level of investment. They show that an interest-bearing CBDC promotes efficiency in exchange because it lowers the opportunity cost of holding money, thereby increasing the demand for real money balances. However, it increases the funding costs of financially-constrained banks, thereby reducing the level of investment.

Kim et al. (2018) investigate the role of CBDC using a model of public liquidity like Williamson (2012, 2016) which integrates financial intermediation theory with a New Monetarist monetary model. In the presence of a limited commitment problem with bank which requires it to hold collateral, CBDC is essential in the sense that any allocation achievable without CBDC is achievable with CBDC, and in some cases better allocations are available due to the central bank's ability to issue a short-term debt, i.e. CBDC, as a perfect collateral at the appropriately chosen interest rate. Also, Davoodalhosseini (2018) assumes that CBDC is costly for agents because they lose their anonymity when using CBDC instead of cash. Using the framework of Lagos and Wright (2005) in which both cash and CBDC are available as means of payment, he shows that if the cost of using CBDC is not too high, the first best can be achieved by using CBDC than with cash.

The paper is organized as follows. Section 2 describes the model of bank liquidity provision with limited communication across locations where commercial bank deposits compete with the central bank deposits in CBDC account. Section 3 investigates the effects of CBDC on financial stability when the central bank simply keeps all the deposits in CBDC account without making any loans to commercial banks. In section 4 we allow for the central bank's lending of deposits in CBDC account to commercial banks and examine its implications for financial stability. Section 5 summarizes the paper with a few concluding remarks.

2 Model

The basic structure comes from an overlapping-generations model of Champ, Smith, and Williamson (1996). Time is discrete and goes forever, indexed by $t = 1, 2, \ldots.$ In each time period t, a $[0, 1]$ continuum of agents is born and they live for two periods, t ("young") and $t + 1$ ("old"). Half of young agents are "lenders" and the remaining young agents are "borrowers". All agents born at t have preferences given by

$$\mathbb{E}\left(\ln c_t + \beta \ln c_{t+1}\right)$$

where $c_t > 0$ is consumption when young in period t, $c_{t+1} > 0$ is consumption when old in period $t + 1$, $\mathbb{E}$ denotes the expectation operator, and $\beta \in (0, 1)$ is the discount factor.

Each lender born in period t has endowment $x > 0$ of perishable consumption good when young at t and no endowment when old at $t + 1$, whereas a borrower born in period t has no endowment when young at t and $y > 0$ when old at $t + 1$. Assume that $\beta x < y$. In each location there are a finite and large number of infinitely lived banks which play the roles of not only intermediating between lenders and borrowers, but also providing liquidity as in Diamond and Dybvig (1983).

At $t = 1$, there is also a $[0, 1]$ continuum of old agents in each location. They are each endowed with paper currency $M > 0$ issued by the central bank. There is no subsequent change in the supply of paper currency. The central bank is also ready to provide a deposit account in a new central bank currency of an electronic form, called central bank digital currency (CBDC), to a fraction $\theta \in [0, 1)$ of young lenders. Just like paper currency and coins, CBDC is fixed in nominal terms, valid as legal tender for all transactions, and universally accessible for all agents in all locations. Each period the central bank can use young lenders' deposits to purchase one-period government bond which yields one-period real gross return $R^c \geq 1$ in the following period.

In the model economy the events occur in the following sequence within a period:

- At the beginning of period t, agents born in a location receive their endowment. Young lenders deposit goods either at a bank or at the central bank in the form of account-based CBDC.

- Young lenders consume and cannot contact other agents until they learn whether they are to be relocated.

- Young borrowers contact bank to take loans and then young lenders learn whether they should be relocated. A random fraction π_t of young lenders ("movers") must relocate where $\pi_t \in [0, 1]$.

- Movers who have bank deposits can contact their bank and withdraw deposits plus interest. All period-t resources have been consumed so that these agents receive claims to future consumption in the form of paper currency. Movers who have deposits in a CBDC account at the central bank do not have to withdraw deposits since the account-based CBDC is accessible for all agents in all locations.

- At $t + 1$, old agents can use these liabilities to purchase goods when they contact commercial banks or the central bank in their new location.

Let the distribution function of the random variable π_t be denoted as $F(\pi_t)$ and its continuously differentiable density function as $f(\pi_t)$. Following Townsend (1987), in the absence of communication across locations, the quality of checks drawn on bank deposit from another location or claims on borrowers in another location, from being verified. However, the central bank paper currency can be verified in all locations and hence in the event of relocation lenders demand currency. The account-based, interest-bearing CBDC is also not subject to limited communication problem in the sense that it is universally verified across locations as an account-based legal tender.

Let $r_t^m(\pi_t)$ and $r_t(\pi_t)$ denote the gross real rate of return on deposit made by movers and nonmovers, respectively, contingent on π_t. Each bank simply accepts all deposits offered and makes loans charging the competitively determined gross real interest rate R_t independent of π_t. Notice that borrowers do not observe π_t, making it natural to make R_t not depend on π_t. The central bank accepts all deposits in CBDC account and pays one-period return $r_t^c \leq R^c$ per unit deposited for both movers and nonmovers independent of π_t. Notice that the central bank simply keeps all the deposits in CBDC account without making any loans to commercial banks or directly providing credit to non-bank sector.

2.1 Agent's Problem

Having observed commercial banks' repayment schedules at t, each lender chooses a deposit d_t^b to maximize her expected utility:

$$V^b \equiv \mathbb{E}\left\{\ln\left(x - d_t^b\right) + \beta \int_0^1 \pi \ln\left[r_t^m(\pi) d_t^b\right] f(\pi) d\pi + \beta \int_0^1 (1-\pi) \ln\left[r_t(\pi) d_t^b\right] f(\pi) d\pi\right\} \quad (1)$$

The optimal deposit (or saving) in a commercial bank is

$$d_t^b = \frac{\beta x}{1+\beta},$$

and each lender chooses the commercial bank whose repayment schedules maximize her expected utility. Each borrower chooses a quantity of loan l_t to maximize expected utility for given R_t:

$$V^l \equiv \mathbb{E}\left\{\ln l_t + \beta \ln\left(y - R_t l_t\right)\right\} \tag{2}$$

The optimal quantity of loan (or borrowing) from a commercial bank is

$$l_t = \frac{y}{(1+\beta)R_t}.$$

Finally, given the CBDC's return r_t^c, each lender who deposits in CBDC account at the central bank chooses a deposit d_t^c to maximize her expected utility given by:

$$V^c \equiv \mathbb{E}\left\{\ln\left(x - d_t^c\right) + \beta \int_0^1 \ln\left(r_t^c d_t^c\right) f(\pi) d\pi\right\}. \tag{3}$$

The optimal deposit in the central bank's CBDC account is the same as that in a commercial bank:

$$d_t^c = d_t^b = \frac{\beta x}{1+\beta}.$$

Each lender chooses to deposit either at a commercial bank or at the central bank's CBDC account depending on which one delivers a higher expected utility:

$$\max\{V^b, V^c\}.$$

That is, each lender will deposit at a commercial bank if $V^b \geq V^c$, whereas she will deposit at the central bank's CBDC account if $V^b \leq V^c$. In equilibrium where both commercial bank deposit and central bank deposit exist, the central bank should set $r_t^c \leq R^c$ such that $V^b = V^c$ for a given choice of $\theta \in [0, 1)$ by the central bank.

2.2 Commercial Bank's Problem

Against deposits d_t per depositor, a commercial bank holds cash reserves z_t and makes loans $d_t - z_t$ where d_t and z_t are all in real terms. Let $\gamma_t \equiv z_t/d_t$ be a commercial bank's reserve-deposit ratio. Loans earn the one period real gross return R_t, whereas cash reserves earn p_{t+1}/p_t where p_t denotes the *inverse* price level. Commercial banks take both R_t and p_{t+1}/p_t as given.

After reserve-deposit ratio is chosen and loans are made, π_t is realized. Then a commercial bank faces real per-depositor withdrawal demand equal to

$$d_t \pi_t r_t^m(\pi_t) \frac{p_t}{p_{t+1}},$$

which is paid by the commercial bank in the form of paper currency. The term p_t/p_{t+1} captures the fact that the commercial bank gives paper currency to movers at t, who will take it to their new location to make purchases at $t+1$. It earns p_{t+1}/p_t which is the real gross rate of return on currency between t and $t+1$. Therefore, payment of $r_t^m(\pi_t)p_t/p_{t+1}$ to movers at t yields a perceived return to the movers of $r_t^m(\pi_t)$.

Note that borrowers cannot liquidate loans at the end of t since they have no resources and have already consumed. Let $\alpha_t(\pi_t)$ denote the fraction of cash reserves that the commercial bank pays out to movers at t (as a function of π_t). Then, the commercial bank faces the following constraints in making payments to movers at t and nonmovers at $t+1$, respectively:

$$\pi_t r_t^m(\pi_t) \frac{p_t}{p_{t+1}} \leq \alpha_t(\pi_t)\gamma_t \tag{4}$$

$$(1-\pi_t) r_t(\pi_t) \leq \gamma_t \left[1 - \alpha_t(\pi_t)\right] \frac{p_{t+1}}{p_t} + (1-\gamma_t) R_t. \tag{5}$$

In equilibrium, zero profit condition for a commercial bank implies that (4) and (5) hold with equality. Also, $r_t^m(\pi_t), r_t(\pi_t), \alpha_t(\pi_t)$, and γ_t should be chosen to maximize the depositors' expected utility, taking their deposits as given:

$$\mathbb{E}\left\{\ln\left(\frac{x}{1+\beta}\right)+\beta\int_0^1 \pi\ln\left[r_t^m(\pi)\frac{\beta x}{1+\beta}\right]f(\pi)d\pi+\beta\int_0^1(1-\pi)\ln\left[r_t(\pi)\frac{\beta x}{1+\beta}\right]f(\pi)d\pi\right\} \tag{6}$$

subject to (4) and (5) with equality. Further, the reserve payout contingent on π_t can be expressed as

$$\alpha_t(\pi_t)\leq\pi_t\left[1+\left(\frac{1-\gamma_t}{\gamma_t}\right)R_t\frac{p_t}{p_{t+1}}\right] \tag{7}$$

where the equality holds if $\alpha_t(\pi_t)<1$ in which $r_t^m(\pi_t)=r_t(\pi_t)$. Then, from (4) and (5),

$$r_t^m(\pi_t)=r_t(\pi_t)=\gamma_t\frac{p_{t+1}}{p_t}+(1-\gamma_t)R_t. \tag{8}$$

The optimal reserve-deposit ratio can be expressed as [4]

$$\gamma_t=1-\int_{\pi_t^*}^1 F(\pi)d\pi, \tag{9}$$

where π_t^* is defined to be the value of π_t that satisfies (7) as an equality with $\alpha_t(\pi_t^*)=1$ so that banks pay out all the reserves (i.e., bank panic); that is,

$$\pi_t^*=\left[1+\left(\frac{1-\gamma_t}{\gamma_t}\right)R_t\frac{p_t}{p_{t+1}}\right]^{-1}\equiv g(\gamma_t,I_t) \tag{10}$$

and $I_t\equiv R_t\frac{p_t}{p_{t+1}}$ denotes the gross nominal interest rate. Given the definition of π_t^* in (10), the optimal liquidation strategy for the bank, (7), can be written as

$$\alpha_t(\pi_t)=\min\left[\frac{\pi_t}{\pi_t^*},1\right]. \tag{11}$$

When $\pi_t\geq\pi_t^*$ holds, some banks exhaust cash reserves so that a "bank panic" occurs.

[4] We obtain the optimal reserve-deposit ratio from the first-order condition with respect to γ_t after substituting the following payment schedules:
$r_t^m(\pi_t)=r_t(\pi_t)=\gamma_t\frac{p_{t+1}}{p_t}+(1-\gamma_t)R_t$ if $\pi_t<\pi_t^*$; $r_t^m(\pi_t)=\frac{\gamma_t}{\pi_t}\frac{p_{t+1}}{p_t}$ and $r_t(\pi_t)=\frac{1-\gamma_t}{1-\pi_t}R_t$ if $\pi_t\geq\pi_t^*$.

Moreover, in a bank panic, $r_t^m(\pi_t) \leq r_t(\pi_t)$ or $r_t(\pi_t)/r_t^m(\pi_t) \geq 1$–i.e., those agents needing liquidity (movers) suffer relative to nonmovers. Since the ratio of returns $r_t(\pi_t)/r_t^m(\pi_t)$ captures the currency premium, $r_t(\pi_t)/r_t^m(\pi_t) \geq 1$ implies that there is a positive currency premium when the bank panic occurs.

Now we can characterize the optimal reserve-deposit ratio by defining the function $H : [0,1] \to [0,1]$ as

$$H(x) = \int_x^1 F(\pi)d\pi. \tag{12}$$

Then (9) can be written as

$$1 - \gamma_t = H[g(\gamma_t, I_t)] \tag{13}$$

Figure 1 shows that $H[g(\gamma, I)]$ is decreasing and concave in γ, $H[g(0, I)] = H(0) < 1$, and $H[g(1, I)] = H(1) = 0$ for $I \geq 1$. The slope of $H[g(\gamma, I)]$ is greater than one in absolute term at $\gamma = 1$ for $I > 1$, whereas it is equal to one in absolute term for $I = 1$. It follows that, if $I_t = 1$, (13) is satisfied only by $\gamma_t = 1$. If the nominal interest rate is positive ($I_t > 1$), then (13) has two solutions. It can be shown that the interior solution solves a commercial bank's optimization problem. From (10) and the definition of $H(\bullet)$, an increase in I shifts $H[g(\gamma, I)]$ upward, as depicted in Figure 1 where $1 < I_1 < I_2$. That is, the optimal reserve-deposit ratio $\gamma_t(I_t)$ has the property of $\gamma_t(1) = 1$ and $\gamma_t' < 0$. Therefore, the fractional reserves ($\gamma_t < 1$) imply not only a positive nominal interest rate, but also a positive probability of bank panics–i.e., $\pi_t^* < 1$ from (9).

2.3 General Equilibrium

We describe a general equilibrium with $\theta \geq 0$ in which some deposits are held in CBDC account at the central bank. Note first that, in equilibrium, bank loans should be made in positive quantities. Since $\gamma_t(1) = 1$ and $\gamma_t' < 0$ for $I_t \geq 1$, it then follows that $I_t > 1$ must hold, or

$$R_t > \frac{p_{t+1}}{p_t}. \tag{14}$$

for all $t \geq 1$; that is, nominal interest rates should be always positive in equilibrium.

Moreover, in equilibrium net savings of young generation in commercial banks must equal the supply of real balances of old generation in each period:

$$(1-\theta)\frac{\beta x}{1+\beta} - \frac{y}{(1+\beta)R_t} = p_t M, \tag{15}$$

and commercial banks hold all real balances as cash reserves:

$$\gamma_t(1-\theta)\frac{\beta x}{1+\beta} = p_t M. \tag{16}$$

These two equations can be combined to represent a market-clearing condition for private credit market, which equates supply of private credit with demand for private credit:

$$(1-\theta)(1-\gamma_t)\frac{\beta x}{1+\beta} = \frac{y}{(1+\beta)R_t} \tag{17}$$

It is worth noting that a positive quantity of deposits in the CBDC account ($\theta > 0$) essentially decreases supply of private credit for a given demand for private credit. As will be shown below, this then results in a higher nominal interest rate (R_t) than in the paper currency only regime.

In a stationary equilibrium where $p_t M = p_{t+1} M$ for all t, $p_{t+1}/p_t = 1$. Also, (14) and $p_t M > 0$ (a positive stock of valued paper currency) in (15) imply

$$R_t > \frac{y}{(1-\theta)\beta x} > 1. \tag{18}$$

Hence, for given $\theta \in [0,1)$ and $\beta \in (0,1)$, nominal interest rate is positive ($R_t > p_{t+1}/p_t = 1$)

in equilibrium if y is sufficiently large compared to x. Further, Figure 1 implies that the reserve-deposit ratio remains relatively small (e.g., $\gamma_t < \frac{1}{2}$) as long as y is sufficiently large relative to x for $\theta = 0$ and $\beta \in (0, 1)$ so that nominal interest rate is relatively high.

For a given $\theta \in [0, 1)$, a general equilibrium consists of quantity γ_t and prices $r_t^m(\pi_t)$, $r_t(\pi_t)$, R_t that satisfy (4), (5), (13), (15), (16). This will also determine the equilibrium value of bank panic cut-off π_t^* by (10). Finally, r_t^c is determined by $V^b = V^c$ where V^b and V^c are respectively given by (1) and (3). It can be shown that r_t^c is determined as a convex combination of $r_t^m(\pi_t)$ and $r_t(\pi_t)$.

3 CBDC and Financial Stability

We now investigate the general-equilibrium effects of an increase in the quantity of CBDC on financial stability (i.e., bank panic) via changes in supply of private credit, nominal interest rate, and commercial bank's reserve-deposit ratio.

Proposition 1 *As θ increases, the equilibrium reserve-deposit ratio (γ_t) decreases and the equilibrium nominal interest rate (R_t) increases.*

Proof. From (15) and (16), we have $R_t = \frac{y}{(1-\theta)(1-\gamma)\beta x}$. Then by substituting R_t and $p_t = p_{t+1}$ into (10), we can redefine g as a function of θ; that is, $\pi_t^* \equiv g(\gamma_t, \theta)$. From the implicit function theorem and the Leibniz rule, (13) gives

$$\frac{\partial \gamma}{\partial \theta} = -\frac{F(g(\gamma,\theta))\frac{\partial g}{\partial \theta}}{-1 + F(g(\gamma,\theta))\frac{\partial g}{\partial \gamma}} = -\frac{F(g(\gamma,\theta))\frac{y}{\gamma(1-\theta)^2\beta x}\frac{1}{[1+\frac{y}{\gamma(1-\theta)\beta x}]^2}}{1 - F(g(\gamma,\theta))\frac{y}{\gamma^2(1-\theta)\beta x}\frac{1}{[1+\frac{y}{\gamma(1-\theta)\beta x}]^2}} < 0,$$

where the last inequality follows from $F(g(\gamma,\theta)) \leq 1$ and $\frac{y}{\gamma^2(1-\theta)\beta x} < [1 + \frac{y}{\gamma(1-\theta)\beta x}]^2$.
Now, $\frac{\partial R_t}{\partial \theta} = \frac{y}{(1-\gamma)(1-\theta)\beta x}\left(\frac{1}{1-\theta} + \frac{1}{1-\gamma}\frac{\partial \gamma}{\partial \theta}\right) > 0$ since it can be shown that $-\frac{1-\theta}{1-\gamma}\frac{\partial \gamma}{\partial \theta} < 1$ as below:

$$-\frac{1-\theta}{1-\gamma}\frac{\partial \gamma}{\partial \theta} = \frac{\gamma R F(\pi^*)}{[\gamma + (1-\gamma)R]^2 - RF(\pi^*) + \gamma RF(\pi^*)} < 1,$$

where the last inequality follows from $[\gamma + (1-\gamma)]^2 - F(\pi^*) > 0$ and $[\gamma + (1-\gamma)R]^2 - RF(\pi^*)$ is increasing in $R \geq 1$ for any $\gamma < \frac{1}{2} \leq 1 - \frac{F(\pi^*)}{2}$. ■

An increase in the deposits in CBDC account means a decrease in the deposits in commercial banks. For a given reserve-deposit ratio, this implies a decrease in the supply of credit relative to the demand for credit by borrowers, leading to an increase in the equilibrium nominal interest rate at which borrowers take out loans from commercial banks.

Notice that, from the credit-market clearing condition (17), an increase in θ shifts the supply curve of private credit to the left as depicted in Figure 2, raising nominal interest rate. Also, an increase in the supply of private credit due to a decrease in reserve-deposit ratio (γ_t) following a rise in nominal interest rate is shown as a movement along the new supply curve of private credit.

Now, the following proposition shows that a decrease in the reserve-deposit ratio increases the probability of bank panic in the sense that it decreases the cut-off value of a relocation probability above which a commercial bank is short of reserves for paying out to movers.

Proposition 2 *As θ increases, the bank panic cut-off (π_t^*) decreases in equilibrium.*

Proof. Note that (10) can be rearranged as

$$\pi_t^* = \frac{\gamma}{\gamma + (1-\gamma)R}. \tag{19}$$

Then, it is obvious from **Proposition1**. ■

This proposition implies that the likelihood of bank panic increases as the quantity of CBDC increases.[5] One might claim that the minimum reserve requirements on bank deposits would prevent bank panic from happening in the real world. With the introduction of CBDC,

[5] The model lacks a credit multiplier effect since borrowers use the credit only once without re-depositing it in another bank. This is inevitable in a two-period overlapping generations model. However, noting that a credit multiplier effect would only strengthen negative effects of the introduction of CBDC on financial stability, allowing for a credit multiplier effect would not alter the main result that the likelihood of bank panic increases with the introduction of CBDC.

however, the following proposition shows that the likelihood of bank panic can increase due to higher nominal interest rate despite the minimum reserve requirements in place.

Proposition 3 *Suppose that the minimum reserve requirements are binding. Then, as θ increases, the bank panic cut-off (π_t^*) decreases in equilibrium.*

Proof. Obvious from $R_t = \frac{y}{(1-\theta)(1-\gamma)\beta x}$ and (10) or (19). ■

4 Central Bank Lending and Financial Stability

We now consider the case where the central bank makes loans to commercial banks. We assume that the central bank accepts young lenders' deposits in CBDC account and lends them all to commercial banks at the interest rate $r_t(\pi_t)$. The central bank then pays its depositors $r_t^c \leq r_t(\pi_t)$ per unit deposited in CBDC account.

4.1 Commercial Bank's Problem

Suppose that the central bank can lend young lenders' deposits to commercial banks. Then, a commercial bank's payments to movers must satisfy the constraint

$$(1-\theta)\pi_t r_t^m(\pi_t)\frac{p_t}{p_{t+1}} \leq \alpha_t(\pi_t)\gamma_t^c, \tag{20}$$

while payments to nonmovers and the central bank at $t+1$ must satisfy

$$(1-\pi_t)r_t(\pi_t) + \theta\pi_t r_t(\pi_t) \leq \gamma_t^c \left[1-\alpha_t^c(\pi_t)\right]\frac{p_{t+1}}{p_t} + (1-\gamma_t^c)R_t. \tag{21}$$

where γ_t^c is a commercial bank's reserve-deposit ratio and $\alpha_t^c(\pi_t)$ is the reserve payout ratio with the central bank lending to commercial banks. Notice that a commercial bank pays its moving and non-moving depositors respectively $r_t^m(\pi_t)$ and $r_t(\pi_t)$ per unit deposited, whereas it pays $r_t(\pi_t)$ per unit deposited in the central bank's CBDC account by both moving and non-moving depositors.

In equilibrium, zero profit condition for a commercial bank implies that (20) and (21) hold with equality. Also, as in the case of no central bank lending, $r_t^m(\pi_t), r_t(\pi_t), \alpha_t^c(\pi_t)$, and γ_t^c should be chosen to maximize the expected utility of depositors, (6), taking their deposits and central bank lending as given, subject to (20) and (21) with equality. Now, the reserve payout contingent on π_t can be expressed as

$$\alpha_t^c(\pi_t) \leq (1-\theta)\pi_t \left[1 + \left(\frac{1-\gamma_t^c}{\gamma_t^c}\right) R_t \frac{p_t}{p_{t+1}}\right] \tag{22}$$

where the equality holds if $\alpha_t^c(\pi_t) < 1$ in which $r_t^m(\pi_t) = r_t(\pi_t)$. This can be interpreted as reserve payout being relevant only to the $(1-\theta)$ fraction of deposits which are made in commercial banks. Then, from (20) and (21),

$$r_t^m(\pi_t) = r_t(\pi_t) = \gamma_t^c \frac{p_{t+1}}{p_t} + (1-\gamma_t^c)R_t$$

which is of the same form as in (5) without central bank lending.

In the presence of CBDC lending, the optimal reserve-deposit ratio can be expressed as [6]

$$\gamma_t^c = 1 - \int_{\pi_t^{c*}}^{1} F(\pi)d\pi - \theta\pi_t^{c*}F(\pi_t^{c*}) \tag{23}$$

where π_t^{c*} is defined to be the value of π_t that satisfies (22) as an equality with $\alpha_t^c(\pi_t^{c*}) = 1$ so that commercial banks pay out all the reserves (i.e., bank panic); that is,

$$\pi_t^{c*} = \min\left\{\frac{1}{1-\theta}\left[1 + \left(\frac{1-\gamma_t^c}{\gamma_t^c}\right) R_t \frac{p_t}{p_{t+1}}\right]^{-1}, 1\right\} \equiv \kappa(\theta, \gamma_t^c, I_t) \tag{24}$$

[6] We obtain the optimal reserve-deposit ratio from the first order condition with respect to γ_t^c after substituting the following payment schedules:
$r_t^m(\pi_t) = r_t(\pi_t) = \gamma_t^c \frac{p_{t+1}}{p_t} + (1-\gamma_t^c)R_t$ if $\pi_t < \pi_t^{c*}$; $r_t^m(\pi_t) = \frac{\gamma_t^c}{(1-\theta)\pi_t}\frac{p_{t+1}}{p_t}$ and $r_t(\pi_t) = \frac{1-\gamma_t^c}{1-(1-\theta)\pi_t}R_t$ if $\pi_t \geq \pi_t^{c*}$.

Notice that the reserve-deposit ratio in (23) decreases with θ, the fraction of deposits made in the central bank's CBDC account. This comes from the fact that, unlike the deposits in commercial banks, the deposits in CBDC account do not require reserve holdings. Given the expression of π_t^{c*} in (24), the optimal liquidation strategy for the bank, (22), can be written as

$$\alpha_t^c(\pi_t) = \min\left[\frac{\pi_t}{\pi_t^{c*}}, 1\right]. \tag{25}$$

Now we can characterize the optimal choice of reserve-deposit ratio by defining the function $J : [0,1] \times [0,1] \to [0,1]$ as

$$J(x,\theta) = \int_x^1 F(\pi)d\pi + \theta x F(x). \tag{26}$$

Then (23) can be written as

$$1 - \gamma_t^c = J\left[\kappa(\theta, \gamma_t^c, I_t), \theta\right]. \tag{27}$$

As depicted in Figure 3, it can be shown that an increase in θ shifts $J\left[\kappa(\theta, \gamma_t^c, I_t), \theta\right]$ upward for a given I_t where $\theta_1 < \theta_2$. The optimal reserve-deposit ratio (γ_t^c) that solves (27) then decreases as the quantity of CBDC increases.

4.2 General Equilibrium with Central Bank Lending

As in a general equilibrium without central bank lending, net savings of young generation must equal the supply of real balances of old generation in each period:

$$\frac{\beta x}{1+\beta} - \frac{y}{(1+\beta)R_t} = p_t M, \tag{28}$$

and commercial banks hold all real balances as cash reserves:

$$\gamma_t^c \frac{\beta x}{1+\beta} = p_t M. \tag{29}$$

Central bank lending of all the deposits in CBDC account to commercial banks implies total deposit (or saving) $\theta d_t^c + (1-\theta)d_t^b = \beta x/(1+\beta)$ in (28) where $d_t^c = d_t^b = \beta x/(1+\beta)$. These two equations can be combined to represent a market-clearing condition for private credit market as follows:

$$(1-\gamma_t^c)\frac{\beta x}{1+\beta} = \frac{y}{(1+\beta)R_t} \tag{30}$$

Notice that, as shown in Figure 3, an increase in θ leads to a decrease in reserve-deposit ratio (γ_t^c) by commercial banks in (27), which increases supply of private credit in (30).

For a given $\theta \in [0,1)$, a general equilibrium with central bank lending consists of quantity γ_t^c and prices $r_t^m(\pi_t), r_t(\pi_t), R_t, r_t^c$ that satisfy (20), (21), (27), (28), (29), and $V^b = V^c$ where V^b and V^c are given by (1) and (3), respectively. This will also determine the equilibrium value of bank panic cut-off π_t^{c*} by (24).

4.3 CBDC and Financial Stability with Central Bank Lending

In the presence of central bank lending to commercial banks, we examine the general-equilibrium effects of an increase in the quantity of CBDC on financial stability (i.e., bank panic) through changes in supply of private credit, nominal interest rate, and reserve-deposit ratio. For simplicity, hereafter, we assume that the random variable π_t follows a uniform distribution with $F(\pi)$ and $f(\pi)$ its distribution function and density function, respectively.

Proposition 4 *As θ increases, both the equilibrium reserve-deposit ratio (γ_t^c) and the equilibrium nominal interest rate (R_t) decrease in equilibrium.*

Proof. Since F is the distribution function of a uniformly-distributed random variable, (23) can be rewritten as

$$\gamma_t^c = 1 - \int_{\pi_t^{c*}}^{1} \pi d\pi - \theta(\pi_t^{c*})^2. \tag{31}$$

Then, from the implicit function theorem, it can be shown that

$$\frac{\partial \gamma^c}{\partial \theta} \quad = \quad -\frac{\frac{\theta}{1-\theta}\kappa(\gamma^c,\theta,I)^2}{1+(2\theta-1)\kappa(\gamma^c,\theta,I)^2(1-(1-\theta)\kappa(\gamma^c,\theta,I))} \leq 0$$

where the last inequality follows from $(2\theta-1)\kappa(\gamma^c,\theta,I)^2\left[1-(1-\theta)\kappa(\gamma^c,\theta,I)\right] > -1$ for $\theta \in [0,1)$. Furthermore, this implies that $R_t = \frac{y}{(1-\gamma^c)\beta x}$ decreases as θ increases. ■

When the central bank lends all the deposits in CBDC account to commercial banks, an increase in the deposits in the central bank's CBDC account implies an increase in the supply of private credit. This is because, unlike the deposits in commercial banks, the deposits in CBDC account do not require reserves to be held and hence more resources are available for supply of private credit.[7] Therefore, reserve-deposit ratio falls and, as depicted in Figure 4, nominal interest rate falls as well in equilibrium.

Moreover, the following proposition shows that, according to (24), an increase in θ and a decrease in R_t as in **Proposition 4** increase π_t^{c*}, the cut-off value of a relocation probability above which a commercial bank is short of reserves for paying out to movers. Despite a decrease in reserve-deposit ratio (γ_t^c) which has the effect of increasing the probability of bank panic, the direct effect of an increase in θ plays a dominant role in decreasing the probability of bank panic.

Proposition 5 *As θ increases, the bank panic cut-off (π_t^{c*}) increases in equilibrium.*

Proof. From (24), we have

$$\frac{\partial \pi_t^{c*}}{\partial \theta} = \frac{1}{(1-\theta)^2}\frac{1}{(1+\frac{y}{\gamma^c\beta x})}\left[1+(1-\theta)\frac{1}{(1+\frac{y}{\gamma^c\beta x})}\frac{y}{\gamma^{c2}\beta x}\frac{\partial \gamma^c}{\partial \theta}\right]. \tag{32}$$

[7] Since the deposits in CBDC account do not require reserves, the central bank lending in CBDC would maximize its credit multiplier effect. Therefore, a credit multiplier effect of the central bank lending in CBDC would lead to a even greater increase in the supply of private credit.

Now, we will find the condtion under which $1+(1-\theta)\frac{1}{(1+\frac{y}{\gamma^c\beta x})}\frac{y}{\gamma^{c2}\beta x}\frac{\partial\gamma^c}{\partial\theta}$ is greater than 0:

$$\begin{aligned}
(1-\theta)\frac{1}{(1+\frac{y}{\gamma^c\beta x})}\frac{y}{\gamma^{c2}\beta x}\frac{\partial\gamma^c}{\partial\theta} &> -1 \\
\Leftrightarrow -\frac{\theta\frac{1}{(1+\frac{y}{\gamma^c\beta x})}\frac{y}{\gamma^2\beta x}\kappa(\gamma^c,\theta,I)^2}{1+(2\theta-1)\kappa(\gamma^c,\theta,I)^2\left[1-(1-\theta)\kappa(\gamma^c,\theta,I)\right]} &> -1 \\
\Leftrightarrow \frac{\frac{\theta}{(1-\theta)^2}(1-\theta)^2\kappa(\gamma^c,\theta,I)^2\left[1-(1-\theta)\kappa(\gamma^c,\theta,I)\right]}{1+\frac{(2\theta-1)}{(1-\theta)^2}(1-\theta)^2\kappa(\gamma^c,\theta,I)^2\left[1-(1-\theta)\kappa(\gamma^c,\theta,I)\right]} &< 1 \\
\Leftrightarrow \theta Y < (1-\theta)^2+(2\theta-1)Y \\
\Leftrightarrow \theta < 1-Y \quad or \quad \theta > 1.
\end{aligned}$$

where $Y \equiv (1-\theta)^2\kappa(\gamma^c,\theta,I)^2\left[1-(1-\theta)\kappa(\gamma^c,\theta,I)\right]$. Finally, we can easily check that $1-\theta > Y = (1-\theta)^2\kappa(\gamma^c,\theta,I)^2\left[1-(1-\theta)\kappa(\gamma^c,\theta,I)\right]$ for all $\theta\in[0,1)$. ■

4.4 Welfare Implications

We define welfare in a stationary equilibrium as the ex-ante expected utility of a representative agent born at t in a given location before her status as a lender or a borower is known. Then welfare can be written as follows:

$$\begin{aligned}
W &= \left[(1-\theta)V^b+\theta V^c\right]+V^l \\
&= \mathbb{E}\left\{\ln\left(x-d_t^b\right)+\beta\int_0^1\pi\ln\left[r_t^m(\pi)d_t^b\right]f(\pi)d\pi+\beta\int_0^1(1-\pi)\ln\left[r_t(\pi)d_t^b\right]f(\pi)d\pi\right\} \\
&\quad +\mathbb{E}\left\{\ln l_t+\beta\ln\left(y-R_tl_t\right)\right\}.
\end{aligned}$$

where $V^b=V^c$ in a stationary equilibrium and the second equality comes from V^b and V^l respectively given by (1) and (2).

The following proposition shows that the introduction of CBDC with central bank lending can actually increase welfare.

Proposition 6 $\frac{\partial W}{\partial\theta}\big|_{\theta=0}=0$ *and* $\frac{\partial W^2}{\partial^2\theta}\big|_{\theta=0}=\infty$.

Proof.

$$\frac{\partial W}{\partial \theta} = \beta \int_0^{\pi^{c*}} \frac{1}{\gamma^c + \frac{y}{\beta x}} \frac{\partial \gamma^c}{\partial \theta} d\pi + \beta \int_{\pi^{c*}}^1 \pi \frac{1}{\gamma^c} \frac{\partial \gamma^c}{\partial \theta} d\pi + \beta \int_{\pi^{c*}}^1 \pi \frac{1}{1-\theta} d\pi$$
$$-\beta \int_{\pi^{c*}}^1 (1-\pi) \frac{\pi}{1-(1-\theta)\pi} d\pi - \frac{1}{1-\gamma^c} \frac{\partial \gamma^c}{\partial \theta}$$

Then $\frac{\partial \gamma^c}{\partial \theta}\big|_{\theta=0} = 0$ gives $\frac{\partial W}{\partial \theta}\big|_{\theta=0} = 0$. Moreover, we have

$$\frac{\partial W^2}{\partial^2 \theta} = \beta \frac{1}{\gamma^c + \frac{y}{\beta x}} \frac{\partial \gamma^c}{\partial \theta} \frac{\partial \pi^{c*}}{\partial \theta} + \beta \int_0^{\pi^{c*}} \frac{\frac{\partial \gamma^{c2}}{\partial^2 \theta}(\gamma^c + \frac{y}{\beta x}) - (\frac{\partial \gamma^c}{\partial \theta})^2}{(\gamma^c + \frac{y}{\beta x})^2} d\pi$$
$$-\beta \pi^{c*} \frac{1}{\gamma^c} \frac{\partial \gamma^c}{\partial \theta} \frac{\partial \pi^{c*}}{\partial \theta} + \beta \int_{\pi^{c*}}^1 \pi \frac{\frac{\partial \gamma^{c2}}{\partial^2 \theta} \gamma^c - (\frac{\partial \gamma^c}{\partial \theta})^2}{(\gamma^c)^2} d\pi$$
$$-\beta \pi^{c*} \frac{1}{1-\theta} \frac{\partial \pi^{c*}}{\partial \theta} + \beta \frac{1}{2} (1 - (\pi^{c*})^2) \frac{1}{(1-\theta)^2}$$
$$+\beta (1-\pi^{c*}) \frac{\pi^{c*}}{1-(1-\theta)\pi^{c*}} \frac{\partial \pi^{c*}}{\partial \theta} + \beta \int_{\pi^{c*}}^1 (1-\pi) \frac{\pi^2}{(1-(1-\theta)\pi)^2} d\pi$$
$$-\frac{1}{(1-\gamma^c)^2} \frac{\partial \gamma^c}{\partial \theta} - \frac{1}{1-\gamma^c} \frac{\partial \gamma^{c2}}{\partial^2 \theta}.$$

Then $\int_{\pi^{c*}}^1 \frac{\pi^2}{1-\pi} d\pi = \infty$ gives $\frac{\partial W^2}{\partial^2 \theta}\big|_{\theta=0} = \infty$. ■

Proposition 6 implies that welfare is strictly increasing in CBDC when its quantity is close to zero. That is, the introduction of CBDC with central bank lending increases welfare locally for a sufficiently small quantity of CBDC. However, a global characterization of welfare implications for $\theta \in [0, 1)$ is not analytically tractable.

Figure 5 shows a numerical illustration that an increase in the quantity of CBDC increases welfare for $\theta \in [0, 1)$ if the central bank lends all the deposits in CBDC account to commercial banks. As the quantity of CBDC increases, the supply of private credit increases due to central bank lending of CBDC to commercial banks. This results in a lower equilibrium nominal interest rate which makes borrowers better off, while making lenders worse off. Moreover, an increase in the quantity of CBDC has the effect of improving financial stability by decreasing the likelihood of bank panics, which makes lenders better off. Except for a sufficiently large quantity of CBDC, the positive financial-stability effect on lenders slightly dominates the negative interest-rate effect on lenders. Therefore, together with the positive interest-rate effect on borrowers, overall welfare increases in the quantity of CBDC as long as the size of borrowers is sufficiently large relative to that of lenders.

4.5 Discussion on Central Bank Lending

When the central bank accepts deposits in CBDC account and lends them to commercial banks, we have assumed complete enforcement in the loan contract between the central bank and commercial banks. That is, as in (21), repayment to the central bank is assured by unpaid reserves and borrowers' loan repayment.

In the absence of complete enforcement, however, the central bank may require collateral from commercial banks to eliminate its exposures to balance sheet risk by ensuring loan repayment. In that case, a commercial bank's assets such as its loans to borrowers can serve as a collateral in the loan contract with the central bank.

Alternatively, noting that CBDC substitutes demand deposits at commercial banks, deposit insurance for central bank's CBDC lending can essentially prevent the central bank from being exposed to balance sheet risk. Providing deposit insurance for CBDC lending can be regarded equivalent to providing deposit insurance for the demand deposits when there is no CBDC.

5 Concluding Remarks

In this paper, we have examined the implications of the adoption of central bank digital currency (CBDC) for financial stability. A monetary general equilibrium model is constructed in which commercial bank deposits compete with the central bank deposits in CBDC account and commercial banks provide liquidity in the form of paper currency. CBDC is a national currency-denominated, interest-bearing and account-based claim on the central bank. People have access to CBDC via direct deposit at the central bank.

The introduction of deposits in CBDC account essentially decreases supply of private credit by commercial banks, which raises the nominal interest rate and hence lowers a commercial bank's reserve-deposit ratio. This has negative effects on financial stability by increasing the likelihood of bank panic in which commercial banks are short of cash reserves to pay out to depositors. However, once the central bank can lend all the deposits in CBDC account to commercial banks, an increase in the quantity of CBDC which does not require reserve holdings can enhance financial stability by essentially increasing supply of private credit and hence lowering nominal interest rate. Together with the positive interest-rate effect on borrowers, this positive financial-stability effect of CBDC tends to dominate its negative interest-rate effect on depositors (or lenders) except for a sufficiently large quantity of CBDC. Therefore, overall welfare increases in the quantity of CBDC as long as the size of borrowers is sufficiently large relative to that of lenders.

This paper appears to be among the first economic analyses on the relationship between CBDC and financial stability. However, some further works are desired. First, it will be useful to investigate explicitly whether introducing CBDC along with an option of the central bank lending would enhance welfare when an economy faces a bank-panic risk. Second, the overall impact of CBDC on financial stability would in general depend on the behavior of economic agents over time, which probably depends also on the specific attributes of the CBDC. For instance, CBDC accounts could be made available via deposits at commercial banks instead of being held directly at the central bank itself as we considered in this paper. Also, transfers between paper currency and CBDC can be allowed possibly with some fees. Finally, noting that the interest rate on CBDC could act as the main tool in the conduct of monetary policy, the interaction between monetary policy and financial stability needs to investigated including the optimal interest rate on CBDC.

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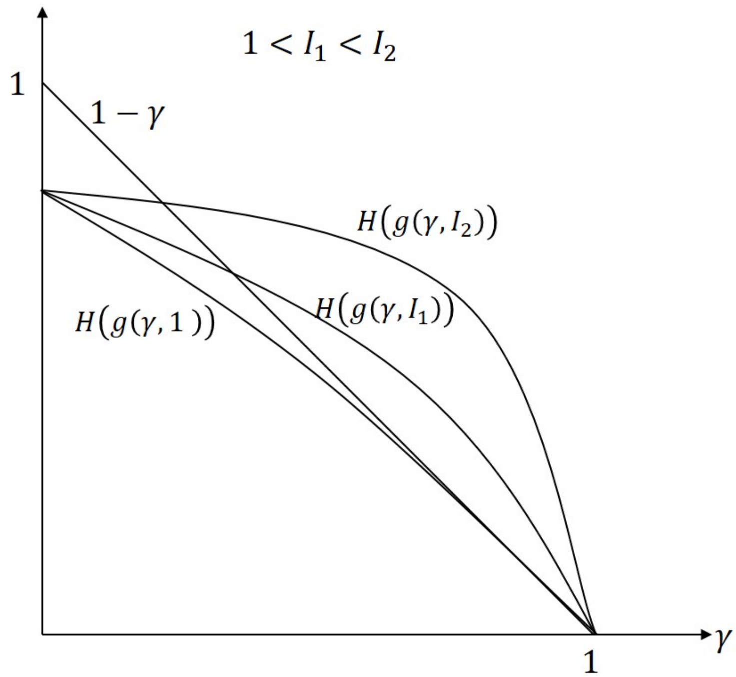

Figure 1: Optimal reserve-deposit ratio

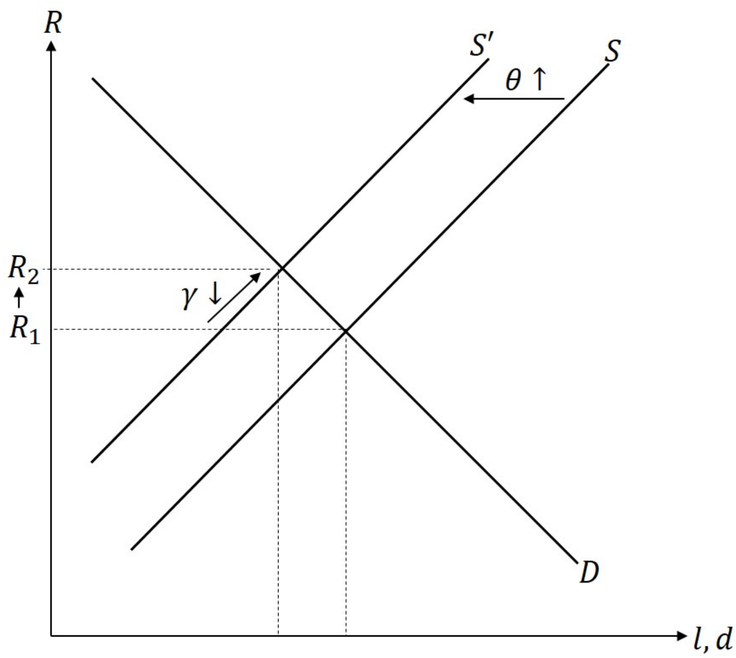

Figure 2: Equilibrium in the private credit market

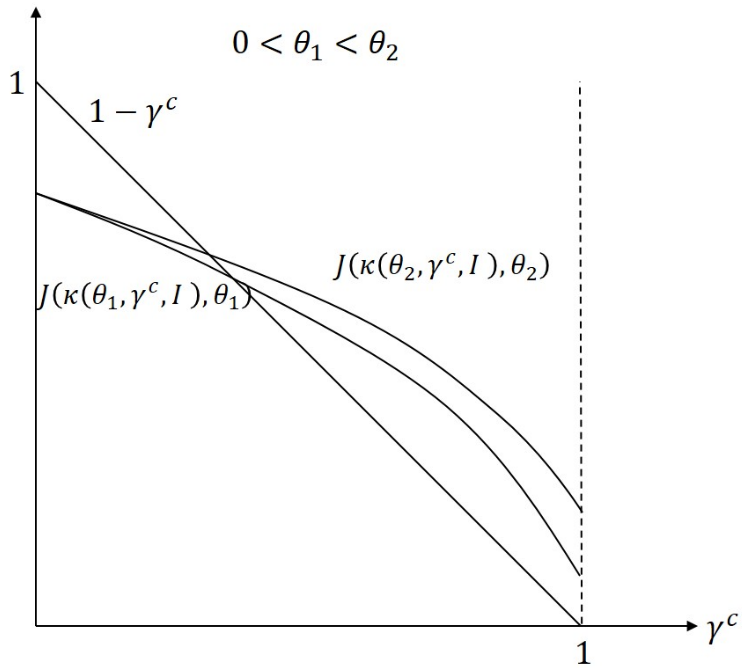

Figure 3: Optimal reserve-deposit ratio with central bank lending

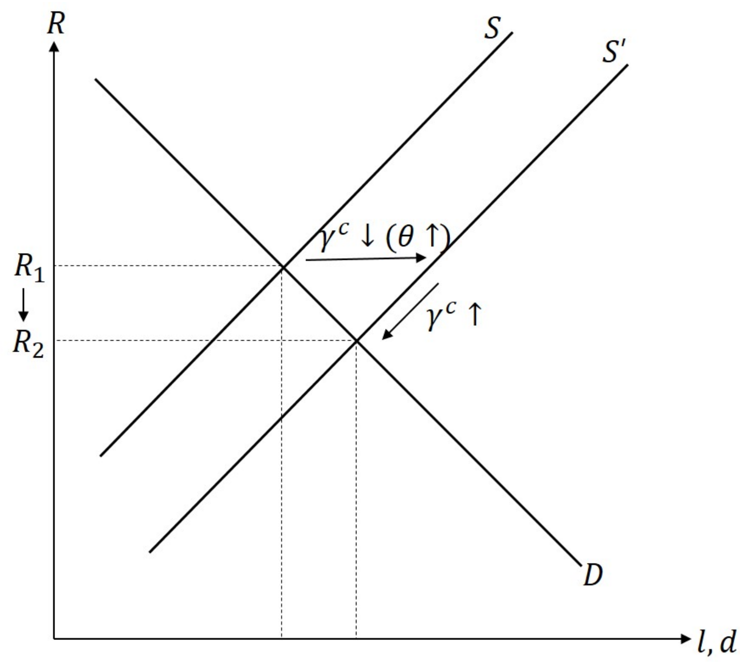

Figure 4: Equilibrium in the private credit market with central bank lending

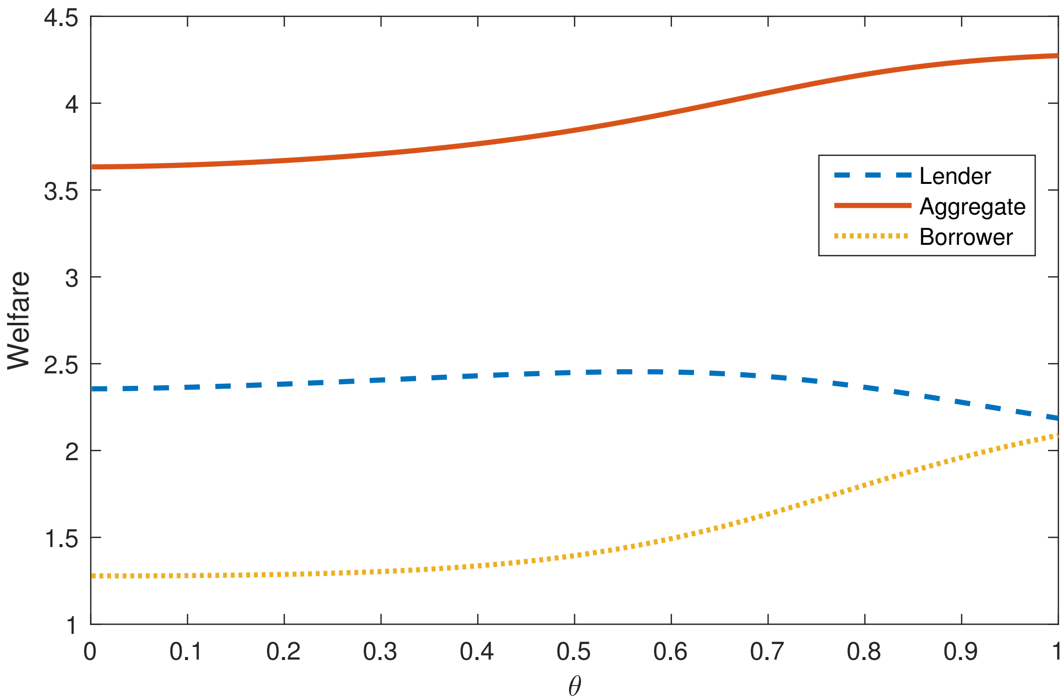

Figure 5: Welfare with central bank lending