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Credit creation under multiple banking regulations: The impact of balance sheet diversity on money supply

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ABSTRACT

Since the recent financial crisis along with more concentration of banking supervision, we have stepped into a new regulatory regime where multiple regulations are at play simultaneously. In this paper, we study the collective impacts of multiple regulations on credit creation in a heterogeneous banking system. Each single regulation imposes a constraint on credit creation for each bank, while with multiple regulations, only the most stringent one plays the determinant role on money supply. For the homogeneous banking system with identical balance sheets, they share the same binding regulation. In contrast, for the heterogeneous banking system with diverse balance sheets, the binding regulation for each bank may be different from other's. Those banks, who are bound by different regulatory constraints from homogeneous banks, would bring about an overall reduction in money supply, because those binding regulations impose a lower capacity (compared with the one in the case of homogeneous banks) for the banks to extend their balance sheets in this condition. We put forward an agent-based model of commercial banks integrated with two processes: credit creation and fund transfer, to demonstrate the reduction effect. The results facilitate the understandings of the transmission mechanism of monetary policy via banks and its interaction with prudential regulations.

1. Introduction

The financial crisis erupted in 2008 and the subsequent recession have reignited broad interest and heated debates on banking systems. Many reasons have been taken account for this crisis but the main culprit should be the banking system who is prone to underestimate risks and enjoys the privilege of offering credit (Bernanke, 2010; Gourinchas and Obstfeld, 2012; Mian and Sufi, 2011; Stiglitz, 2009). Aiming to promote a more resilient and robust financial system and prevent future collapse, the Basel Committee on Banking Supervision (BCBS) has published Basel III documents and made several reforms to strengthen banks' capital and liquidity positions. On the one hand, Basel III strengthens the capital supervision on banks' equity position against default risk by raising the required capital adequacy ratio (CAR), and leverage ratio (LR). While the leverage ratio is a non-risk capital requirement, which serves as a backup limit on the expansion of bank balance sheet (BCBS, 2010a; BCBS, 2010b). On the other hand, Basel III introduces liquidity coverage ratio (LCR) and net stable funding ratio (NSFR) in order to improve banks' liquidity profile under stressed conditions (BCBS, 2013).

There have been a profusion of efforts in evaluating and predicting the impacts of the Basel III accord on the banking system as well as its macroeconomic influence (Kashyap et al., 2014; Martynova, 2015). Higher capital requirements are introduced to ensure that banks are holding more safer assets, while liquidity regulations require banks to hold sufficient stock of unencumbered high-quality liquid assets preventing them from runs in a stressed scenario. It is the original objective of the Basel III to promote financial stability. However, facing higher capital requirements, banks may possibly cut down lending since raising equity is relatively costly for them (Martynova, 2015; Bridges et al., 2014). Moreover, higher regulatory requirements would raise banks' marginal cost of funding, it will then lead to higher bank lending rates (Cosimano and Hakura, 2011; Gavalas, 2015). The increase of lending rates will give rise to reduced demand for credit, which in turn slows down economic growth (Martynova, 2015; Slovik and Cournde, 2011).

However, this paper differs from them in several aspects. First, we focus on the liability side (money) of the bank's balance sheet, rather than the bank's asset side (debt) which has gained much atten-

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tion (Kashyap et al., 2014; Gersbach and Rochet, 2017; Aiyar et al., 2016). Concerning the impacts of prudential regulations on credit supply, it is well demonstrated by the existing literature that bank lending would be decreased if capital related prudential requirement is tightened, especially in the short term (Martynova, 2015; VanHoose, 2007; Peek and Rosengren, 2010). At the same time, it is equally important to pay attention to money supply in the context of policy analysis (Mallick and Mohsin, 2010; Rafiq and Mallick, 2008). Especially after the unconventional monetary policy, quantitative easing, is implemented, its expected effect on money supply does not appear, that is to say, the expansion of commercial banks' balance sheets does not synchronize with that of the central bank. This leads us to concentrate on the analysis of money supply. We may still find some exceptions, to the best of our knowledge, who paid attention on the changes of money supply, resulting from variations in the regulatory constraints faced by banks (Honda, 2004; Panagopoulos, 2010; Li et al., 2017; Xiong and Wang, 2018). Specifically, Yuzo Honda extends the textbook money creation model to incorporate the impact of capital related regulations and disentangle the "money channel" (via bank's liability side) of monetary policy from the "credit channel" (via bank's asset side) (Honda, 2004). Yannis Panagopoulos examines the influence of Basel II type CAR regulation on the Greek monetary system and empirically demonstrates that its money supply process can be favorably explained by the Post Keynesian Structuralism theory of endogenous money (Panagopoulos, 2010). Boyao Li et al. investigate the role of LCR regulation in money creation and find that such regulatory constraint might lead to a reduction in the money multiplier (Li et al., 2017). Wanting Xiong et al. revisit the mechanics of credit creation process and complements the traditional money multiplier story which only focuses on the reserve requirement by elaborating on the roles of multiple prudential regulations proposed in the Basel III accord. They find that the corresponding money multiplier will vary across different economic states and bank balance sheet conditions due to diverse effective binding regulations (Xiong and Wang, 2018; Xiong et al., 2019).

Second, as credit creation theory of banking argues, commercial banks are able to create deposits and loans simultaneously through balance sheet expansion. Thus commercial banks are both credit suppliers as well as money suppliers. According to the conventional understandings, commercial banks are those who absorb deposits from their savers and then lend them out to the investors, hence, commercial banks simply play the role of financial intermediaries. Since commercial banks are able to lend out a proportion of the deposits which is restricted by the fractional reserve requirement, as a multiple of the monetary base, the aggregate money supply is determined by the amount of base money and required reserve ratio. In other words, the ultimate restriction on bank loans is the quantity of pre-existing loanable funds collected by banks from depositors. However, it is gradually recognized and admitted by some economists and policymakers that individual banks are able to grant loans by writing the same amount of deposits on the borrower's account (McLeay et al., 2014; Werner, 2014a, 2014b; Abel et al., 2016; Biondi and Zhou, 2017; Xiong et al., 2017). For a few economists from the Bank of England, the credit creation theory of banking plays a significant role in their new macro-model constructions and policy analyses (Jakab and Kumhof, 2015; Michael and Xuan, 2018). Moreover, Richard Werner presents empirical evidence on the question of whether banks can create money by monitoring bank's internal records. In his work, Werner concludes that the money supply is "fairy dust" produced by the banks individually, which totally differs from the classic story of money creation supported by fractional reserve theory of banking (Werner, 2014a). Furthermore, Boyao Li et al. emphasize the causation that the flow of lending creates the stocks of deposit and loans while the flow of repayment annihilates them in their work (Li et al., 2017). Based on these understandings how banking system works, we are able to study how money supply is influenced by prudential regulations by considering the their respective constraining effects on banks' balance sheets.

Third, with the proposal of the Basel III accord, the regulatory regime has shifted from the framework centered around capital adequacy to a new direction where multiple regulatory constraints are simultaneously at play (Haldane, 2015; Krug et al., 2015; Goodhart et al., 2013). While the benefits of such a multi-polar regulatory regime in addressing different types of risks and frictions are straightforward, there is considerable uncertainty about the collective consequences of multiple prudential regulations when being imposed at the same time (Haldane, 2015). In response to the call by Haldane for more attempts in examing the complexity of the multi-polar regulatory framework, this paper firstly investigates the standalone impact of each regulatory ratio, and compares their effects thus the most stringent regulation is identifies, through this way, the interactions of multiple regulations can be analytically resolved.

Finally, most of the theoretical researches emphasize on homogeneity as making policy analysis while this paper insists on the paradigm where bank heterogeneity should be incorporated. In support of this, there are plenty of empirical evidence that heterogeneous responses to the common monetary policy do exist, and the same holds for prudential regulations as well (Rafiq and Mallick, 2008; Barigozzi et al., 2014). Concerning the studies on banking, they have almost exclusively put attention either on responses by a single, presumably "representative" bank or on a banking system made up of homogeneous banks. The one-size-fits-all framework would fail to capture the effects between bank-level choices and market-level outcomes, for instance, the real banking systems are composed of institutions displaying diverse management capabilities and utilizing heterogeneous levels of technological sophistication (VanHoose, 2007). Recent efforts allowing for bank heterogeneity in responses to capital regulations are provided by (Almazan, 2002; Barth and Seckinger, 2018; Muller, 2018). In this context, bank heterogeneity always refers to diverse level of capitalization (Almazan, 2002), monitoring technologies (Barth and Seckinger, 2018) and production efficiency (Muller, 2018). Generally, these results predict that heterogeneous banks in these dimensions would behave differently in reaction to a certain regulatory environment. Since capital and liquidity regulations in the Basel III accord are related to the corresponding items of banks' balance sheets, both reserve and equity holdings would play a role in determining banks' behaviors, the bank heterogeneity in this paper is thereby defined as the diverse reserve and equity holdings on banks' balance sheets.

In this paper, we take into account the simultaneous imposition of multiple regulatory instruments in a banking system with diverse balance sheets, namely reserve requirement proposed by the central bank (RR) and three other prudential regulations in the Basel III accord (LCR, CAR, LR). Each of the regulations requires banks to hold either sufficient liquid assets or capital in case they would have liquidity or solvency problems. Given certain amount of reserves and equity, both banks' loan issuance and money provision through balance sheet expansions are bound by these regulations, and therefore each one of these regulatory instruments has a corresponding constraint for banks' balance sheet capacities (Li et al., 2017; Xiong and Wang, 2018; Xiong et al., 2019). When multiple regulations are implemented at the same time, only the most stringent one determines both loan issuance and money provision. Among multiple regulations, which one binds basically depends on bank's balance sheet structure. Suppose a single bank is bound by the reserve requirement, its balance sheet extension must be governed by the reserve requirement. Once capital regulation is implemented, the bank has to check whether the current extension of balance sheet exceeds the capacity that the capital regulation requires. If the answer is yes, the bank has to cut down both assets and liabilities to meet the requirements of capital regulations, therefore the capital regulation plays a more stringent role than the reserve requirement. Otherwise, the bank's balance sheet keeps unchanged so that it can simultaneously meet the requirements of both reserve policy and the capital regulation, and it is obvious that the reserve requirement is more stringent now. This logic can also be stretched to other regulations. As a result, we can conclude that in a homogeneous banking system where all banks hold identical balance sheets, they share the same binding regulation. While in a heterogeneous banking system where banks hold their respectively diverse balance sheets, each bank is constrained by its corresponding binding regulation, thus binding regulation diversity arises. Suppose that all banks are bound by the liquidity coverage regulation if they are homogeneous, but when they are heterogeneous, some banks may be short of capital, and either one of capital regulations plays a more stringent role in controlling their balance sheet expansion. Those capital-regulated banks would issue less money and debt in comparison with the case that they are bound by the liquidity coverage regulation. The same goes for the situation where homogeneous banks are bound by the capital regulations or the reserve requirement. Under that circumstance, the reduction in money supply should be attributed to the banks who are in shortage of high quality liquid assets and are bound by the liquidity coverage regulation.

With the aim of contributing to the understandings about the interactions among different regulations in terms of banks' behaviors of credit creation, three questions are addressed. The first is, how broad money supply and money multiplier are determined when multiple regulations are imposed in a heterogeneous banking system where banks are diverse in reserve and equity holdings. Second, when multiple regulations are implemented at the same time, which one of them is the binding regulation that constrains the capacity of credit creation for each bank. Last but not least, it is also vital to know how the resulted variation of money supply depends on the change of the degree of bank heterogeneity. Based on the theoretical interpretation mentioned above, we put forward an agent-based yet simplified stock-flow consistent framework to model bank heterogeneity[1] and the credit creation process according to the work of Wanting Xiong et al. (Xiong and Wang, 2018). We firstly obtain the expressions for money supply and money multiplier under multiple regulations in a homogenous banking system and a heterogeneous one respectively. Then we examine the difference in money supply once bank heterogeneity is introduced and analyze what is the underlying reason for this variation. Additionally, we propose an index which characterizes the degree of bank heterogeneity (Gini index), and investigate the dependency between this index and changes in money supply. The remainder of the paper is organized as follows. Section 2 shows the standalone impact of each singe regulation as well as the collective impacts of multiple regulations by deriving at the expressions of money supply and money multiplier. Subsection 3.1 provides a theoretical comparison of total money supplies between the homogeneous banking system and the heterogeneous one. Subsection 3.2 puts forward the agent-based model integrating the credit creation process with the fund transfer mechanism. Subsection 3.3 presents the simulation results in various combinations of parameters. Section 3.4 elaborates the changes resulting from the variation of the degree of bank heterogeneity. Subsection 4 draws the conclusion.

2. Credit creation, bank balance sheet and prudential regulations

In this section, we will firstly give an introduction to the credit creation theory of banking. And then we will put forward a simplified bank balance sheet, through which the standalone impacts of single regulations on money supply can be analyzed by deriving the corresponding maximum money supply when only one regulatory instrument is implemented. Finally, we will investigate the collective impacts of the simultaneous imposition of all regulations, and determine which is the binding constraint according to the actual response of each bank and derive the corresponding money supply.

Concerning the question how money supply is determined, the controversies can be tracing back to 1980s. For a long time, the most recognized story on monetary aggregate is that the central bank is capable of controlling the quantity of money by adjusting the amount of monetary base and the reserve requirement, thus money supply is deemed to be decided exogenously. However, the exogenous money theory has been seriously refuted by a minor but long existing group of Post-Keynesian economists who argued that money is endogenous (Moore, 1983, 1988; Palley, 1997; Wray, 2001; Goodhart et al., 2001). From this point of view, commercial banks act as credit creators who can supply money to accommodate demand, thus ending up with the conclusion that the quantity of credit money is mainly governed by the demanders of credit rather than the central bank.

The credit creation theory of banking just began to attract growing attention after the 2008 financial crisis due to the consensus that the banking system was the main culprit of the recent crises for offering too much credit. However, the prevailing analytical framework fails to understand the role of credit for its neglect of commercial banks. In fact, the credit level and its growth have profound impacts on macroeconomic performances. It has been put forward by some minority economists that credit has its separate channel in stimulating the macroeconomy, especially in times of stress (Bernanke and Blinder, 1988; Bernanke and Gertler, 1995; Blinder and Stiglitz, 1983). Also, it has been empirically revealed that the recent crises were almost always preceded by excessive credit booms (Jord et al., 2013; Schularick and Taylor, 2012), and the excessive stock and rapid expansion of credit created by banks could even destroy macroeconomic stability (Bernanke, 2010; Gourinchas and Obstfeld, 2012; Mian and Sufi, 2011; Glick and Lansing, 2010; Sutherland and Hoeller, 2012). To sum up, credit should be naturally the heart of the macroeconomic models, let alone the analysis of monetary and bank regulatory regime.

The banking regulations generate up to indirect and secondary impacts on the lending of banks, according to the conventional viewpoint that the supply of bank loans is restricted by the quantity of pre-existing loanable funds in terms of deposits. In contrast to the prevailing view on banks, the credit creation theory of banking argues that money is created through commercial bank lending. When a bank makes a loan to a borrower, it writes the same amount of deposits on his account, which thereby expands both sides of the bank's balance sheet. In the opposite operation, when the loans are repaid, they would then be erased from the debtor's account, and the corresponding deposits are annihilated simultaneously (McLeay et al., 2014; Werner, 2014a, 2014b; Abel et al., 2016; Biondi and Zhou, 2017; Xiong et al., 2017). Thanks to substantial progress in data collection and analysis, this theory has even been supported by the empirical study (Werner, 2014a). Recently, the credit creation theory of banking has been applied to analyze the present monetary systems (McLeay et al., 2014; Jakab and Kumhof, 2015; Michael and Xuan, 2018; Borio and Disyatat, 2011; Disyatat, 2011; King, 2016), among which the current paper is one of the attempts to integrate the theory into the prudential regulation analysis.

Moreover, according to the assumption that banks are credit creators, it seems that commercial banks could expand their balance sheets at their willingness through making loans. Actually, due to the risks they may face and the corresponding defensive buffers they need to hold, the commercial banks' lending behaviors are always constrained by a capacity of credit creation arising from their internal liquidity and solvency managements. However, driven by the desire for more profit, commercial banks are often prone to lend without properly estimating these risks and guaranteeing their liquidity and equity positions. Therefore, from a macro-perspective of maintaining financial stability and safeguarding the integrity, efficiency and functioning of the banking systems, prudential regulations are indispensable (Borio, 2003; Mallick and Sousa, 2013). From the perspective of credit creation, these externally enforced bank regulations would have direct constraining effect on both sides of a bank's balance sheet.

[1] Hereafter, bank heterogeneity refers to only the diversity in equity and reserve holdings on the balance sheet.

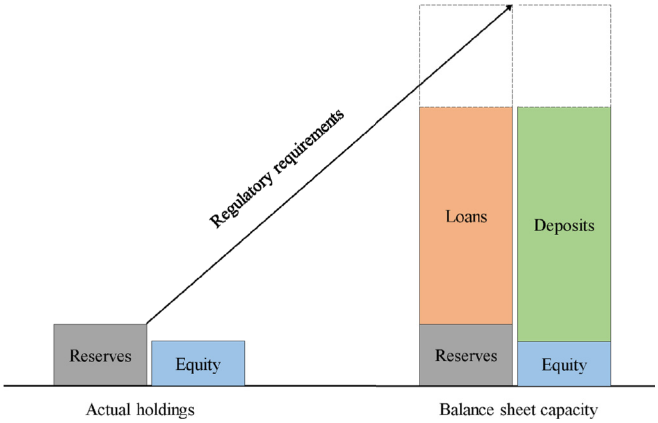


Fig. 1. Schematic illustration of how regulatory requirements affect balance sheet capacity given actual holdings of reserves and equities.

In this paper, we consider four regulatory instruments, including reserve requirement, liquidity coverage regulation, capital adequacy regulation and leverage regulation. For the purpose of preventing bank runs, reserve requirement sets a minimum amount of reserves each bank should hold relative to that of deposits. In addition, liquidity coverage regulation requires each bank to have sufficient high quality liquid assets to cover the net cash outflows in 30 days under stressed conditions. For the purpose of solvency risk prevention, capital adequacy regulation sets a minimum ratio of equity relative to risk weighted assets. While leverage regulation plays as a backup role which requires a minimum amount of equity holdings relative to total assets. Suppose that a commercial bank holds a certain amount of reserves, high quality liquid assets, and a constant equity, there exists a corresponding balance sheet capacity for the bank, which is determined by the binding regulatory instrument in terms of a specific required ratio. The magnification from the actual holdings to the capacity of balance sheet is illustrated in Figs. 1 and 2. Capital regulations could restrict the bank's balance sheet capacity according to the required ratios and the amount of equity. Meanwhile, liquidity regulations could restrict the bank's balance sheet capacity according the required ratios and the amount of reserves or high quality liquid assets. Since in this simplified case, high quality liquid assets consist only reserves, the basis of this magnification is just equity and reserves. And regulatory requirements determine the magnification ratio in this process. Through this channel, the bank's maximum money supply is constrained by prudential regulations.

2.1. The simplified balance sheet

It is the prerequisite of examining the impact of regulations on how a commercial bank behaves and their role in the credit creation process to figure out the structure of bank balance sheet. A simplified balance sheet of the representative commercial bank in a cashless economy is presented in Table 1. On the assets side, there are two items: reserves R with zero risk-weight and loans L with an average risk-weight of γ. On the liabilities side, we only consider deposits D and equity E. Since there is no cash in the economy, the broad money consists of only deposits, that is,

$$M_s = D. \tag{1}$$

According to the balance sheet consistency, the following identity should always hold,

$$R + L = D + E. \tag{2}$$

For the sake of simplicity, we introduce the ratio of equity to reserves, which is denoted by

$$e = \frac{E}{R}. \tag{3}$$

Table 1
Balance sheet for a representative commercial bank.

Assets	Liabilities
Reserves (R)	Deposits (D)
Loans (L)	Equity (E)

2.2. The standalone impact of single regulations on money supply

2.2.1. The reserve requirement (RR)

The reserve requirement sets a minimum ratio of reserves to deposits of commercial banks to ensure that banks are able to meet the demands of their customers for withdrawls in most cases and prevent them from liquidity risk. Firstly, we consider the constraint of reserve requirement on credit creation. Denoting the reserve ratio as r and the required reserve ratio as $r_{\min}$, we can express the reserve requirement as follows,

$$r = \frac{R}{D} \geq r_{\min}. \tag{4}$$

Correspondingly, we can derive at the maximum money supply under the reserve requirement as follows,

$$M_s^{RR} = \frac{1}{r_{\min}} R. \tag{5}$$

According to the consistency of balance sheet given by Equation (2), we can also derive at the maximum amount of outstanding loans (denoted by $L_{\max}^{RR}$) that the bank can issue under the reserve requirement, which is given by

$$L_{\max}^{RR} = \left(\frac{1}{r_{\min} + e - 1}\right) R. \tag{6}$$

As shown in Equation (5), the maximum amount of money supply from this regulatory point of view is the same as the textbook story of money creation which claims that the money multiplier is the inverse of required reserve ratio.[2] Likewise, we can obtain the formulas of maximum money supply and loans for the three Basel III regulations that we are concerned with via the same manipulations.

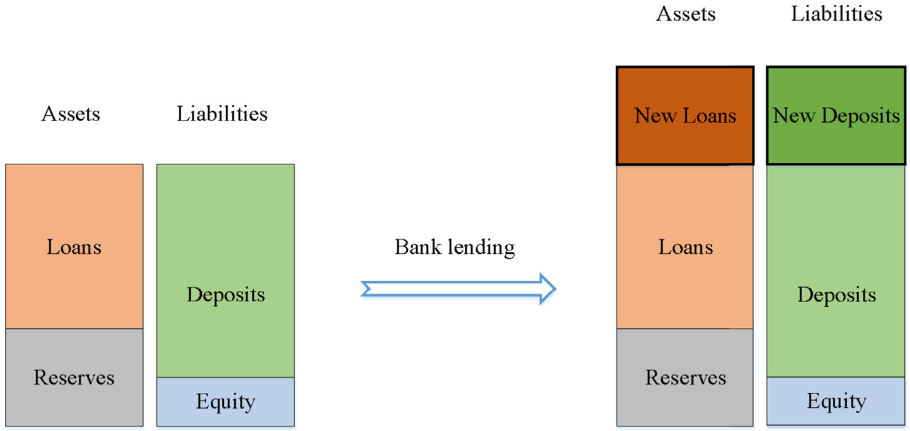
In the framework of Basel III accord, the regulation on liquidity coverage ratio (LCR) is introduced as a precaution against liquidity risk while the solvency risk is addressed by requirements on the risk-based capital adequacy ratio (CAR) and the leverage ratio (LR). Next, we will present the calculations of these ratios and how Basel III regulations constrain banks' capacity of credit creation individually and collectively.

2.2.2. The liquidity coverage ratio (LCR)

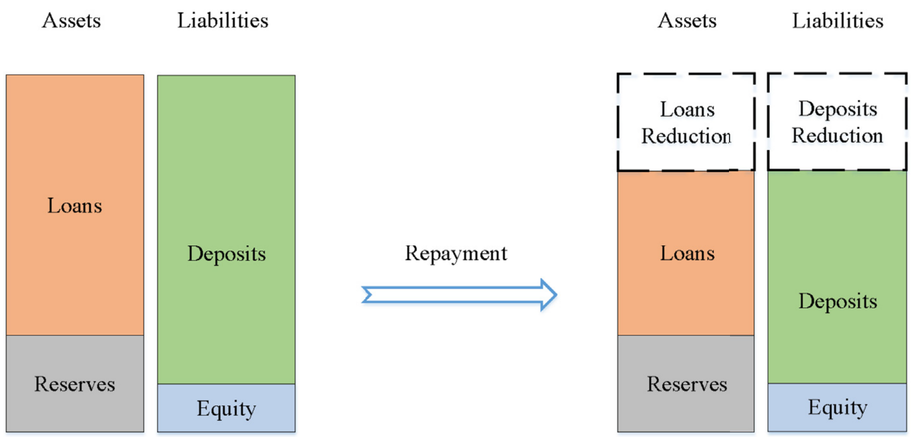
The LCR regulation requires banks to hold sufficient high quality liquid assets (HQLA) that can cover the expected net cash outflows (NCOF) during a 30-calendar-day period under liquidity stressed conditions. The actual liquidity coverage ratio is denoted by LCR and we assume the required minimum of LCR is represented by $LCR_{\min}$, so the restriction of LCR can be written as

$$LCR = \frac{HQLA}{NCOF} \geq LCR_{\min}. \tag{7}$$

[2] Although the expressions of money multipliers in both theoretical frameworks are the inverse of required reserve ratio, we have to note that there are essential differences between them. In the textbook story of money creation which views commercial banks as financial intermediaries, the process where commercial banks keep their reserve account in a fraction of deposits can iterate unlimitedly, thus the actual money multiplier gets close to the inverse of required reserve ratio along with the iterations. While we obtain the form of money multiplier based on the creation theory of banking, and the result is derived by balance sheet approach.



a) Bank lending expands balance sheet.



b) Repayment shrinks balance sheet.

Fig. 2. Schematic illustration of credit creation and annihilation.

Since only reserves are considered as high quality liquid assets in the simplified balance sheet, we then have

$$HQLA = R. \tag{8}$$

In addition, according to the Basel III accord, the net cash outflow is defined as

$$NCOF = OF - \min\{IF, 0.75OF\}, \tag{9}$$

where OF is the expected total cash outflows, and IF is the expected total cash inflows within the 30-day horizon. OF is calculated by multiplying the nominal value of liabilities by the rates at which they are expected to run off in the concerned stressed period. In our model, the run-off rate of deposits is denoted by μ, and one unit of time is set to be 30 days, so we have

$$OF = \mu D. \tag{10}$$

On the other hand, IF is computed according to the total amount of repayment (denoted by RP) with a discount of 50% due to the hypothesis of stressed scenario,[3] which is given by

$$IF = 0.5RP. \tag{11}$$

Suppose RP is proportional to the outstanding loans with a rate of λ, then IF can be rewritten as

$$IF = 0.5\lambda L. \tag{12}$$

Combining Equations (7)–(10) and (12), we can obtain the maximum loan provision of the banking system under LCR regulation, which is given by

[3] We neglect the influence of interest rate so as to keep the analysis as simple as possible, and therefore the inflows of banks are solely composed of loan repayment.

$$L_{\max}^{LCR}=\begin{cases}(\dfrac{4}{\mu\cdot LCR_{\min}}+e-1)R, & \lambda\geq\dfrac{1.5\mu}{1+0.25\mu(e-1)LCR_{\min}};\\ (\dfrac{1+0.5\lambda(e-1)LCR_{\min}}{(\mu-0.5\lambda)LCR_{\min}}+e-1)R, & \lambda<\dfrac{1.5\mu}{1+0.25\mu(e-1)LCR_{\min}}.\end{cases} \quad (13)$$

Meanwhile, the expression of money supply under the requirement of LCR under different conditions can be derived according to Equations (2) and (13), which is given by

$$M_s^{LCR}=\begin{cases}\dfrac{4}{\mu\cdot LCR_{\min}}R, & \lambda\geq\dfrac{1.5\mu}{1+0.25\mu(e-1)LCR_{\min}};\\ \dfrac{(1+0.5\lambda(e-1)LCR_{\min})}{(\mu-0.5\lambda)LCR_{\min}}R, & \lambda<\dfrac{1.5\mu}{1+0.25\mu(e-1)LCR_{\min}}.\end{cases} \quad (14)$$

From Equation (14), we can easily find that M_s^{LCR} is negatively associated with $LCR_{\min}$, indicating that money supply would shrink under a stricter liquidity coverage regulation. And it is obvious that M_s^{LCR} is also negatively related to μ, representing that a larger expected run-off rate of deposits would bring about a reduction in total money supply. In addition, both the repayment rate λ and equity to reserve ratio e only take effect on money supply when the amount of inflows is at a relatively low level (specifically less than 0.75 times the quantity of outflows) while M_s^{LCR} is an increasing function of λ and e.

2.2.3. The risk-based capital adequacy ratio (CAR)

The regulation on CAR requires banks to hold adequate capital to guard against solvency risks. Suppose that the actual and minimum risk-based capital adequacy ratios are denoted by CAR and $CAR_{\min}$ respectively, and the only risky asset is loans with an average risk weight of γ, then the risk-weighted assets RWA can be computed as

$$RWA=\gamma L. \quad (15)$$

Therefore, the bank must comply with CAR requirement where the real CAR must be greater than or equal to $CAR_{\min}$, which can be expressed as

$$CAR=\frac{E}{RWA}=\frac{E}{\gamma L}\geq CAR_{\min}. \quad (16)$$

The maximum amount of loans under CAR regulation can be obtained straightforwardly, that is,

$$L_{\max}^{CAR}=\frac{e}{\gamma CAR_{\min}}R. \quad (17)$$

Combining Equations (2) and (17), the maximum money supply under CAR requirement can be derived at as follows

$$M_s^{CAR}=[(\frac{1}{\gamma CAR_{\min}}-1)e+1]\cdot R. \quad (18)$$

From Equation (18) we can draw the conclusion that M_s^{CAR} is an increasing function of e but a decreasing function of γ. Since CAR regulation is mainly imposed on the amount of equity, it is not difficult to understand that a stricter CAR (i.e. larger $CAR_{\min}$) would lead to a lower level of money supply as well.

2.2.4. The leverage ratio (LR)

With the similar purpose of CAR requirement, LR is a non-risk requirement that restricts the overall volume of assets. The actual leverage ratio is denoted by LR, which can be computed as

$$LR=\frac{E}{TA}, \quad (19)$$

where E is the amount of equity and TA is that of total assets. In this model, total assets can be calculated by the summation of loans and reserves, which is given by

$$TA=L+R. \quad (20)$$

According to the requirement of leverage regulation, the actual LR should be no less than the corresponding minimum level $LR_{\min}$, that is

$$LR=\frac{E}{L+R}\geq LR_{\min}. \quad (21)$$

In the same way, we can derive at the maximum amount of loans under LR regulation which takes the following form

$$L_{\max}^{LR}=(\frac{e}{LR_{\min}}-1)\cdot R. \quad (22)$$

And the corresponding money supply under LR regulation can be given by

$$M_s^{LR}=(\frac{1}{LR_{\min}}-1)e\cdot R. \quad (23)$$

From Equation (23), we can see that M_s^{LR} is a decreasing function of $LR_{\min}$. Moreover, LR regulation, similar to CAR, is also primarily implemented on equity, so a tighter LR requirement would also decrease total money supply.

2.3. Collective impacts of multiple regulations on money supply

In Subsection 2.2, we have obtained the expressions of money supply solely derived by each single regulation from which the dependence of maximum money supply on related parameters can be analyzed. However, banks are subject to reserve requirement and all other possible regulations simultaneously in reality. Next, we will put forward the framework of multiple regulations and examine their collective impacts on money supply. When a bank is under the restrictions of more than one prudential regulations, its capability of credit creation is confined to the most stringent constraint. By comparing the values of maximum loans the bank could extend, we can obtain the effective binding regulation and the corresponding expression of maximum outstanding loans is

$$L_{\max}=\min\{L_{\max}^{RR},L_{\max}^{LCR},L_{\max}^{CAR},L_{\max}^{LR}\}. \quad (24)$$

Following the same procedure, we can also obtain the expression of the constrained money supply under multiple regulations, which is given by

$$M_s=\min\{M_s^{RR},M_s^{LCR},M_s^{CAR},M_s^{LR}\}. \quad (25)$$

Since the most stringent constraint on the bank depends heavily on equity to reserve ratio, we can then establish a piecewise function of money supply in terms of e and R, each corresponding to a specific binding regulation, that is,

$$M_s(R,e)=\begin{cases}\dfrac{1}{r_{\min}}R,\\ \dfrac{R}{\mu LCR_{\min}}R,\\ \dfrac{[1+0.5\lambda(e-1)LCR_{\min}]}{(\mu-0.5\lambda)LCR_{\min}}R,\\ [(\dfrac{1}{\gamma CAR_{\min}}-1)e+1]\cdot R,\\ (\dfrac{1}{LR_{\min}}-1)e\cdot R.\end{cases} \tag{26}$$

In Equation (26), we can infer that the money supply must take either one of the five expressions. In order to identify which one would be the final solution, we need to see the conditions for the transition from one binding regulation to another to occur. Actually, this can be done by solving the equality of the values of any pairs of those five expressions by changing the value of equity to reserve ratio.[4] According to these equations, the range of equity to reserve ratio can be divided into five segments, each of which corresponds to one specific binding regulation, and is denoted by φ_k ($k=1,2,3,4,5$) respectively. For the sake of simplicity, we express the money multiplier as the following

$$m(e)=\frac{M_s}{R}=\begin{cases}\dfrac{1}{r_{\min}}, & e\in\varphi_1;\\ \dfrac{4}{\mu LCR_{\min}}, & e\in\varphi_2;\\ \dfrac{1+0.5\lambda(e-1)LCR_{\min}}{(\mu-0.5\lambda)LCR_{\min}}, & e\in\varphi_3;\\ (\dfrac{1}{\gamma CAR_{\min}}-1)e+1, & e\in\varphi_4;\\ e\cdot(\dfrac{1}{LR_{\min}}-1), & e\in\varphi_5.\end{cases} \tag{27}$$

Since the five expressions of money multiplier are linear with respect to e, the above equations can then be generalized as

$$m(e)=a_k+b_k\cdot e,(k=1,2,3,4,5), \tag{28}$$

where $a_k = a_k(r_{\min}, LCR_{\min}, CAR_{\min}, LR_{\min}, \mu, \lambda, \gamma)$ and $b_k = b_k(r_{\min}, LCR_{\min}, CAR_{\min}, LR_{\min}, \mu, \lambda, \gamma)$, and each of k specifies one single regulation. For a specific case of $e\in\varphi_4$, $a_4=1$ and $b_4=\frac{1}{\gamma CAR_{\min}}-1$.

Moreover, in Equation (27), $r_{\min}$, $LCR_{\min}$, $CAR_{\min}$ and $LR_{\min}$ are the regulation-related parameters representing the regulatory environment, among which $r_{\min}$ is set by the central bank and $LCR_{\min}$, $CAR_{\min}$, $LR_{\min}$ are prescribed in the Basel III accord. The parameters μ, λ, γ indicate the environment of risk that banks are exposed to. The average run-off rate of deposits μ characterizes banks' sources of funds, and a well-functioning bank is always associated with a stable volume of funds. The average repayment rate of outstanding loans λ together with the average risk weight γ, characterize banks' uses of funds. Loans with lower repayment rate λ and higher risk weight γ are often associated with high profits, while these highly profitable loans are more likely to expose banks to higher probabilities of maturity mismatch and insolvency. Obviously, the values of these environmental parameters depend on the current economic conditions.

As the conventional theory says, an increase in monetary base would trigger an increase in broad money supply, and the effect is multiplied by the inverse of reserve requirement ratio. However, this is no longer true along with the implementation of Basel III accord. Based on Equation (27), we may find that when the bank is bound by leverage regulation, injecting more reserves to banks sometimes cause money multiplier to shrink ($R\uparrow$, $e\downarrow$, $m_{LR}\downarrow$). Under such circumstances, it is worth noting that raising additional capital would be an appropriate way to expand money supply.

[4] The detailed mathematical derivations are shown in Appendix A.

3. The impacts of heterogeneity of balance sheets

We have demonstrated that money supply is not only governed by the regulation-related parameters, but also correlated with banks' balance sheet positions in the previous section. The representative commercial bank with one simplified balance sheet mentioned above can be regarded as a homogeneous banking system, which we take as a benchmark model in this paper. In this section, what we aim to investigate is how the credit creation works if the banking system becomes heterogeneous in terms of balance sheets. In Subsection 3.1, we conduct theoretical analyses by deriving at the formulas of money supply under the homogeneous banking system and the heterogeneous one. In Subsection 3.2, we propose an agent-based model integrating fund transfer mechanism and credit creation process to mimic the heterogeneous banking system. By performing numerical simulations in Subsection 3.3, we compare the simulation results on this model with those of the benchmark, from which we could figure out the main causes of changes in money supply. In Subsection 3.4, we obtain the amount of balance sheet capacity for each bank and then calculate the aggregate money supply in different static banking systems with various degree of heterogeneity.

In the following analyses, the amount of equity E is set to be exogenous, but that of reserves R is endogenous on account of the following considerations. Since e is the ratio of equity to reserves, thereby it is endogenous as well. At the first place, the relative value between equity and reserves plays a dominant role in the binding constraint for each bank in this framework. Second, the transactions of reserves along with those of deposits between commercial banks take place highly frequently in the real world.[5] We employ a random fund transfer mechanism inspired by several econophysicists so that diverse reserve holdings across banks can be produced and thus a kind of diversity of balance sheets is achieved endogenously (Dragulescu and Yakovenko, 2000; Chakraborti and Chakrabarti, 2000; Yakovenko, 2010). Last but not least, we take the equity holdings as constant and exogenously given since we only focus on the structure of bank's balance sheet characterized by the ratio of equity to reserves as mentioned above. This assumption accounts for the fact that several frictions make equity costly for banks, and equity might be relatively more costly than debt due to distortions in the pricing of debt from the financing perspecitve.[6] By taking these assumptions, we are able to easily control the value of equity to reserve ratio just by varying the amount of reserves in this model.

However, we have to note that the assumptions of both random reserve assignment and fixed equity have their limited applications. Compared with the random reserve assignment, the determination of reserve holding for each bank is a complicated process in the real world. Reserves are issued by the central bank to commercial banks through open market operations (OMO). The injected reserves in the banking system can be traded in the interbank market, where the trading mechanism is determined not only by liquidity regulations but also by banks' self-disciplinary behaviors, thus leading to a reallocation of reserves. Nevertheless, the initial distribution of reserves could be altered due to random transfer among banks, no matter what type it is assumed. As being driven by customers' depositing and withdrawing behaviors,

[5] Poszar mentioned in his paper that net deposit flows between banks are settled via transfers of reserves between banks' reserve accounts maintained at the central bank (Pozsar, 2014), and Mcleay et al. provided an example of house purchase and show the changes of balance sheets of both the buyer and seller as well as their respective commercial banks (McLeay et al., 2014). Both of them pointed out that the transactions of both deposits and reserves between the two banks occur simultaneously in a cashless economy, thus naturally leading to reserve volatility.

[6] Empirical evidence can be found that the quantity of equity grows at a very low rate compared with other liabilities. In balance sheet management, the amount of equity seems to be predetermined (Barth and Seckinger, 2018; Adrian and Shin, 2011).

the mechanism of random transfer plays a dominant role in forming the final stable distribution of reserves across banks, while the initial condition is not significant. With respect to the fixed equity assumption, it must be noted that banks do take measures in order to retain earnings and deleverage in reaction to some bad economic situations. First of all, banks' retaining earnings would give rise to an accumulation of capital, which lowers the diversity of balance sheet when capital regulation binds, but the reduction effect cannot be completely neutralized as long as balance sheet diversity exists. Second, the fixed capital assumption we have made is not in conflict with the possibility that banks may deleverage. Moreover, the aim of deleverage is to cut down banks' both assets and liabilities while keep the amount of capital unchanged, the realization of reduction in both loan and money supply is exactly through this process. After deliberate considerations, we conduct a quasi static analysis while neglect the dynamic process in this paper. There are shortcomings for this simplified theoretical framework though. On the one hand, banks in the real world may sometimes lend more than the capacity for more profits with the cost of taking more risk. Most of the banks would choose to bear liquidity risk since reserves are relatively easy to acquire than capital. On the other hand, some banks even take solvency risk for more profits. Those banks would have to fire-sell some of their assets if they are forced to deleverage under bad conditions. So that questions such as how would interbank market facilitate money supply process, how would banks react to capital loss, deserve our immediate investigation.

3.1. Theoretical analysis

In this section, we conduct a theoretical analysis on money supply in a banking system with diverse balance sheets of individual banks comparing with that of the system with homogeneous balance sheets. The derivation of the money supply for each of the regulations we have mentioned in Section 2 is performed for a representative banking system. However, there are numerous commercial banks in an economy where their balance sheet positions, specified by the relative amounts of liquid assets and equity, may be different in somewhat degree from each other. Moreover, these banks could interact with each other in various ways. To accord with these facts, we propose an agent-based model to depict such a banking system consisting of N banks. Suppose that bank i holds reserves of R_i and equity of E_i respectively, so the ratio of equity to reserve for bank i can be written as

$$e_i = \frac{E_i}{R_i}, (i = 1, 2 \dots N). \tag{29}$$

Table 2 demonstrates a simplified balance sheet for bank i, and the following identity should always hold according to the balance sheet consistency

$$R_i + L_i = E_i + D_i, \tag{30}$$

where L_i represents the amount of outstanding loans and D_i represents that of deposits. The summation of the following two items over the balance sheets of all banks is equal to that of the whole banking system, so we have straightforwardly

$$R = \sum_{i=1}^{N} R_i, \tag{31}$$

$$E = \sum_{i=1}^{N} E_i. \tag{32}$$

As given by Equation (26) in Section 2, $M_s(R, e)$ represents the function of money supply in terms of reserves and equity to reserve ratio. We employ $\widetilde{M_s}$ to denote money supply in a heterogeneous banking system, and given the balance sheet of bank i, we can obtain the maximum amount of deposits that bank i can produce is

$$D_i = M_s(R_i, e_i), \tag{33}$$

Table 2
Balance sheet for bank i.

Assets	Liabilities
Reserves(R_i)	Deposits(D_i)
Loans(L_i)	Equity(E_i)

and thus

$$\widetilde{M_s} = \sum_{i=1}^{N} D_i = \sum_{i=1}^{N} M_s(R_i, e_i). \tag{34}$$

Substituting Equation (28) into (34), we can get

$$\widetilde{M_s} = \sum_{i=1}^{N} (a_k + b_k e_i) R_i, (k = 1, 2, 3, 4, 5). \tag{35}$$

We then introduce $x_i = R_i/R$, $y_i = E_i/E$, where x_i and y_i represent the share of reserves and equity respectively for bank i, thus we get

$$\sum_{i=1}^{N} x_i = 1, \tag{36}$$

$$\sum_{i=1}^{N} y_i = 1. \tag{37}$$

We further introduce $z_i = y_i/x_i$, we then have

$$e_i = z_i \cdot e, \tag{38}$$

where e is the equity to reserve ratio in the homogeneous banking system while e_i represents that of bank i in the heterogeneous system. Nevertheless, as for the homogeneous banking system, once e is given, and suppose that $e \in \varphi_h$, in which money supply takes the minimum amount and is given by

$$\overline{M_s} = M_s(R, e) = (a_h + b_h e) R, \tag{39}$$

where $\overline{M_s}$ denotes the quantity of money supply in the homogeneous banking system. And it should be noted that a_h and b_h are regulation-specific according to the range φ_h it lies in.

Alternatively, for any one individual bank i, given its equity to reserve ratio e_i, the corresponding money multiplier $m(e_i)$ has the following generalized form

$$m(e_i) = a_k + b_k \cdot e_i, \tag{40}$$

due to the fact that $e_i \in \varphi_k$. Since the actual money multiplier takes the minimum value only in the range of φ_k, we can evidently have the following inequality, which is given by

$$m(e_i) = a_k + b_k \cdot e_i \le a_h + b_h \cdot e_i, (k = 1, 2, 3, 4, 5). \tag{41}$$

Thus, we can obtain the following relation:

$$\widetilde{M_s} = \sum_{i=1}^{N} (a_k + b_k e_i) R_i \le \sum_{i=1}^{N} (a_h + b_h e_i) R_i. \tag{42}$$

Based on Equations (36) and (37), we can rewrite Equation (42) as

$$\widetilde{M_s} \le \sum_{i=1}^{N} (a_h + b_h z_i e) x_i R = \sum_{i=1}^{N} (x_i a_h + y_i b_h e) R = (a_h + b_h e) R, \quad (k = 1, 2, 3, 4, 5). \tag{43}$$

That is to say,

$$\widetilde{M_s} \le \overline{M_s}, \tag{44}$$

This result indicates that the diversity in balance sheets of banks would lessen money supply compared with the homogeneous banking system. And we may find that the reduction is attributed to the balance sheet diversity of banks, specifically the diversity of equity to reserve ratios.

3.2. The model

In order to describe the operation of commercial banks and their interactions, two types of processes should be included in this model, namely *credit creation process* and *fund transfer process*. The credit creation process spells out how the banking system creates money and loans simultaneously, i.e. how the dynamics of the amount of money and that of loans are governed by bank lending and repayment. During this process, stock-flow consistency holds all the time. Taking the homogeneous banking system as the benchmark, the fund transfer mechanism interprets how reserves are transferred among banks, resulting in diverse balance sheets of banks. Following a specific random rule, the fund transfer process would eventually yield a steady distribution of reserves across banks.

We assume that each bank is initially endowed with the same amount of equity and also the same amount of reserves, which are expressed respectively as

$$E_i(t) = E_0, \tag{45}$$

$$R_i(0) = R_0. \tag{46}$$

Since the monetary base MB is exogenously given and there is no cash in the economy, the total amount of reserves must be equal to the monetary base, that is,

$$R = \sum_{i}^{N} R_i(0) = N \cdot R_0 = MB. \tag{47}$$

For the sake of simplicity, we further presume that the amount of equity of each bank is exogenous, this is to say, all equities are identical and constant during the processes of credit creation and fund transfer. Consequently, the diversity of balance sheet positions comes solely from the unequal distribution of reserves.

3.2.1. Credit creation process

As we have stated in Section 2, money and debt are created through bank lending, while annihilated through repayment. As shown in Fig. 2(a), once the commercial bank grants a loan to its borrower, deposits and loans are created simultaneously, and thereby both sides of its balance sheet would be added by the same amount. Conversely, once the loans are repaid to the commercial bank, the corresponding deposits and loans would be erased from the bank's balance sheet, which is demonstrated in Fig. 2(b). Accordingly, both the amount of money and that of outstanding loans are governed by bank lending and repayment behaviors. Taking bank i as an example, the dynamics of its outstanding loans on the assets side can be presented by

$$L_i(t+1) = L_i(t) + BL_i(t) - RP_i(t), \tag{48}$$

where $BL_i(t)$ represents the level of lending flows of bank i at period t and $RP_i(t)$ represents that of current repayment flows. It is obvious that bank lending increases the amount of loans while repayment decreases it. And the above dynamic process holds the same for that of deposits on the liabilities side, that is,

$$D_i(t+1) = D_i(t) + BL_i(t) - RP_i(t). \tag{49}$$

Moreover, the amount of repayment is determined by both quantity of outstanding loans and repayment rate, denoted by λ, which can be expressed as follows

$$RP_i(t) = \lambda L_i(t). \tag{50}$$

There exists a credit capacity of each bank $L_{\max,i}$ which we have already obtained in Section 2 since the commercial bank cannot expand its balance sheet unrestrictedly. The lending flow of the banks is determined by both the repayment and the bank's capability to expand its balance sheet. For bank i, its lending flow can be specifically computed as the summation of repayment and the gap between its credit capacity and current outstanding loans, which takes the following form

$$BL_i(t) = RP_i(t) + \rho[L_{\max,i}(t) - L_i(t)], \tag{51}$$

where ρ denotes banks' propensity of expanding their balance sheets. From Equation (51), we can obviously find that the amount of loans would reach its capacity $L_{\max}$ when credit creation process attains equilibrium. Otherwise, the difference between lending and repayment flows triggers the stock of loans to grow as demonstrated by the dotted area in Fig. 1.

3.2.2. Fund transfer process

We now introduce the mechanism of fund transfer among individual banks. It is important to note that fund transfer process may occur multiple rounds in each time period because the transfer of funds occurs as a result of the customers' depositing (withdrawing) their money into (from) the banks which happen frequently. In this model, we assume that there are 50 rounds of fund transfer in each period. So as to illustrate how the banking system runs, we present a flowchart in Fig. 3. Once a round of fund transfer takes place, the payer bank would not only transfer a certain quantity of deposits to the receiver bank but also transfer the same amount of reserves. In our model, we suppose that bank i has reserves of $R_i(\tau)$ at round τ and may exchange it with bank j who has reserves of $R_j(\tau)$, in which the amount of exchanges at this round $\Delta R_{ij}(\tau)$ is defined as

$$\Delta R_{ij}(\tau) = \frac{1}{2}\delta \cdot [R_i(\tau) + R_j(\tau)], \tag{52}$$

where δ is randomly chosen from 0 to 1. So we have respectively

$$R_i(\tau+1) = R_i(\tau) + \Delta R_{ij}(\tau), \tag{53}$$

$$R_j(\tau+1) = R_j(\tau) - \Delta R_{ij}(\tau). \tag{54}$$

In addition, each bank, either as receiver or payer, is randomly selected from N banks in every transfer of reserves. If the payer has no ability to pay, this round of reserve transfer would be abandoned, and then move directly to the next round. Correspondingly, deposits in bank i and j would also be transferred according to this rule since the these two banks' assets and liabilities sides have to be balanced, so that

$$D_i(\tau+1) = D_i(\tau) + \Delta R_{ij}(\tau), \tag{55}$$

$$D_j(\tau+1) = D_j(\tau) - \Delta R_{ij}(\tau). \tag{56}$$

By iterating this procedure continuously, we can finally obtain a stable distribution of reserves across banks, which is plotted in Fig. 4.

What we are concerned with is how money supply would react to the diversity of bank balance sheets, specifically the amount of reserves of these individual banks, so at the end of each time period, we obtain the aggregate amount of deposits as follows,

$$D(t) = \sum_{i=1}^{N} D_i(t). \tag{57}$$

3.3. Simulation results

In this section, we perform several computer simulations so as to present the reduction in money supply triggered by diverse balance sheets of banks. Our first concern is the collective impacts of multiple regulations on money supply, so we need to identify which regulation dominates, in other words, which one is the binding constraint for banks' credit creation process. Our second concern is how this type of bank heterogeneity affects money supply, so we simulate a model of

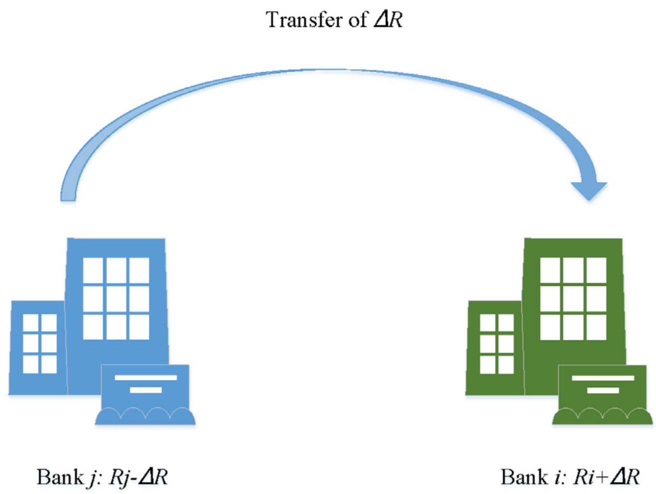


Fig. 3. Flowchart of the fund transfer process in one round.

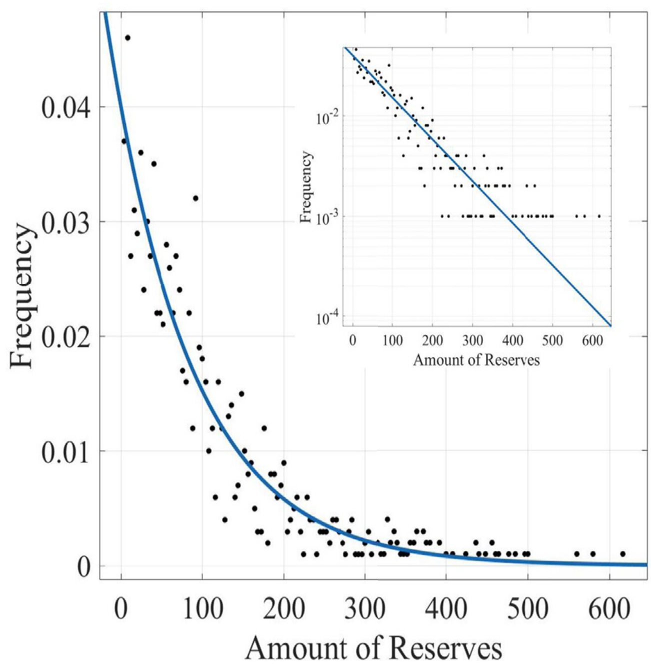


Fig. 4. The steady distribution of reserves in the stage of $T = 5000$ with a stetting of $N = 1000$, $MB = 10^5$ and the fitting curve takes exponential form of $exp(-\frac{R}{100})$.

homogeneous banks and that of heterogeneous banks under the same setting and compare the final results of money supply.

The setting of the model of heterogeneous banks is given by $N = 1000$, $MB = 10^5$, $E_0 = 100$, $\rho = 0.02$, and $r_{\min} = 0.05$, $LCR_{\min} = 1$, $CAR_{\min} = 0.07$, $LR_{\min} = 0.03$. Fig. 5 shows the evolution of money supply over time in this model with fixed $\mu = 0.08$, $\lambda = 0.005$, $\gamma = 0.8$, and the numerical result derived from the model of representative bank is presented as well. From both simulation results, we find that the amount of money rises at a high rate at the very beginning, where the credit creation process dominates. Then the stock of money supply attains its equilibrium in the representative bank model. However, the result of the model of heterogeneous banks is obviously distinct: firstly, the total amount of money decreases rapidly after reaching the peak and finally attains a constant; secondly, after a plenty of times of fund transfer, the distribution of bank reserves presents a stable form as given in Fig. 4, indicating that the diversity of balance

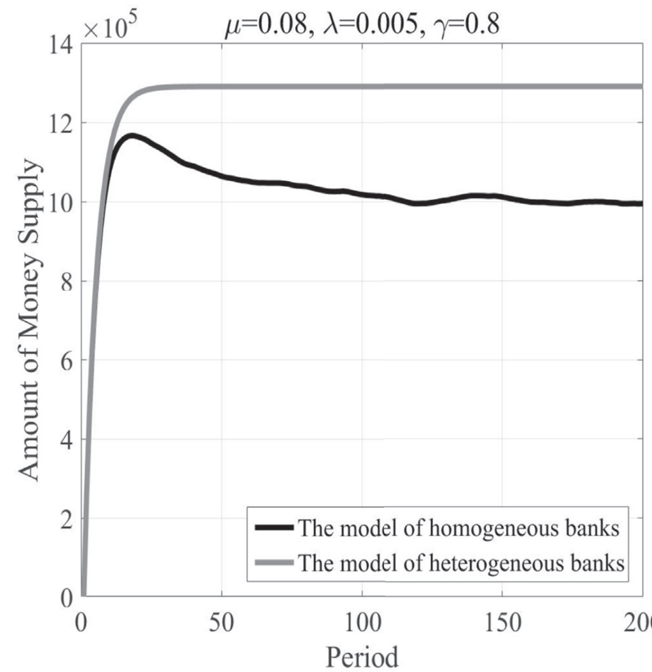


Fig. 5. Evolutions of money supply over time for the model of homogeneous banks (gray curve) and the model of heterogeneous banks (black curve) with $\mu = 0.08$, $\lambda = 0.005$, $\gamma = 0.8$.

sheets is also stabilized. Then we would like to know why there appears to be a reduction in overall money supply comparing the heterogeneous banks to the homogeneous ones. Under these settings, it is easy to find that money supply of the homogeneous banking system is constrained by liquidity coverage regulation, for its equity to reserve ratio is equal to 1.[7] Suppose that the heterogeneous banks are all bound by liquidity coverage regulation as well, the aggregation of their provision of money supply would be just the same as that of the homogeneous banking system. As some of them may hold too few equities to meet the requirements of capital adequacy regulation or leverage regulation, their credit creations are possibly bound by CAR or LR. For these banks, their binding regulations are capital regulations rather than LCR, as a result, the amount of their credit creations is reduced. Therefore, the reduction in overall capacity of credit creation is attributed to the diversity of binding regulations. If a banking system is bound by single regulation, no matter it has a heterogeneous balance sheet structure or not, the overall money supply would not be altered. As shown in Fig. 6(a), which plots the proportions of banks sorting by their corresponding binding regulations with different colors, liquidity coverage requirement takes effect at the beginning though (blue area), both capital adequacy regulation and reserve requirement start to bind approximately 25% of banks along with the formation of stable distribution of reserves (yellow and red areas). Thus, for the whole banking system, not only liquidity coverage regulation would bind, but the other two requirements (CAR and RR) would come into play as well. Due to the existence of multiple regulations, each bank would have its minimum amount of money supply, resulting from the most stringent regulation. Consequently, the overall money supply would shrink when multiple regulations are at work compared with that when single regulation takes effect.

It is already known that the reduction in money supply results from the diversity of binding regulations, which is determined by both the current economic environment and multiple regulations, given banks' balance sheet structures. Specifically, it is not difficult to understand

[7] The detailed interpretation are presented in Appendix B.

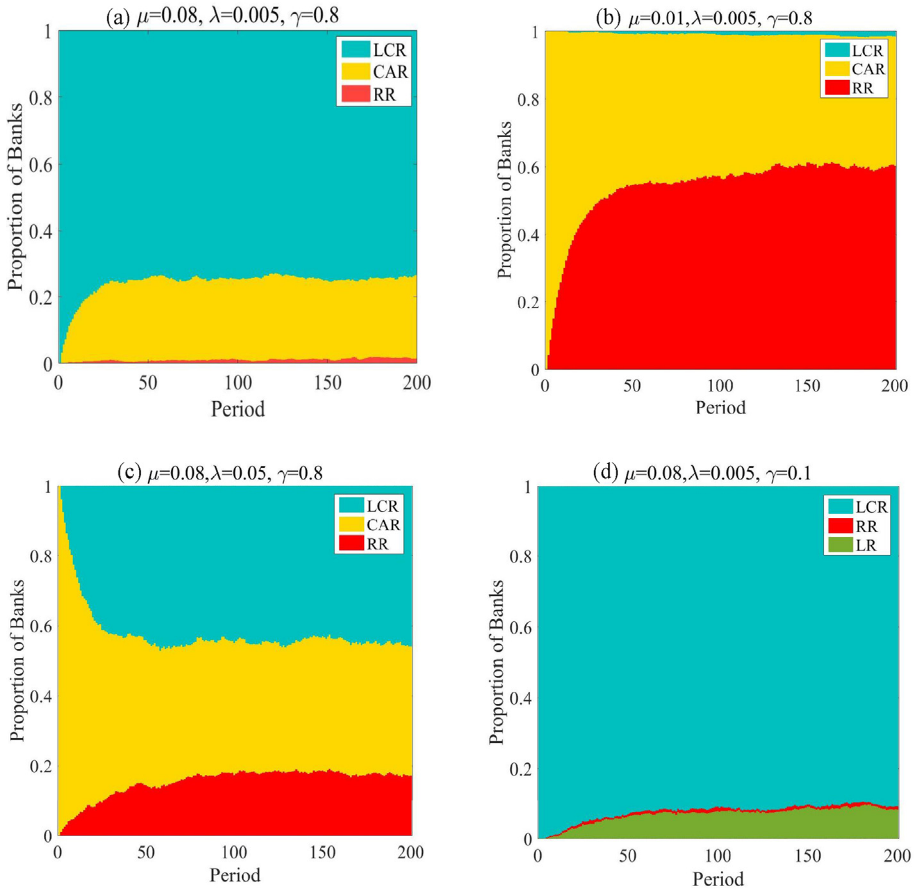


Fig. 6. Evolutions of proportion of banks whose binding regulation corresponds respectively to reserve requirement (red area), liquidity coverage regulation (blue area), capital adequacy regulation (yellow area), leverage regulation (green area) in the model of heterogeneous banks with the following four settings of parameters: (a) $\mu = 0.08$, $\lambda = 0.005$, $\gamma = 0.8$; (b) $\mu = 0.01$, $\lambda = 0.005$, $\gamma = 0.8$; (c) $\mu = 0.08$, $\lambda = 0.05$, $\gamma = 0.8$; (d) $\mu = 0.08$, $\lambda = 0.005$, $\gamma = 0.1$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

that the binding regulation would change for a single bank if economic condition varies. Thus we design several scenarios to demonstrate the influence of environmental parameters (μ, λ, γ) on binding regulation diversity. As shown in Fig. 6, the proportions of banks sorting by their corresponding binding regulations are plotted with different colors under different scenarios. In order to show the impact of each environmental parameter, we change them one by one and present the corresponding results in Fig. 6(b), (c), and (d) respectively. Taken Fig. 6(a) as the benchmark, Fig. 6(b) shows that the decrease in run-off rate (μ) would lead to a very different outcome, with CAR and RR dominating instead of LCR. A lower run-off rate means there would be fewer cash outflows for every bank at each period, implying that banks do not need to hold that many liquid assets. Relatively, loosing liquidity regulation to some degree would result in a dominance of capital regulations, as demonstrated by Fig. 6(b). Comparing Fig. 6(c) with Fig. 6(a) we can see that a higher repayment rate (λ) causes fewer banks to be constrained by liquidity coverage regulation, while the proportions of banks regulated by both reserve requirement and capital adequacy regulation increase significantly. Repayment acts as inflows for commercial banks, so that more inflows may as well imply that banks do not need to hold so many liquid assets as before. Besides, a lower loan risk (γ) makes CAR lose its dominance, as exhibited by Fig. 6(d), because capital adequacy regulation is designed to avoid banks from holding too much risky assets. And we can see from Fig. 6(d) that liquidity regulations dominate while leverage regulation only takes effect for a minority of banks.

With the aim of illustrating the combined effects of multiple regulations and different positions of banks' balance sheets, we pick one typical bank randomly from each scenario in the above simulations and present the switching of these four banks between different binding regulations in Fig. 7. We use numbers 1, 2, 3, and 4 to specify the corresponding binding regulations and color of the line to match the corresponding scenario in Fig. 7. From this figure, we see that there are several switches from one binding regulation to another for all scenarios during the entire period of simulations.

3.4. *The impacts of distribution of reserves*

As mentioned in Subsection 3.3, the reduction in money supply is originated that different binding regulations take effect simultaneously, which is the result of balance sheet diversity. In this section, we aim to investigate the dependency between the reduction effect and the degree of this type of bank heterogeneity. In order to depict the degree of bank heterogeneity, we choose Gini index as a measurement. To get a wide range of Gini index, we choose a static pareto distribution[8] of reserves and solely calculate the balance sheet capacity, especially the maximum amount of money that the banking system can extend. By simply controlling the value of α, we may produce a series of distributions of reserves with different degrees of heterogeneity. As shown in Fig. 8, the dependency of reduction in money supply on Gini index is strong and monotonically, implying that the reduction increases along with the degree of heterogeneity increasing. Furthermore, we demonstrate the proportions of banks under each binding constraint when the index varies in Figs. 9 and B1. It is obvious that when Gini index is at a low level, the banking system is only constrained by two regulations, LCR and CAR. LR starts to bind only when Gini index arrives at a certain level. Thus we may firmly conclude the diversity of responses to multiple regulations increases along with Gini index rises.

To sum up, our results show that reserve requirement and prudential regulations have constraining effect on banks' balance sheet expansion. Banks are able to create both money and debt at the same time

[8] If X follows a pareto distribution, then $P(X > x) = (x/x_{\min})^{-\alpha}$.

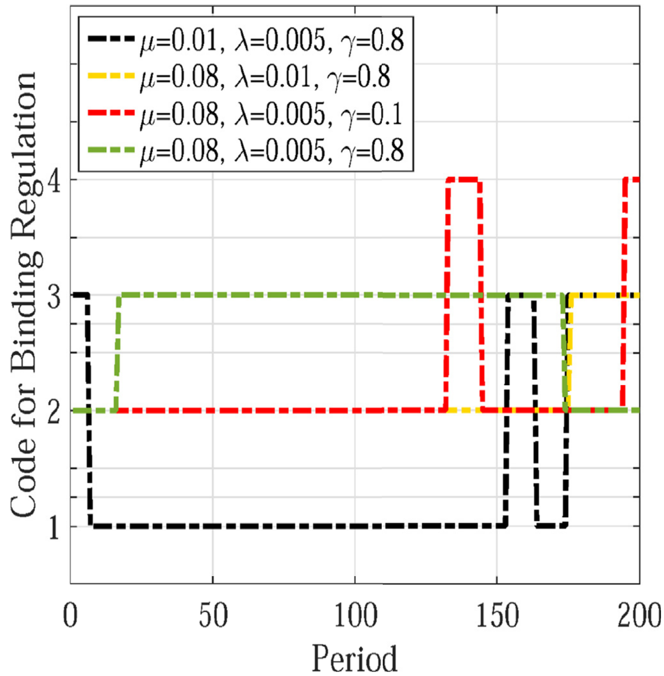


Fig. 7. The switching behavior of four typical banks, each is randomly selected from the above four simulations. Number 1, 2, 3 and 4 represent the bank's binding constraint on reserve requirement, liquidity coverage regulation, capital adequacy regulation and leverage regulation respectively.

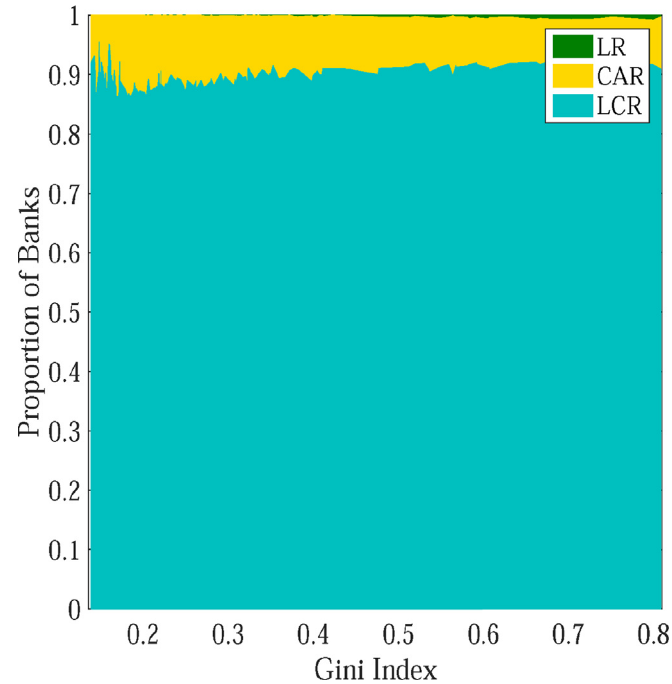


Fig. 9. Proportion of banks under liquidity coverage regulation (red area), capital adequacy regulation (yellow area), and leverage regulation (green area) calculated in the model of heterogeneous banks with $\mu = 0.08$, $\lambda = 0.005$, $\gamma = 0.8$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

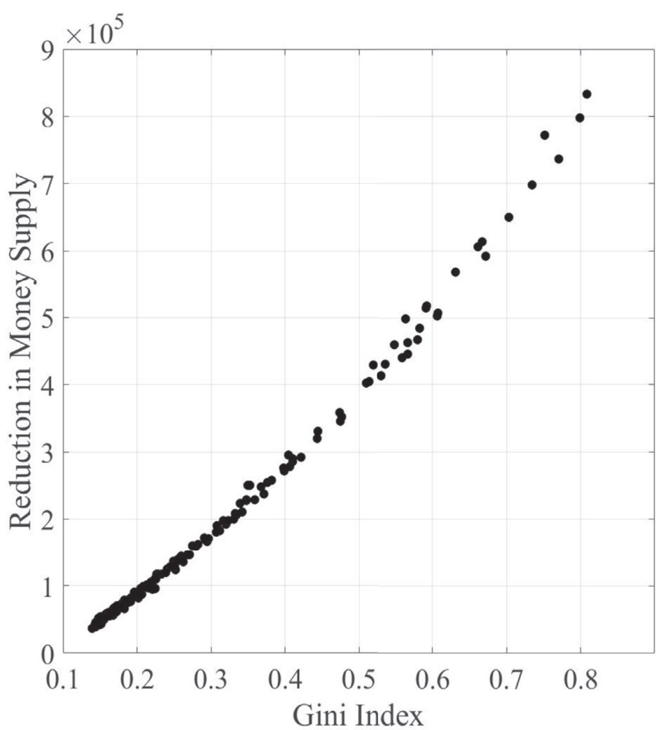


Fig. 8. Dependency of reduction in money supply on Gini index with $\mu = 0.08$, $\lambda = 0.005$, $\gamma = 0.8$.

through bank lending, thus expanding their balance sheets. Through this channel, reserve requirement and prudential regulations matter for banks' credit creation process. Banks' desire for creating credit would be limited by their corresponding balance sheet capacity, which can be dictated by binding regulations and equity or reserve holdings. For each bank, which regulatory requirement takes effect depends on its balance sheet structure, described by equity to reserve ratio. With multiple regulations, for homogeneous banks, they are bound by the same most stringent regulation. In contrast, for heterogeneous banks with diverse balance sheets, they are constrained by different regulations, through which multiple regulations lead to an overall reduction in money supply.

4. Conclusion

This paper studies the collective impacts of multiple regulations on credit creation in a banking system with diverse balance sheets. We present an agent-based model of commercial banks where each is endowed initially with the same amounts of equity and reserves. The following two processes are integrated in this model: credit creation and fund transfer. In the process of credit creation, commercial banks create money and debt simultaneously through bank lending, while the amount of both money and outstanding loans would be cut down through repayment. Consequently, the amount of money and that of loans will attain an equilibrium once bank lending exactly equals repayment. In the fund transfer process, the deposits are randomly transferred among banks along with reserves, yielding an exponential distribution of reserves. By employing this mechanism, we are able to generate a heterogeneous banking system with diverse balance sheets. With the aim of demonstrating the constraining impacts of multiple regulations on bank's credit creation, we firstly derive at the expressions of money supply and money multiplier when multiple regulations are implemented simultaneously based on a representative bank model. We find that the most stringent constraint for a representative bank is determined by its balance sheet structure described by the equity to reserve ratio. In a heterogeneous banking system with diverse balance sheets, each bank's binding constraint might be different from other's. The binding regulation diversity would lead to a reduction in the overall money supply, as both the theoretical analyses and computational results have demonstrated in this paper. Based on these results, we further propose a static model in which the bank heterogeneity is characterized by a given Pareto distribution of reserves, then the degree of this type of bank heterogeneity can be measured by the corresponding Gini index. The results show that the reduction in money supply increases along with increasing degree of this type of bank heterogeneity.

This paper brings it to light that banks' responses to multiple regulations could be different from each other, especially in credit creation. The results obtained in this paper should act as the inspiration for both economists and policymakers to think over the process of money supply mechanism under multiple regulatory regime nowadays. For instance, the understandings should be facilitated why money multiplier would drop along with the loosening monetary policy in the United States. If the bank is reserve-strapped, injecting reserves is certainly an effective strategy to promote money supply. Nevertheless, if the bank is capital-strapped, the bank should seek for additional capital rather than reserves, and the increase in reserves would even have some adverse impacts on money multiplier. With the aim of offering more money and credit, while still meeting the requirements of the central bank and the banking supervisory authorities, the bankers should realize what position the bank is situated, which can be actually identified based on the data of balance sheets.

Moreover, what we propose in the current paper is just a simplified theoretical framework where the assumptions of both random reserve assignment and fixed capital are made. It is worthy noting that both assumptions have a limited scope in their applications. Nevertheless, the current work serves as the first stage for further investigations. Specifically, a promising research avenue that we aim to explore refers to the transmission mechanism of monetary policy via banks, and its interaction with prudential regulations, so as to address the question why monetary policy has failed in boosting real economic activity in the wake of the financial crisis (Mallick et al., 2017). In this context, bank capital matters in the propagation of different types of shocks to lending, owing to the existence of regulatory capital constraints (Gambacorta and Mistrulli, 2004). Moreover, on the bank-level viewpoint, its credit creation behavior can be examined whether on the basis of liquidity or that of capital. The central bank's role of the lender of last resort would be of help only when it provides what the banks are just in shortage.

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Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.econmod.2019.09.030.

Appendix A. Mathematical derivations of transition conditions

In order to identify which regulatory requirement would be the final solution, we need to figure out the conditions for the transition from one binding regulation to another. This can be done by solving the equality of the values of any pairs of those five expressions of money multipliers. In specific, the transition conditions between RR and LCR regulations are respectively given by

$$\frac{1}{r_{\min}}R = \frac{4}{\mu LCR_{\min}}R, \tag{A1}$$

$$\frac{1}{r_{\min}}R = \frac{[1+0.5\lambda(e-1)LCR_{\min}]}{(\mu-0.5\lambda)LCR_{\min}}R. \tag{A2}$$

The transition condition between RR and CAR regulations is

$$\frac{1}{r_{\min}}R = [(\frac{1}{\gamma CAR_{\min}}-1)e+1]\cdot R. \tag{A3}$$

The transition condition between RR and LR regulations is

$$\frac{1}{r_{\min}}R = (\frac{1}{LR_{\min}}-1)e\cdot R. \tag{A4}$$

The transition conditions between LCR and CAR regulations are respectively

$$\frac{4}{\mu LCR_{\min}}R = [(\frac{1}{\gamma CAR_{\min}}-1)e+1]\cdot R, \tag{A5}$$

$$\frac{[1+0.5\lambda(e-1)LCR_{\min}]}{(\mu-0.5\lambda)LCR_{\min}}R = [(\frac{1}{\gamma CAR_{\min}}-1)e+1]\cdot R. \tag{A6}$$

The transition conditions between LCR and LR regulations are respectively

$$\frac{4}{\mu LCR_{\min}}R = (\frac{1}{LR_{\min}}-1)e\cdot R, \tag{A7}$$

$$\frac{[1+0.5\lambda(e-1)LCR_{\min}]}{(\mu-0.5\lambda)LCR_{\min}}R = (\frac{1}{LR_{\min}}-1)e\cdot R. \tag{A8}$$

And the transition condition between CAR and LR regulations is

$$[(\frac{1}{\gamma CAR_{\min}}-1)e+1]\cdot R = (\frac{1}{LR_{\min}}-1)e\cdot R. \tag{A9}$$

For the two expressions for LCR regulation to be identical, the following equality must holds

$$\frac{4}{\mu LCR_{\min}}R = \frac{[1+0.5\lambda(e-1)LCR_{\min}]}{(\mu-0.5\lambda)LCR_{\min}}R. \tag{A10}$$

Since the left terms and the right terms of all equations characterizing the transition conditions given above contain the reserves R, thus we know that only the level of equity to reserve ratio determine which one of the equations holds. In the next step, we can obtain the following transition conditions for e according to each of the above equations. According to Equation (A.1), we have

$$\mu^* = \frac{4r_{\min}}{LCR_{\min}}. \tag{A11}$$

According to Equation (A.2), we have

$$e^* = \frac{(\mu - 0.5\lambda)LCR_{\min} - r_{\min}}{0.5\lambda LCR_{\min} \cdot r_{\min}} + 1. \tag{A12}$$

According to Equation (A.3), we have

$$e^* = \frac{(1 - r_{\min})\gamma CAR_{\min}}{(1 - \gamma CAR_{\min})r_{\min}}. \tag{A13}$$

According to Equation (A.4), we have

$$e^* = \frac{LR_{\min}}{r_{\min}(1 - LR_{\min})}. \tag{A14}$$

According to Equation (A.5), we have

$$e^* = \frac{\gamma CAR_{\min}(4 - \mu LCR_{\min})}{\mu LCR_{\min}(1 - \gamma CAR_{\min})}. \tag{A15}$$

According to Equation (A.6), we have

$$e^* = \frac{\gamma CAR_{\min}(1 - \mu LCR_{\min})}{LCR_{\min}(\mu - 0.5\lambda - \mu\lambda CAR_{\min})}. \tag{A16}$$

According to Equation (A.7), we have

$$e^* = \frac{4LR_{\min}}{\mu LCR_{\min}(1 - LR_{\min})}. \tag{A17}$$

According to Equation (A.8), we have

$$e^* = \frac{LR_{\min}(1 - 0.5\lambda LCR_{\min})}{LCR_{\min}((1 - LR_{\min})\mu - 0.5\lambda)}. \tag{A18}$$

According to Equation (A.9), we have

$$e^* = \frac{\gamma CAR_{\min} \cdot LR_{\min}}{\gamma CAR_{\min} - LR_{\min}}. \tag{A19}$$

According to Equation (A.10), we have

$$e^* = \frac{\frac{6}{\lambda} - \frac{4}{\mu}}{LCR_{\min}} + 1. \tag{A20}$$

Appendix B

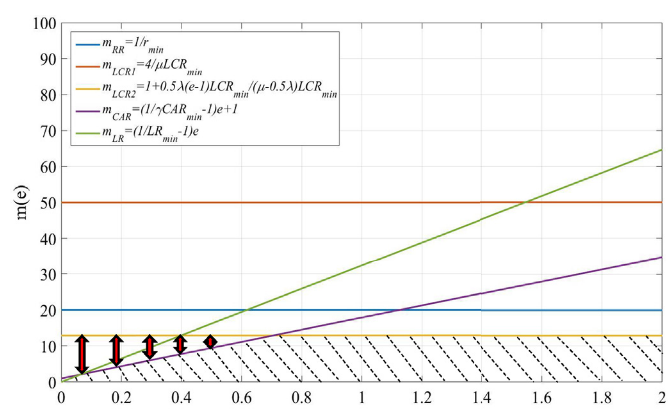

Fig. B1 The dependency relationship between money multiplier (m) and equity to reserve ratio (e) in a specific case with $\mu = 0.08$, $\lambda = 0.005$, $\gamma = 0.8$.

To illustrate the channel of reduction in overall money supply graphically, we demonstrate money multiplier in terms of equity to reserve ratio in an $m - e$ coordinate, given the value of regulation-related parameters $(r_{\min}, LCR_{\min}, CAR_{\min}, LR_{\min}) = (0.05, 1, 0.07, 0.03)$ and environmental parameters $(\mu, \lambda, \gamma) = (0.08, 0.005, 0.8)$. Substituting these parameters into Equation (27), we have

$$m(e) = \begin{cases} 20, & e \in \varphi_1; \\ 50, & e \in \varphi_2; \\ \dfrac{1}{31}e + \dfrac{399}{31}, & e \in \varphi_3; \\ \dfrac{118}{7}e + 1, & e \in \varphi_4; \\ \dfrac{97}{3}e, & e \in \varphi_5. \end{cases} \tag{B1}$$

Under these settings, it is worthy noting that the intersection points could be derived. For example, $(e_1^\star, m_1^\star)$ represents the one between $m_{LR}(e)$ and $m_{CAR}(e)$, and $(e_2^\star, m_2^\star)$ represents the one between $m_{CAR}(e)$ and $m_{LCR1}(e)$. As shown in Fig. B1, these two intersection points have divided the range of e into three segments, to be specific, $e_1^\star = 0.065$, $m_1^\star = 2.096$, $e_2^\star = 0.666$ and $m_2^\star = 12.892$. Then the expressions of φ can also be obtained, that is, $\varphi_1 = \emptyset$, $\varphi_2 = \emptyset$, $\varphi_3 = \{e \mid e >= 0.666\}$, $\varphi_4 = \{e \mid 0.065 <= e < 0.666\}$, $\varphi_5 = \{e \mid 0 <= e < 0.065\}$ respectively.

As mentioned in the main text, the overall equity to reserve ratio is equal to 1, and therefore the binding constraint for the homogeneous banking system is LCR under these settings, shown by the yellow line in Fig. B1. Thus the reduction in overall money supply would be more clearly interpreted by the differences between the yellow line and the one composed of the most stringent and piecewise lines, where the former line represents the binding constraint in a homogeneous system here.

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