Master Thesis :
Currency Substitution Due to Cross-border CBDC and Its Implications in Financial Stabilities

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Abstract

This paper considers the risk on bank run as cross-border central bank digital currency (CBDC) enters an emerging country. Bank run is a main consideration on the literatures of CBDC, as interest bearing CBDC might compete with demand deposits offered by commercial bank. Means can be legislated to prevent the risk, but cross-border CBDC, especially that coming from a highly developed country, which is overwhelmingly popular as a global means of payment, might be difficult to regulate as the technology of CBDC is digitalized, hence exacerbating the emergence of a bank run. In this paper, an agent-based model is used to approach this issue to simulate the dynamic currency substitution episode, as well as the emergence of a bank run episode.

1 Introduction

During the outbreaks of Covid-19, physical cash and coins are considered to be one of the possibilities of invisible route of transmission, and more and more individuals choose to pay with digital payments. (introduction of CBDC) One major consideration is its risk of financial disintermediation[cite]. As it allows people to hold an “account” directly in the central bank, people used to digital payment have incentives to transfer their cash and deposit into holding CBDC if it offers the same interest rate[cite], since CBDC is by definition backed by central

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bank, and typically has no risk of run. The withdrawal might cause commercial banks to shrink their balance sheet, hence increasing their leverage on credits. The signal of high leverage and low money holding further causes withdrawal from non-digital payment users, and the economy enters a bank-run episode.

As mentioned by Diamond and Dybvig (1983), measures like deposit insurance can be used to alleviate the fear of a bank run, hence preventing bank runs to happen. However, this will fail to be the solution if the CBDC that is held widely in the current country is issued by a foreign country. When the foreign currency is also a potential candidate of a global means of payment, this currency substitution effect will be especially difficult to prevent. For potential agents about to withdraw, deposit insurance is no longer a convincing solution of stability, since central banks may also run out of foreign reserves.

As dreadful as it looks, currency substitution might not necessarily happen. Decisions of means of payment is a global coordination game through a self-fulfilling process[cite], and without the foreign CBDC being widely utilized, the episode is unlikely to happen. As most literatures in CBDC considers the policy and welfare implications in an economy purely embedded with CBDC, the era where physical cash and CBDC coexists might not be happening so quickly, and countries with different levels of development might also adapt to this new system in different paces, therefore the scenario of currency substitution is worth considering. In this paper, I deploy an Agent-Based Model (ABM) to fill the gap of the past literature by considering the effect of the adoption of a mean of payment. The decision of means of payment for each individual can be dynamically observed, and it is closely determined by the network and interaction protocol (Kiyotaki and Wright, 1989).

The model consists of three sectors: buyer sector, seller sector, and commercial bank sector. The buyers and sellers toggle to each other periodically, so that the interaction strategically complements the popularity of some means of payments, reinforcing (and as well suppressing) the adoption of CBDC. The usage of a certain means of payment thus determines their portfolio decision, and hence affecting the balance sheet of a commercial bank. The balance sheet as well as its leverage ratio is publicly observed by all agents, and agents with difference tolerance rate react and withdraw accordingly. The fear is spread along the social network, potentially causing a bank run.

The key different between CBDC and other existing means of payment is that CBDC can

	H-Cash	F-Cash	H-Deposit	F-Deposit	F-CBDC
Return	1	1	i_{HD}	i_{FD}	i_{CBDC}
Risk	Low	Low	High	High	Low
Accessibility	High	Medium	High	Low	High

Table 1: Comparison for different asset/means of payments. The evaluation is done from a home-country agent's perspective. Prefix H represents "Home"; prefix F represents "Foreign".

be designed to have high interoperability, where substitution from domestic bank deposit to foreign CBDC is more effortless and cheaper compared to foreign bank deposits, as traditional cross border payment usually involves a multitude of intermediates. See table 1.

The rest of this paper is organized as follows. In section # I review some literatures regarding the financial implications of CBDC and a brief introduction to ABM. Section # describes the model in detail. Section # demonstrates the simulation result with some sensitivity check. Finally, I conclude the policy implications and future extensions regarding this issue.

2 Literature Review

2.1 Financial Stability of CBDC

The literature on the financial disintermediation cause by CBDC is growling rapidly. Fernandez-Villaverde et al. (2021) use a Diamond and Dybvig (1983) framework to show that central bank has the monopolistic power in the deposit market that can endanger the maturity transformation for commercial banks. Keister and Sanches (2019) uses a new monetary search model to prove that while CBDC increases the efficiency in exchange, it inevitably crowd out bank deposits, and cause the funding cost of a commercial bank to increase.

(To be continued)

2.2 CBDC in an Open Economy

CBDC in an open economy is gaining large attention recently. Minesso et al. (2022) proves that the international spillover effect might be amplified using a two-country DSGE model.

(To be continued)

The closest model that addresses the issue of bank runs under cross-border CBDC design is written by Popescu (2022). Following Diamond and Dybvig (1983), the paper tries to show that there are multiple equilibria of domestic bank is exposed in the risk of a run. The model, however, only sees CBDC as a safe deposit, which is an asset with interest rate, being a liability of the central bank. In reality, agents might not want to deposit money in CBDC accounts solely due to it being riskless, as it might not be the mean of payment widely used. This motivates the methodology of using agent-based modelling, since it is capable of observing the endogenous formation of CBDC as a means of payment, while simultaneously activates an episode of fear through sentimental spreading.

2.3 Agent-based Modeling

Agent-based modeling intro

To motivate endogenous adoption of a certain means of payment, it is necessary to embed a trading system. Several literatures propose the designs of this system. The Complex Adaptive Trivial System (CATS) mentioned in Dawid and Delli Gatti (2018), agents (households) choose firms from the lowest price in the market during a consumption bundle decision stage; also in Dawid and Delli Gatti (2018) the two framework EUBI and EBGE chooses the goods to buy according to a logistic probability depending on the price firms offer. As for the decision process of the selection of which means of payment to use during a trade, these macroeconomic agent-based models do not implement this as they focus more on quantitatively matching the stylized fact of a business cycle. Marimon et al. (1990) studies a Kiyotaki and Wright (1989) economy using a classifier system evolving genetically to study the emergence of a medium of exchange. Tzouvelekas (2021) transforms an ABM model for language spreading into a study for parallel circulation of currencies under a scale-free social network.[1] His model, however, does not study the formation during trading process, but through simply a spreading process. A more structural model that studies the selection of a payment system during a repetitive trading process is Rigopoulos et al. (2006). They study how agents adopt new payments systems using ABM, and the probability of selecting a means of payment depends on the utility function of

[1] In Tzouvelekas (2021), he generates a trading network using preferential attachment, and according to network literatures, this network has the property known as "scale-free" (Price, 1976). As you shall see in my model, I also follow this idea to create a synthetic scale-free bipartite network as my international trading net.

selecting it.

Although the literature of ABM is abundant regarding the trading process, there is a crucial component that is missing, which unfortunately is the key to my research — the expectation for events. For macroeconomic agent-based models, the expectation can be addressed by artificial neural networks (ANN) or genetic algorithms (GA). In the case of ANN, for each agent, several indicators and errors between past expectation and realization are passed in as parameters, go through several additional hidden layers, to receive the expectation for the next period (see Salle, 2015). The GA approach considers a series of evolutionary procedure such as selection, crossover, and mutation(see Arifovic et al., 2018).

In this paper, the expectation comes in three ways: expectation of future benefit for holding a certain portfolio, expectation of a bank run episode, and the expectation of the CBDC to be riskless. The second and third is a rare event, so the above learning procedure is not suitable for the two expectation. Bank run, however, can be triggered by simply implementing an imitation rule in an ABM setting (Santos and Nakane, 2021)

3 Model

3.1 Basis Flow and Structure

The model is composed of two open economies and three sectors — buyers/sellers banks, and government. Each country issues its own currency, but all buyers have the freedom to decide what means of payment (hereafter MoP) to use. There is an alternation of roles between buyers and sellers, with each transitioning to the other role once a successful trade is conducted. This setting is to assure that agents have the incentives to adjust its portfolio of MoP, conceptually similar to the idea given in Trejos and Wright (1995). For each period, buyers decide how much to consume and save, and base on the consumption budget, buyers meet with sellers during a search and matching process.

MoP is then decided under each trade. Both buyers and sellers observe the popularity of each Mop, hence deciding the optimal portfolio of MoP to hold. [2] For every trade and portfolio

[2]Under rational expectations, a representative agent looks forward and chooses the optimal mean of payment that provides one the largest lifetime utility. In the absence of perfect coordination and perfect foresight, however, an agent might possibly hold a depreciating currency solely due to the fact that it is the only means of payment widely used regionally.

reallocation that involves altering the banks' ledger, the bank immediately records it. This in turn causes the leverage of the bank to alter. The leverage of the bank is globally visible to all agents, signalling the soundness of the financial environment. Sensitive agents are then urged to withdraw any premature assets from the bank (in this model I consider only the deposit) if they sense a signal of instability, and through a herding behavior that bank is thus exposed to a risk of run. This herding behavior can be modeled through introducing an imitation rule (Santos and Nakane, 2021). For simplicity, the bank has an exogenous credit level. Doing so allows the result to be focused on the effect of cross-border CBDC, instead of other financial acceleration coming from the capital market (Bernanke et al., 1996).

Central banks interest rates are temporarily set exogenously.

3.2 Consumption Decision

Following Dawid and Delli Gatti (2018), consumption decision for a buyer is separated into two steps: consumption budget and consumption bundle.

Consumption Budget

We follow the simple keynesian setting and let the consumption be a proportion of its disposable income

Definition 1 (General Rule of Consumption)**.**
For each buyer b at time t, one consumes

$$C_{b,t} = \mathrm{MPC} \times \mathrm{DI}_{b,t} + a + \epsilon_t, \tag{1}$$

where MPC is the marginal propensity to consume, DI is the disposable income, a is the minimal amount of expenditure, and ϵ is a random shock on consumption.

Consumption Bundle

After all buyers complete deciding its consumption budget, they proceed to decide the consumption bundle.

Definition 2 (Consumption Bundle Step)**.**

1. Buyer b selects candidate sellers $\{s \in \mathcal{N}_b\}$ from its trading network $\mathcal{N}_b$.[3]

2. If seller s is out of stock, proceed to the next candidate.

3. If buyer b itself is out of budget, one stops the consumption and the next buyer consumes.[4]

4. During each trade, the agents go through a payment decision process.

The payment decision process (hereafter PDP) depends on the frequency of past appearance, its opportunity cost of using it as a MoP (interest rate), its cost of holding the asset (risk of confiscation or inflation rate), following the functionalism view of money. Holding a MoP has different incentives from a payment aspect and an asset aspect. The next part describes the procedure of a PDP.

3.3 Payment Decision

Notations

At every moment (a tick in the simulation), an agent recognizes a set of MoP, denoted as $\mathrm{MOP}_{a,t} = \{\mathrm{mop}_1, \mathrm{mop}_2, \ldots, \mathrm{mop}_{n(a,t)}\}$, where mop denotes one kind of MoP, such as foreign country bank deposit or foreign CBDC; $n(a,t)$ denotes the total number of means of payment that an agent sees up to time t. If an agent discovers a new type of MoP, $n(a,t)$ increases by 1.

Every agent has a record of the occurrence of each MoP it saw previously, denoted as

$$F_{a,t} = \{f_t^m \mid m \in \mathrm{MOP}_{a,t}\}, \tag{2}$$

where f_t^m represents the memorized occurrence of MoP m at time t, accumulated according to an AR(1) process:

$$f_{t+1}^m = \rho f_t^m + \Delta_t^m. \tag{3}$$

The damping factor ρ captures the "memory" of an agent, and Δ_t^m is the amount of MoP m an agent has seen during all the transaction one done during time t. Also define the frequency of observation

$$\tilde{F}_{a,t} = \left\{ \tilde{f}_t^m = \frac{f_t^m}{n_f} \mid m \in \mathrm{MOP}_{a,t} \right\}, \tag{4}$$

[3] See Appendix A for detail on the network.

[4] In this agent-based model, buyers are activated randomly, but in order. In computer science this is called "synchronous".

where n_f is the normalization factor, defined as the sum of all f_t^m

$$n_f = \sum_{m \in \mathrm{MOP}_{a,t}} f_t^m \quad \forall a,$$

Definition 3 (Acceptance of MoP)**.**

An agent accepts or pays with a MoP if and only if the frequency of observation exceeds some threshold. Denote the set of acceptance as

$$A_{a,t} = \left\{ m \in \mathrm{MOP}_{a,t} \mid \tilde{f}_{at}^m > threshold_a \right\} \tag{5}$$

Random Utility Model

An agent makes decision according to a probability vector. An agent has, for each MoP, a collection of information regarding the specific MoP, and calculates the utility for using it (Csik, 2003; Matsatsinis and Samaras, 2000; Rigopoulos et al., 2006)

Assume that an agent's utility function for using a MoP m is

$$V_{at}^m = U_{at}^m(\tilde{f}_{at}^m, i_t^m, X_t) + \varepsilon_{at}^m, \tag{6}$$

where $U(\cdot)$ is a deterministic utility function depending on the past frequency of observing this MoP $\tilde{f}_{a,t}^m$, the interest rate i_t^m, and other factors that an agent might take into consideration when choosing.

The error term ε_{at}^m captures the idiosyncratic shock that an agent faces when choosing. If we assume that the error term follows a T1EV distribution

$$F(\varepsilon) = e^{-e^{-\varepsilon}}$$

the probability function will be in a logistic form (McFadden, 1974)

Definition 4 (Probability of MoP Selection)**.**

$$P(m \mid \tilde{f}_{at}^m, i_t^m, X_t) = \frac{\exp(U_{a,t}^m)}{\sum_{j \in \mathcal{S}} \exp(U_{a,t}^j)}, \qquad \text{for } m \in \mathcal{S}, \tag{7}$$

where $\mathcal{S} = A_{a,t} \cap A_{b,t}$ is the set of mutual MoPs, which is the MoPs that both a buyer and a seller in the current transaction agree to use.

For now, I simply assume that the deterministic part of the utility takes a linear form

$$U_{at}^m(\tilde{f}_{at}^m, i_t^m, X_t) = \beta_1 \tilde{f}_{at}^m + \beta_2 i_t^m \tag{8}$$

Intuitively, we would expect β_1 to be positive since a more common MoP is more likely to provide the agent with successful consumption, thus increasing their future utility. On the other hand, we would expect β_2 to be negative since using an MoP to purchase goods incurs a higher opportunity cost compared to holding it as an asset and receiving interest. This is because using the MoP for consumption means the agent cannot earn interest on the amount spent, whereas holding the MoP as an asset allows them to earn interest on it.

3.4 Portfolio Reallocation

In the baseline model of Dawid and Delli Gatti (2018), sellers (firms) observe their inventories and price distribution of ones' neighbor and make adjustments on price and production accordingly. In this model, however, the price mechanism is pulled out to have a better focus on the transmission of new MoPs. Therefore, the seller only has to reallocate its portfolio after receiving MoPs from buyers. Imagine a shop owner depositing all his earnings in cash form to his bank account.

During the reallocation, an agent considers three key components — usage in payment, future return, and cost in holding. Notice that there is actually a tradeoff between using a monetary asset as an asset or not, hence you may notice the symmetry between the decision process of using it as a means of payment or an asset.

In the monetary search literature, a representative agent makes decision on the portfolio to maximizes ones value function in a centralized market, where the return of an asset is realized (Lagos and Wright, 2005; Li and Li, 2019). The value function of the centralized market includes the value function of the decentralized market, therefore the decision making of an agent's holding in the centralized market indirectly affect the success rate of an exchange in the next subperiod.

In an ABM setting, however, we are unable, and unrealistic, to construct a Bellman equation that captures the decision of MoP in the decentralized market and the reallocation of the MoP as an asset simultaneously. Therefore I approach this with another random utility model, with the same indicators an agent used for MoP decision, but with a different set of parameter.

Similar to Eq. 6

$$T_{at}^m = W_{at}^m(\tilde{f}_{at}^m, i_t^m, X_t) + \nu_{at}^m, \tag{9}$$

is the myopic utility of holding a MoP to the next period after reallocation.

(To be continued) (Trouble deciding what to do)

3.5 Banks

There is a home bank (HB) and a foreign bank (FB); each has its own deposit. While ABM is capable of simulating a real-time gross settlement (RTGS) payment system and endogenously capture the optimal process to cope with a liquidity shock (Galbiati and Soramaki, 2008), for simplicity I set the proportion of illiquid assets for a bank as an exogenous variable

Definition 5 (Depositor's money allocation)**.**
Assume that the depositor puts in v amount of MoP m into a bank b, depending on its interoperability level $\xi_{m,b} \in [0, 1]$, the bank adds $\xi_{m,b}v$ to its liability, and adds $\ell_b v$ to its capitals, and $(1 - \ell_b)v$ to its reserves. ℓ_b is the capital adequacy ratio of the bank, and is set exogenously.

I do not explicitly model the bank's asset portfolio, as well as its returns, since this is not the focus of this paper. The reserves, however, is clearly recorded. Moreover, the agents have transparent information about the leverage rate (using dept-to-equity). Agents trigger a bank run panic through observing this publicly announced information.

3.6 Bank Run

The bank run is triggered by an panic criteria and the followed up imitation behavior (Santos and Nakane, 2021).

Definition 6 (Panic criteria)**.**
For an agent that has a D/E ratio tolerance ratio ϕ_a, if the D/E ratio of a bank is higher than its tolerance ratio, $\text{D/E}_b < \phi_a$, the agents withdraw all its deposits from the bank.

Note that the tolerance ratio is heterogenous, so the bank run episode is not going to happen like an avalanche. The key mechanism is the imitation behavior, or herding behavior, that will spread the fear and causing the bank run to realize.

Definition 7 (Imitation Rule)**.**
If more than $\zeta \in [0, 1]$ ratio of agents in its network withdraws from bank b in past T_{br} period, then the agent also withdraws, no matter whether the D/E ratio exceeds it tolerance ratio or not.

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Appendix A Network for Trading