A Macroeconomic Model with Interbank Markets and Regulated Banks

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Abstract

We propose an enhanced dynamic model in which counterparty banks suffer idiosyncratic liquidity shocks and are connected by an interbank market for liquidity risk management. The aim of this paper is to shed new light on the impact of the interbank market on the bank lending activity, under different requirement regimes. Banks are subject to loan investment risk, consisting of both permanent and transitory components, and idiosyncratic liquidity shocks leave them in liquidity surplus or liquidity deficit. The increase in the transitory risk volatility, keeping the total volatility constant, will noticeably deactivate the interbank market; however, the effect of a permanent risk volatility increase is insignificant. This finding indicates that the interbank market is more sensitive to the transitory effects of financial shocks. We also find that once the liquidity supply or demand is not satisfied by the interbank market, banks are more likely to curtail lending, especially in the case of the liquidity-deficit banks; therefore, we argue that central bank intervention in the distressed banks will help to sustain loan investment scale and contribute to social welfare growth. In normal times, the liquidity requirement (represented by Liquidity Coverage Ratio) lowers social welfare by limiting bank lending and interbank participation, while in extreme scenarios such as financial crises, the liquidity requirement is more effective in creating social welfare than the capital regulation by stabilizing the bank lending activity.

JEL Classification: G21, G28, G33, E58.

Keywords: Interbank market, permanent and transitory shocks, liquidity shocks, capital requirement, liquidity requirement.

1. Introduction

The interbank market channels banks that are either in surplus or in shortage of liquidity, typically after idiosyncratic liquidity shocks. Unlike the bond market, which takes a longer time to obtain liquidity, the interbank market enables banks to manage short-term liquidity risks, and this market is more efficient after the establishment of relationship lending[1]. Plenty of existing literature deals with the functioning of the interbank market in normal and disaster times, and plausibly explains the interbank failure in the 2007-2009 financial crisis. The Basel III Accord is scheduled to be fully implemented around 2019. The Basel III Accord is set up mainly to mitigate the identified systemic risks and, in part, to resolve liquidity risks. Many studies are targeting the impacts on the banking system and the improvement that it has brought to the financial system, but largely from the perspective of the micro-prudential influences. However, the analysis from the macro-prudential perspective, which incorporates the interaction between banks, is regrettably less documented. To have a holistic demonstration of the loan investment, interbank volume and interbank rate, we use Figure 1 and Figure 2 to illustrate the statistics of US and Euro-zone market from 2003 to 2018, with the shaded area indicating the recent recession period, from December 2007 to June 2009, as in FRED Economic Data. We can see that the interbank rate decreases dramatically during the recession periods while the interbank volume reduces noticeably recently. Bank lending increases within the US market, while the trend seems stable for the European market.

<Insert Figure 1 and 2 here>

Our paper contributes to the literature by establishing a model which considers the interactions between the banks that are channelled by the interbank market as a result of idiosyncratic liquidity shocks. To our knowledge, this consideration has not yet been documented. With the consideration of the interbank market, we are enabled to link the individual banks with the whole banking system with different Basel Accords regarding banking regulations.

We build up our model based on De Nicolo *et al.* (2014), who establish a partial equilibrium model, with the valuation approach pioneered by Merton (1977) and Kareken & Wallace (1978). To generalize what De Nicolo *et al.* (2014) focused on, we introduce a recently proposed risk factor model, advocated by Gourio (2012), to feature the economy, which is

[1] Refer to Cocco *et al*. (2009), Brauning & Fecht (2017) and other relevant literature regarding relationship lending for empirical support.

less considered in this field. There are two components, persistent and transitory, for the risk factor model. All banks are assumed to be driven by the same persistent component but different transitory ones, and all the components are governed by the realization of normal and disaster times, which are introduced to feature business cycles (Repullo and Suarez, 2012). Idiosyncratic liquidity shocks are modelled following Freixas *et al.* (2011) to enable the existence of interbank activity. To contribute to the approximation process for simulations with financial situation changes, we propose the construction of a new transition matrix such as the supplement of Rouwenhorst (1995), Danthine & Donaldson (1999) and Bai *et al.* (2018), which largely generalizes the assumptions of this sort of literature. The cross-sectional correlated shocks are transformed as in Lkhagvasuren & Galindev (2008), which allows us to generate correlated series using the combination of independent series. With these considerations included, we can evaluate the impacts of interbank activities under different regulation regimes and the resulting social welfare.

Our model is characterised by five features. First, we assume there exists an interbank market that channels the liquidity surplus and deficit banks, and which is a cheaper and quicker solution for liquidity deficit banks due to the interbank relationship lending, as in Cocco *et al*. (2009) and Brauning & Fecht (2017). This assumption guarantees that bond issuance, another way of obtaining liquidity, will be more costly and time-consuming and thus will be less preferred by the banks. Second, we consider a scenario in which the deposits are fully insured by the government, and thus sunspot-triggered bank runs are ruled out, following Freixas *et al*. (2011) and Allen & Gale (2009). Third, the exogenous credit risks are driven by two independent components, which are respectively at the systemic risk and idiosyncratic risk level. The aggregate liquidity shocks are negatively correlated to the systemic risks due to the increased expected return in investing in alternative projects, thus making excess deposit withdrawals possible, as in De Nicolo *et al.* (2014) and Albuquerque & Schroth (2015). Fourth, there are assumed to be two banks which are affected by the idiosyncratic liquidity shocks, one of them being the liquidity surplus bank and the other being the liquidity deficit one, as in Freixas *et al.* (2011). The two banks' participation in the interbank markets as the result of the idiosyncratic liquidity shock allows us to analyse the macro-prudential effects within the banking system and thus delivers the novelty of our paper. Lastly, as in Gourio (2012), we introduce the effects of the business cycle by permitting the financial situation changes, governed by the Markov process, and the construction of a new transition matrix taking into account these changes significantly updates what has been proposed by Danthine & Donaldson (1999) and Bai *et al*. (2018).

We assess the effects of the interbank market on the loan investment market, and compare the macro-prudential social effects of the banking system. The social welfare considerations include the bank value, depositor value, government revenue and the value of the related stakeholders. Our model enables us to evaluate the effects of different banking regulations, including capital requirement and liquidity requirement, and different types of government intervention, such as the bailout policy and interbank intervention and the effects of which include the interbank market volume, bank value and social welfare.

The results regarding the average interbank lending amount, loan investment amount, and bank and social value under different regulations and interventions are the main findings. The liquidity requirement is the strictest regulation which significantly limits bank's interbank borrowing amount, especially for liquidity deficit banks. Thereby, the social welfare is the lowest among other regulations, although the probability of bankruptcy is reduced, due largely to the reduced overall loan investment. Moreover, the overall interbank market demonstrates an unmatched supply and demand. Under loose regulations, such as the capital requirement, liquidity deficit banks are more freely to borrow and thus an interbank demand surplus is present. On the other bank, when under stricter regulations, as in the liquidity requirement, the deficit banks are largely constrained to borrow, making an overall interbank supply surplus. As for the loan market, we have mathematically proved that banks, no matter whether in the liquidity deficit or surplus position, will curtail the loan investment if the interbank is not fully satisfied, and our simulation results support this proposition. The government is modelled as a bailout policy maker and an interbank intervener, and as it takes on the role of rescuer the overall loan investment volume is reduced and the interbank market is more active. The reason for this is that the introduction of bailout policy makes interbank lending, which is counterparty risk free, a safer way for investment. However, due to the strict characteristics of liquidity requirement that largely limits the interbank borrowing, the liquidity requirement will sometimes outperform the capital requirement when the bailout policy is adopted. When government performs as the interbank intervener, it should provide intervention especially to liquidity deficit banks to sustain overall loan investment volume in order to contribute to social welfare.

Our paper is closely related to the following literature. De Nicolo *et al*. (2012) build up a dynamic model and consider the effects of capital and liquidity requirements of the banks from a micro-prudential perspective. They argue that liquidity requirements will unambiguously reduce the social welfare, which is in line with our baseline analysis, and they reveal that resolution policies, such as prompt corrective action, seem to dominate the regulations in efficiency and welfare terms. However, their research only focuses on specific banks, without considering interactions between banks. Hugonnier and Morellec (2017) also establish a dynamic model in a micro-prudential way and advocate banks' equity refinancing decisions in case of their insolvency. They find that combining liquidity and capital requirements reduces both the probabilities of default and the related default loss, while the consideration of interbank market and business cycle is neglected. Diamond and Rajan (2001) build up a static model and conclude that imposing capital requirements when liquidity risks are anticipated would result in a lower credit availability to borrowers and a lower liquidity creation. Our results confirm with theirs by showing that when stricter requirements are imposed, loan investment volume is reduced and social welfare is hence reduced due to the halved loan amount. Unfortunately, Diamond and Rajan (2001) fail to incorporate the dynamics of banking regulation and the idiosyncratic liquidity shocks. In terms of empirical studies, for example, Cornett *et al.* (2011) reveal that managing liquidity risks will be prone to reduce the overall credit supply, which is also in line with our simulation results.

Regarding the interbank and central bank intervention analysis, Heider *et al.* (2015) argue that due to the existence of counterparty risks the interbank market will be subject to break-down and banks will turn to hold liquidity instead. Our model, although it does not incorporate bond issuance or investment, in a way justifies this argument by showing that loan investment volume is reduced when bailout policy rules out the counterparty risk, which makes interbank lending a more profitable method for investing. Freixas *et al.* (2011) model a scenario where idiosyncratic liquidity shocks and interbank market are present and maintain that to make banks hold enough liquid assets, the interbank rates should be high enough, while the rates should be cut during financial crises to maintain the financial stability. However, the evaluation of the requirement regimes is not considered. Allen *et al.* (2009) develop a model within which the interbank market channels the banks suffering from idiosyncratic liquidity shocks. They conclude that when the interbank market cannot fully hedge banks' liquidity shocks, it will be prone to much volatility, and they suggest that central bank intervention should be implemented in such a situation; however, the impacts of the interbank market on loan investment is not included. Acharya *et al.* (2010) use a model which considers fire sales and they reveal an equilibrium where holding liquid assets is attractive when acquiring other failed banks in the case of fire sale. They also suggest liquidity support to failed banks will reduce incentives to hold liquidity, while support to banks contingent on their liquid assets seems to have the opposite effect. However, Acharya *et al.* (2010) fails to realize the existence of counterparty risk in the interbank market, which in a way limits the application of their work. Berger *et al.* (2016) use empirical analysis to show that regulatory interventions will decrease liquidity creation, while capital support has a marginal effect on the liquidity creation. Our paper aims to fill in these gaps and its contributions are summarized as follows.

Our contributions to the literature are highlighted in three points. Firstly, to our knowledge, this is the first study to consider the macro-prudential analysis by incorporating different banks channelled by the interbank market and to evaluate the interactions between the banks using the theoretical and simulated results. We can thus highlight our contribution by revealing the effects of interbank markets on the loan investment markets. Secondly, we assess the effects of different governmental bailout policies and intervention methods to the interbank markets and loan markets. Thirdly, we have incorporated some novel models regarding the exogenous shocks proposed recently, like the decomposition of the credit shocks, which could be better to mimic the economy.

The rest of our paper is organized as follows. Section 2 builds up the model and Section 3 supplements by introducing the regulation constraints and bailout policies. Section 4 presents a simplified model to mathematically explain the results, and Section 5 gives the simulation results. Section 6 concludes our paper. The additional proofs and procedures of conducting our simulation are summarized in the Appendix.

2. The Model

We set up an infinite-horizon model with discrete time, and in which credit risk (with permanent and transitory components) and liquidity risk drives banks' equilibrium loan investment and interbank lending. The credit risk at time t is denoted by $Z_{j,t}$ and is represented by

$$Z_{j,t} = Z_{p,t} \times Z_{r,j,t} \tag{1}$$

where $Z_{p,t}$ and $Z_{r,j,t}$ represent for the permanent and transitory shocks of credit risk respectively and the subscript j denotes the idiosyncratic credit risks specific to each bank. There exists two banks which are respectively denoted by $j = \pm 1$.

Normal Times.-As in Gourio[2] (2012) and Hajda (2017), the shocks can be computed as

$$\log Z_{p,t} = \log Z_{p,t-1} + \tau + \varepsilon_{p,t} \tag{2}$$

and

$$\log Z_{r,j,t} = \rho \log Z_{r,j,t-1} + \varepsilon_{r,j,t} \tag{3}$$

where $\varepsilon_{p,t}\ i.i.d.N(0,\sigma_p^2)$ and $\varepsilon_{r,j,t}\ i.i.d.N(0,\sigma_r^2)$. The term τ in Equation (2) shows the drift of the shocks in normal times. The term $\rho < 1$ in Equation (3) is the persistence of productivity which guarantees the initial level of transitory component will perish with the time continues, and thus $\log Z_{r,j,t} \cong \varepsilon_{r,j,t}$ in the long term.

Disasters-The economy will switch from 'normal times' to 'disaster times' with probability p each period[3], and will remain in the disaster time for the next period with probability q.[4] Whilst in the disaster time, the permanent component shocks of productivity is governed by a factor $\emptyset_t \in N\left(\mu_\emptyset - \frac{1}{2}\sigma_\emptyset^2, \sigma_\emptyset^2\right)$

$$\log Z_{p,t} = \log Z_{p,t-1} + \tau + \varepsilon_{p,t} + \emptyset_t \tag{4}$$

The transitory component is updated as follows:

$$\log Z_{r,j,t} = \rho \log Z_{r,j,t-1} + \varepsilon_{r,j,t} + \varphi_{j,t} - \emptyset_t \tag{5}$$

where $\varphi_{j,t} \in N\left(\mu_\varphi - \frac{1}{2}\sigma_\varphi^2, \sigma_\varphi^2\right)$ and is specified to individual banks.

Model Summary- Denote x_t an indicator which equals to one when in disaster and zero otherwise, we can summarize the productivity shock in the following equations.

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[2] Gourio (2012) introduces the composition of the permanent and transitory shocks for firm productivity, and thus we follow this concept under the assumption that firm's productivity will directly affect banks' loan income, partially through firm failure (see Repullo & Suarez (2012) for more details).

[3] As in Nakamura *et al.* (2013) and for simplicity, we assume this probability is not time-varying. For the analysis of time-varying, refer to Gourio (2012).

[4] In principle, $p < q$ indicates that bad shocks occur less frequently than normal times, and the expected duration of recessions is shorter than that of expansions (Rouwenhorst (1995) and Repullo & Suarez (2012)).

$$\log Z_{p,t} = \log Z_{p,t-1} + \tau + \varepsilon_{p,t} + \emptyset_t x_t \tag{6}$$

$$\log Z_{r,j,t} = \rho \log Z_{r,j,t-1} + \varepsilon_{r,j,t} + (\varphi_t - \emptyset_t) x_t \tag{7}$$

$$Pr\big(x_{t+1} = 1 \,\big|\, x_t = 1\big) = q \text{ and } Pr\big(x_{t+1} = 1 \,\big|\, x_t = 0\big) = p \tag{8}$$

As in De Nicolo *et al.* (2014) the deposit amount held by banks at time t is

$$\log D_{j,t+1} = (1 - \omega_D) \log \overline{D} + \omega_D \overline{\log D_t} + \varepsilon_{D,t} + ƕ_t x_t + \chi_{j,U>0.5} \xi_{d,t} \tag{9}$$

where $\varepsilon_{D,t}\ i.i.d.N(0, \sigma_D^2)$ denotes the error term of aggregate deposit amount and ω_D calibrates the persistence of the log of deposits, and $ƕ_t\ i.i.d.N\left(\mu_ƕ - \frac{1}{2}\sigma_ƕ^2, \sigma_ƕ^2\right)$ denotes the adjusted liquidity shocks when in recessions[5]. The term $\overline{D}$ is the long-term level of deposits, and the term $\xi_{d,t}\ i.i.d.N(\mu_d - \frac{1}{2}\sigma_d^2, \sigma_d^2)$ denotes the idiosyncratic liquidity risks to individual banks. The term $\chi_{j,U_{>0.5}}$ is an indicator of the realization of the idiosyncratic liquidity risks. If $j = 1$, $\chi_{j=1,U_{>0.5}}$ equals to $+1$ when $U > 0.5$, where U is a variable draws from a uniform distribution within $[0,1]$, and equals to -1 otherwise. While $j = -1$, $\chi_{j=-1,U_{>0.5}}$ equals to $+1$ if $U < 0.5$, and equals to -1 otherwise. [6] This assumption ensures bank-specific liquidity shocks cancels each other within the banking sector and thus allows interbank market to be possible and active. The term $\overline{\log D_t} = \frac{1}{2}\big(\log D_{j=1,t} + \log D_{j=-1,t}\big)$ is thus introduced to ensure the persistence effect is not bank-specific. As discussed in Appendix **B.2**, the idiosyncratic liquidity shocks $\chi_{j,U>0.5}\xi_{d,t}$ is memoryless and is not part of AR(1) process, which means banks' cannot effectively cope with this shock but can only resolve it only after it happens, through interbank lending or loan adjustment, which we will now turn to.

2.1 Bank's balance sheet

At time t, each bank has loans (L_t), and interbank lending (R_t)[7] on the asset side, and deposits (D_t) and capital (K_t) on the liability side. For each period, these two sides must equal, which means

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[5] For simplicity, and due to lacking in theoretical and empirical support, we assume the idiosyncratic liquidity shocks, captured by $\theta_j \xi_{d,t}$, is time-invariant whenever in booms or in recessions.

[6] Refer to Freixas *et al.* (2011) for theoretical evidence.

[7] For the sake of our interest in this paper, we assume banks are not accessible to bond market. This assumption does not lose any generality as we can treat interbank lending as a special bond which only takes one period to mature but subject to counterparty risk (Heider *et al.*, 2015). Moreover, this situation is more generalized when banks are the interbank relationship that enables interbank a more convenient way, compared with bond market, to obtain liquidity,.

$$L_t + R_t = D_t + K_t \tag{10}$$

should be satisfied at any period as long as the banks are in solvency[8]. Interbank lending takes one period to mature while the loans needs an expected longer time to be claimed. Interbank lending will return a rate at r_i, and deposit holders will ask for a rate at r_d. As in Repullo & Suarez (2012) and De Nicolo *et al.* (2014) we assume deposits are under full deposit insurance (paid with interest and principal) once banks are insolvent. Note that R_t can be negative, where $R_t < 0$ implies banks are the interbank borrowers.

Assumption 1 (Loan investment revenue). The revenue of loan investment at time t is defined as follows

$$\pi_j(L_t) = Z_{j,t} L_t^{\alpha} \tag{11}$$

where Z_t is defined in Equation (1) and L_t is the amount of loan outstanding at the beginning of time t, and $0 < \alpha < 1$ ensures $\pi_t(0) = 0, \pi > 0, \pi' > 0$ and $\pi'' < 0$. This assumption is supported by the evidence of decreasing return to scale of bank investments[9]. Note that L_t is determined at the beginning of time t, while Z_t is realized at the end of time t.

Assumption 2. A constant portion $\sigma \in (0, 1/2)$ of the outstanding loans at time $t - 1$ will due at time t. Under this assumption, the law of motion of L_t is

$$L_t = L_{t-1}(1 - \sigma) + I_t \tag{12}$$

where I_t is the new investment in loans if it is positive or negative if banks liquidate the loans in order to obtain cash for liquidity needs or reduced investment preferences. As in De Nicolo (2014), $\sigma < 1/2$ ensures that $1/\sigma - 1 > 1$. This assumption implies that weighted average maturity of the existing loans is longer than one period, assuming no new investments or liquidation of the loans[10]. The loan adjustment costs and fire costs are introduced following Diamond & Rajan (2011), which is summarized below.

Assumption 3 (Loan adjustment costs and loan fire sale costs). The loan adjustment cost function is quadratic:

[8] Since each bank will follow this condition strictly, we drop the subscript j for brevity. We will add the subscript in the rest of this paper when necessary.
[9] Refer to De Nicolo *et al.* (2014) for more details regarding loan investment revenues.
[10] The weighted average maturity of existing loans at time t is $\sum_{s=0}^{\infty} s \frac{\sigma L_{t+s}}{L_t} = \frac{1}{\sigma} - 1$ where the residual of outstanding loans at time $t + s$ is $L_{t+s} = L_t(1 - \sigma)^s$.

$$M(I_t) = |I_t|^2 \left[m + \zeta_{\{I_t<0\}} \cdot \frac{1}{2L_t}\right] \tag{13}$$

where $\zeta_{\{I_t<0\}}$ is the indicator which takes the value of one if $I_t < 0$ and zero otherwise. The parameter m is the unit cost parameters whenever the loan investment is changed, and an additional fire sale cost will be incurred if $I_t < 0$. As in Diamond & Rajan (2011), the fire sale price is linearly decreasing with the amount of loan liquidated, and thus the fire sale loss is calculated as $\left\{\frac{1}{2}[1-(1-I_t/L_t)^2] - I_t/L_t\right\} L_t = -{I_t}^2/2L_t$. This assumption indicates that loan liquidation will incur an exceptionally high fire sale cost. This cost will be deducted from banks' profit[11].

Assumption 4 (Deposit interest and managing cost). Besides interest of deposits, banks are required to make a payment each period in order to honour the outstanding deposits. This payment can attribute to deposit insurance costs and depositor servicing fee. This cost, together with interest payment, is an increasing and convex function[12] and is defined as:

$$C_t = \{r_d + \vartheta D_t^4\} D_t \tag{14}$$

where r_d is the constant rate of deposits and ϑ is the parameter which captures the deposit managing costs. Unlike Hugonnier and Morellec (2017), the deposit face value in our analysis are exogenous, and thus might not explicitly affect deposit amount. However, introducing this force might influence banks' loan and interbank lending behaviour once the costs of deposits vary significantly when the deposits are more volatile.

2.2 Timeline

As long as the banks are solvent, they will follow the timeline framework below during each period. At the beginning of time $t+1$, banks will make their decision choice (L_{t+1}, R_{t+1}) in order to maximize their expected net cash flow. Loan revenue, deposits (with interest) and interbank lending (including interest) are paid off at the end of each period. The timeline is shown in Figure 3. The credit shock Z_t realizes before the end of time t, the corporate tax is levied for this period based on the earnings before taxes (EBT). Then, at the very beginning of time $t+1$, the deposit amount D_{t+1} realizes, causing liquidity shock if $D_{t+1} - D_t < 0$.

[11] Compared with the calibration of De Nicolo *et al.* (2014), our model generally enlarges the costs of fire sales, since in their paper fire sale loss is $m^- - m^+ = 0.01$ (Page 2116) higher than that of loan adjustment costs while in our analysis the loss is larger once $L_t < 50$ which can be easily satisfied in our calibration.
[12] Refer to Hugonnier and Morellec (2017) for more details.

Banks will thus adopt new operation strategy denoted by (L_{t+1}, R_{t+1}), to seek for new investment and to manage liquidity shocks through interbank market.

<Insert Figure 3 here>

2.3 Bank cash flow

Once Z_t is realized at the very end of time t, the state is summarized by the vector $f_{j,t} = (L_{j,t}, R_{j,t}, D_{j,t}, Z_{j,t})$, where loan investment $L_{j,t}$, interbank lending amount $R_{j,t}$, exogenous deposit amount D_t is known at the very beginning of time t, while at the end of which slot the loan investment revenue Z_t is realized. Prior to investment strategy and cash distribution decision, the total internal cash available to bank j is:

$$W_{j,-j,t} = W_{j,-j}(f_t) = y_{j,-j,t} - \varsigma(y_{j,-j,t}) + R_{j,t} \cdot Q_{j,-j,t} + \sigma L_{j,t} + D_{j,t+1} - D_{j,t} \quad (15)$$

where $Q_{j,-j,t} = \left[1 - \frac{|R_{j,t}|+R_{j,t}}{2R_{j,t}} \cdot \left(1 - \chi_{E_{-j,t-1}>0}\right)\right]$ denoting the force of the *counterparty risk* when banks are lending through interbank market to their counterparty. We drop the subscript of $t-1$ in $Q_{j,-j,t}$ for simplicity. The term $\chi_{E_{-j,t-1}>0}$ is an indicator which takes the value of one if the other bank does not fail ($E_{-j,t-1} > 0$) and zero if bank fail ($E_{-j,t-1} = 0$)[13]. The calculation $\left(|R_{j,t}| + R_{j,t}\right)/2\,R_{j,t}$ focuses on the situation when $R_{j,t}$ is positive. The term y_t in Equation (15) denotes the earnings before taxes (EBT), and is represented by

$$y_{j,-j,t} = y_{j,-j}(f_t) = Z_{j,t}L_t^{\alpha} + [(1 + r_i) \cdot Q_{j,-j,t} - 1]R_{j,t} - C_{j,t} \quad (16)$$

After minus corporate tax $\varsigma(y_{j,-j,t})$, plus the due interbank lending ($R_{j,t}$) if the counterparty bank is solvent, and the matured loan investment ($\sigma L_{j,t}$), the internal cash before investment strategies is thus determined. It thus ensures the loss due to counterparty failure can be deducted from the tax payment. The book value of the capital of bank $-j$ is defined by:

$$U_{-j,t} = (1 + Z_{-j,t})L_{-j,t} + (1 + r_i)R_{-j,t} - \left(1 + r_d + \vartheta D_{-j,t}^4\right)D_{-j,t} \quad (17)$$

Additionally, we introduce the market equity value $E_{-j}(f_t) = E_{-j,t}$ to calibrate the bankruptcy of bank $-j$ if the equity value is zero, i.e. $E_{-j,t} = 0$. The corporate taxation regime is then summarized as follows:

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[13] Since bankruptcy is realized at the very beginning of each period, and thus the *counterparty risk* is determined by the insolvency of the banks from the previous time period.

Assumption 5 (Corporate taxation). Corporate tax at each period is levied according to the function of EBT:

$$\varsigma(y_{j,t}) = \epsilon^{+} \max\{y_{j,-j,t}, 0\} + \epsilon^{-} \min\{y_{j,-j,t}, 0\} \tag{18}$$

where ϵ^{-} and ϵ^{+}, $0 \leq \epsilon^{-} \leq \epsilon^{+} < 1$, are the corporate tax rates for the cases of negative and positive EBT respectively[14].

In addition, we define an interbank market clearance condition that is summarized as follows:

Assumption 6 (Interbank market clear and active condition). Since we only introduce two banks and no central bank will take part in the interbank, the market clear condition is:

$$R_{j,t} + R_{-j,t} = 0 \tag{19}$$

Since interbank will be active only if one bank is in demand and the other in supply, the following condition will apply to feature an active interbank market ($|R_{j,t}| = |R_{-j,t}| > 0$). We assume the amount the bank j originally plans to borrow from interbank market is O_j, and the bank $-j$ plans to borrow is O_{-j}. Note that before agreed in interbank market, $|O_j| \neq |O_{-j}|$ might be valid and the condition $O_j O_{-j} < 0$ should be satisfied as there should be only one borrower and one lender in the interbank market to make interbank market active. Additionally, the interbank market will be inactive once $\min(|O_{j,t}|, |O_{-j,t}|) = 0$. The following condition should also apply to feature the actual interbank lending respectively for bank j and $-j$:

$$R_{\pm j,t} = \frac{|O_j O_{-j}| - O_j O_{-j}}{2|O_j O_{-j}|} \cdot \min\{|O_j|, |O_{-j}|\} \cdot \frac{O_{\pm j}}{|O_{\pm j}|} \tag{20}$$

In Equation (20), the first term guarantees that O_j and O_{-j} must be reverse sign so that one bank is the interbank lender and the other is borrower in order to make interbank active. The second term $\min\{|O_j|, |O_{-j}|\}$ indicates once the supply and demand fail to break even the smaller supply/demand amount will be satisfied, similar to ask-bid process. The last term $O_{\pm j}/|O_{\pm j}|$ finalises the signs of $R_{\pm j,t}$, thus the borrower and lender of the active interbank lending is settled down. One more term $O_{j,-j} = 1 - R_{\pm j,t}/\max\{|O_j|, |O_{-j}|\}$ denotes the reduced potential interbank lending due to uneven demand and supply.

[14] Refer to Hennessy and Whited (2007) and De Nicolo *et al.* (2014) for support.

Assumption 7 (Loan adjustment for unmatched interbank market). In general there should be one bank whose demand/supply is not satisfied because either $|O_{j,t}| \leq |R_{j,t}|$ or $|O_{-j,t}| \leq |R_{-j,t}|$ will be valid as in **Assumption 6**. Thus, the unsatisfied bank will further change their loan investment strategy once the interbank lending/borrowing is settled down.

Assumption 8 (Net cash flow and equity issuance costs). After the payment of the costs and corporate taxation determined by Equation (18), receiving the matured loan investment and paying off the liquidity shocks (if $D_{t+1} - D_t < 0$), the residual cash flow to the shareholders is

$$M_{j,-j,t} = M_j(f_t, L_{j,t+1}, R_{j,t+1}) = W_{j,-j,t} - R_{j,t+1} - L_{j,t+1} + L_{j,t}(1-\sigma) - M(I_{j,t}) \quad (21)$$

If $M_{j,-j,t} \geq 0$, bank j will distribute it to the shareholders (in the form of dividend or stock purchase). If $M_{j,-j,t} < 0$, bank j will have to issue new equity in order to make their due payment written off. As in Cooley and Quadrini (2001), we assume issuing equity is costly due partial to underwriting fee, and accordingly a proportional cost κ is payable on the value of the equity that is newly issued. Thus, bank j net cash flow $e_{j,-j,t}$ at time t that contributes to the overall shareholder net worth can be defined as follows:

$$e_{j,-j,t}(f_{j,t}, D_{j,t+1}, L_{j,t+1}, R_{j,t+1}) = \max\{M_{j,-j,t}, 0\} + \min\{M_{j,-j,t}, 0\}(1+\kappa_j) \quad (22)$$

where $\kappa_j = \gamma\kappa$ and $\gamma > 1$ for the liquidity deficit bank and $\kappa_j = \kappa$ for the liquidity surplus bank. This assumption reflects the fact that generally the banks faced with liquidity shocks have higher cost of raising capital (Butler *et al.* 2005).

Assumption 9 (Insolvency). If a bank fails at time t, the corresponding shareholders will leave the market with zero equity value due to limited liability. Government, performing as the deposit insurer, will thus pay off the depositors in full and pay for additional bankruptcy costs at cD_t. Right after a default, a reorganized bank will enter the market with debt at D_{t+1} and equity at $K_{t+1} = K' = D_u - D_{t+1}$, with loans $L_{t+1} = D_u$ and $R_{t+1} = 0$. Similar to Equation (17), the loss the government is responsible for in the event of bankruptcy is

$$C_{G,j,-j,t} = cD_{j,t}(1+r_d) + e_{j,-j,t}(1+\kappa) \quad (23)$$

Equation (23) indicates that in the event of bankruptcy $E_{j,t} = 0$, as the deposit insurer of bank j the government will pay for the additional bankruptcy costs $cD_{j,t}$ proportional to the deposit amount $D_{j,t}$, and the (negative)[15] net cash flow $e_{j,-j,t}$, which is determined by Equation (22).

Assumption 10 (Interbank rate). The interbank rate $r_{i,t}$, as a function of actual interbank borrowing/lending, is summarized as follows:

$$r_{i,t} = r_i \left(\frac{R_{j,t}}{|\bar{R}|}\right)^{\varphi-1} \tag{24}$$

where $\varphi < 1$, and $|\bar{R}|$ is a constant which is introduced to remove the dependency of $Z_{p,t}$. Equation (24) indicates that higher interbank volume reflects higher liquidity in that market, which in turn, tends to be associated with lower interbank rate because of the improved market quality (Colliard & Hoffmann, 2017). In addition, this assumption guarantees a higher bound of the interbank rate and reflects the fact the existence of interbank lending/borrowing relationship with less correlated liquidity shocks which allows interbank demanders borrow at a lower rate, especially for large amount of borrowing (Cocco, *et al.* (2009), Brauning & Fecht (2017)). Additionally, as in Freixas *et al.* (2011), the decrease in the interbank rate can be attributed to the central bank intervention to cut down the interbank rates during the crises, when the interbank market is active enough as in the increased interbank lending/borrowing amount, to maintain the financial stability (Freixas *et al.* (2011)).

2.4 The dynamic of banks and the valuation of shareholder net worth

Let E denote the market value of banks' equity. Suppose for bank j, at each state with $f_{j,t} = (L_{j,t}, R_{j,t}, D_{j,t}, Z_{j,t})$, the equity value of bank j at time t is given by

$$E_j(x_t) = \max_{\{(L_{j,i+1},R_{j,i+1})\in\Delta(D_{i+1}),i=t,\dots,T\}} \mathbb{E}_{j,t}\left[\sum_{i=t}^{T} \beta^i e_{j,-j,t}(f_{j,t}, L_{j,t+1}, R_{j,t+1})\right] \tag{25}$$

where $\mathbb{E}_{j,t}[\cdot]$ is the expectation operator for the cash flows (we drop the subscript $-j$ for simplicity), and β is shareholders' discount factor. Cash flow at the beginning of time $t+1$ is $e_{j,t}(f_{j,t}, L_{j,t+1}, R_{j,t+1})$, which is the result of state $f_{j,t}$ and investment strategies $(L_{j,t+1}, R_{j,t+1})$. Time T is the point where bank j fails, and $(L_{j,i+1}, R_{j,i+1})$ is constrained to the definition of feasible set $\Delta(D_{i+1})$ for different scenarios. Since the model is

[15] It is straightforward to prove that if bankruptcy happens the net cash flow must be negative, otherwise banks will not fail.

stationary, given $\beta < 1$, Bellman Equation involving current and next period could resolve this model. For simplicity, we denote the current period state for bank j using the notation without prime and the next period with prime. The value of equity satisfies the following Bellman Equation:

$$E_j(f) = \max\left\{0, \max_{(L',R')\in\Delta(D)}\{e_j(f,L',R') + \beta\mathbb{E}[E_j(f')]\}\right\} \tag{26}$$

Note that from **Figure 1**, deposits D_{t+1} and revenues $Z_{j,t}$ have one period difference, and thus we denote $D = D_t, D' = D_{t+1}, D'' = D_{t+2}$. Due to limited liability, equity value is modelled to be nonnegative and will be zero if bank is insolvent. To link with **Assumption 8**, we assume the following transition function denoted as ϕ_j regarding the optimal policy with bankruptcy:

$$\phi_j(f) = \begin{pmatrix} L^* \\ R^* \\ D' \end{pmatrix}(1 - \nabla_j) + \begin{pmatrix} D_u \\ 0 \\ D' \end{pmatrix}\nabla_j \tag{27}$$

where $\nabla_j = 1 - \chi_{E_j>0}$ denoting the bankruptcy. When insolvent, the bank will be reconstructed with loan investment at the value of $L' = D_u$, with no interbank lending position $R' = 0$, and debt at the amount of D', which indicates the initial book value of equity of the reorganized bank at $K' = D_u - D'$. On the other hand, if the bank is solvent, it will adopt the optimal decision (L^*, R^*).

3. Bank Regulation and bailout policy

Assumption 10 (Collateral constraint). After the decision of investment strategies (L_t, R_t), banks have to be fully collateralized in order to continue their activities. The constraint, once $R_t < 0$, at time t are

$$\begin{aligned} L_t - M[-L_t(1-\sigma)] + Z_d L_t^{\alpha} + R_t(1+r_i)\cdot\mathbb{E}^{min}(Q_{-j,t+1}) + D_d - \varsigma(y_t^{min}) \\ - D_t(1 + r_d + \vartheta D_t^4) \geq 0 \end{aligned} \tag{28}$$

In addition

$$\mathbb{E}^{min}(Q_{-j,t+1}) = \begin{cases} \varpi & if\ R_t > 0 \\ 1 & if\ R_t < 0 \end{cases} \tag{29}$$ [16]

where ϖ indicates the worst-case probability of counterparty default. In Equation (28), Z_d denotes the worst-case credit shock, and D_d is the worst possible flow of deposits. The

[16] Since a bank, along with the government, cannot observe the counterparty's balance sheet at the beginning of the investment period and thus cannot forecast the worst-case probability of counterparty default as endogenous if it is the interbank lender. Without loss of generality, we assume the counterparty risk in this constraint as

notation $y_{-j,t}^{min} = Z_d L_t^{\alpha} + \left[(1+r_i) \cdot \mathbb{E}^{min}\left(Q_{-j,t}\right) - 1\right] \cdot R_t - (r_d + \vartheta D_t^4) D_t$ represents the worst scenario for the Earnings Before Tax (EBT). Equation (28) ensures that considering worst-case scenario banks' cash inflow by liquidating loans $L_t - M[-L_t(1-\sigma)]$, loan investment revenues $Z_d {L_t}^{\alpha}$, interbank lending principal and interest $\left[(1+r_i) \cdot \mathbb{E}^{min}\left(Q_{-j,t}\right) - 1\right] \cdot R_t$ and next period deposit inflows D_d must exceed the cash outflows due to corporate tax $\varsigma\left(y_{-j,t}^{min}\right)$ and deposit principal, interest and managing cost $D_t\left(1 + r_d + \vartheta {D_t}^4\right)$. Thus, the feasible sets of collateral constraint $Ч(D_t)$ is as follows:

$$
Ч(D_t) = \left\{ (L_t, R_t) \,\middle|\, \frac{L_t - M[-L_t(1-\sigma)] + D_d + Z_d L_t^{\alpha}(1-\epsilon_t)}{1 + (r_d + \vartheta D_t^4)(1-\epsilon_t)} + R_t \cdot \frac{\epsilon_t + (1+r_i)(1-\epsilon_t) \cdot \mathbb{E}^{min}\left(Q_{-j,t+1}\right)}{1 + (r_d + \vartheta D_t^4)(1-\epsilon_t)} \geq D_t, R_t < 0 \right\} \cup \{R_t > 0\} \tag{30}
$$

where $\epsilon_t = \epsilon^{+}$ if $y_{j,t}^{min} > 0$ and $\epsilon_t = \epsilon^{-}$ if $y_{j,t}^{min} < 0$.

3.1 Capital Requirement

We establish a Basel-type capital regulation for the proxy of the capital requirement. The capital ratio in our analysis refers to the ratio of book value of bank capital to the book value of loans. For banks which are under capital requirements, at least an amount of loans $\gamma_t = kL_t$ should be retained as collateral constraint[17]. Accordingly, the feasible set $Л(D_t)$ for banks under capital requirement is

$$
Л(D_t) = \left\{ (L_t, R_t) \,\middle|\, (1-k)L_t + R_t \geq D_t \right\} \tag{31}
$$

Since all banks have to follow collateral constraint as specific in Equation (30), thus the feasible set for banks under capital requirements is $Ч(D_t) \cap Л(D_t)$. Although $Л(D_t)$ is stricter than the second condition of $Ч(D_t)$, it is hard to determine whether $Ч(D_t) \subset Л(D_t)$ or $Л(D_t) \subset Ч(D_t)$.

3.2 Liquidity Requirement

exogenous, this assumption should be unbiased as our later regulation constraints all regard this risk as presumably given.

[17] Similarly, Shleifer & Vishny (2010) and Walther (2016) apply an exogenous 'marked-to-market' collateral constraint to mimic the capital requirement by modelling a 'haircut' on debt to limit the loan investment amount.

Current Basel III regulation (BIS, 2013) introduces a *Liquidity Coverage Ratio* (LCR) requirement for mitigating a 30-day liquidity distress[18]. The LCR is defined as the ratio of *High-quality liquid assets* (HQLAs) to *Net cash outflows* (NCOs). To keep in line with our analysis before, we also adopt worst-case scenario analysis. As in Walther (2016), HQLAs are a weighted sum of bank assets with illiquid assets have low weights, while NCOs are a weighted of bank liabilities with a cash outflow within 30 days assigned with high weights. Following De Nicolo *et al.* (2014), we assume the ratio should exceed h in order to meet the liquidity requirement. Thus, the LCR ratio is as follows:

$$\frac{\sigma L_t + Z_d L_t^{\alpha} - \varsigma(y_t^{min}) + R_t(1+r_i)\cdot \mathbb{E}^{min}(Q_{-j,t+1})}{D_t(1+r_d+\vartheta D_t^4) - D_d} \geq h \tag{32}$$

where the numerator of Equation ((32) is the sum of worst-case cash available, consists of matured loans σL_t, loan revenue $Z_d {L_t}^{\alpha}$, expected ex ante interbank lending income $R_t(1+r_i)\cdot \mathbb{E}^{min}(Q_{-j,t})$, and net of corporate tax $\varsigma(y_t^{min})$. The denominator of Equation ((32) is the worst-case cash outflows $D_t\big(1 + r_d + \vartheta {D_t}^4\big) - D_d$, due to the variation in deposits. Accordingly, the feasible set $Ж(D_t)$ of bank investment choice when under liquidity requirement is:

$$Ж(D_t) = \left\{(L_t, R_t) \,\middle|\, \frac{\sigma L_t + D_d h + (1-\epsilon_t) Z_d L_t^{\alpha}}{h + (h-\epsilon_t)(r_d+\vartheta D_t^4)} + R_t \cdot \frac{\epsilon_t + (1-\epsilon_t)(1+r_i)\cdot \mathbb{E}^{min}(Q_{-j,t+1})}{h+(h-\epsilon_t)(r_d+\vartheta D_t^4)} \geq D_t \right\} \tag{33}$$

Similarly, for banks that are under liquidity requirements only will be subject to feasible set of $Ч(D_t) \cap Ж(D_t)$, while for banks following capital and liquidity requirements the feasible set choice is constrained to $Ч(D_t) \cap Л(D_t) \cap Ж(D_t)$.

3.3 Government bailout policy

In this section, we introduce the government bailout policy and investigate its impacts to loan investment and interbank lending. In order to compare the net effects of this policy, we firstly assume one bank is under the protection of government which guarantees its solvency throughout the time, while the other bank is not[19], we will then consider the case when all the

[18] Basel III also introduces a *Net Stable Funding Ratio* (NSFR) requirement for longer period liquidity stress, typically for one year; however, the analysis for this requirement is beyond this paper.

[19] This assumption is a generalized way of modelling '*Too-Big-To-Fail*' or '*Too-Systemic-To-Fail*' concerns which makes government obliged to rescue certain banks to avoid additional social costs (see Acharya *et al.* 2017 and Freixas & Rochet 2013 for support). Although our assumption to consider '*Too-Big-To-Fail*' deserves comments as we assume banks are initially of the same balance sheet size, we can alternatively regard the other bank which is not under government support as the sum of many small banks that treat bank j as the counterparty in the interbank market. Since bank size and systemic importance is not modelled in our paper, our

banks are protected. Bank $j = 1$ is under the protection of the government, if the bailout policy is considered. For bank $j = 1$, the total internal cash $W_{j=1,t}$[20], earnings before taxes $y_{j=1,t}$ and residual cash flow $M_{j=1,t}$ remains the same as determined in Equations (15), (16) and (21) respectively due to the existing *counterparty risk* of bank $j = -1$. However, the total internal cash flow $W_{j=-1,t}$ for bank $j = -1$ is revised as follows:

$$W_{j=-1,t} = W_{j=-1}(f_t) = y_{j=-1,t} - \varsigma(y_{j=-1,t}) + R_{j=-1,t} + \sigma L_{j=-1,t} + D_{j=-1,t+1} - D_{j=-1,t} \tag{34}$$

where

$$y_{j=-1,t} = y_{j=-1}(f_t) = Z_{j=-1}L_t^{\alpha} + r_i R_{j=-1,t} - \left(r_d + \vartheta D_{j=-1,t}^{4}\right)D_{j=-1,t} \tag{35}$$

To explain Equation (34) and (35), due to the support of the government, bank $j = -1$ is free of *counterparty risk* and thus the indicator of counterparty failure $Q_{j,-j,t}$ is dropped out. Moreover, for the feasible set of choice (L_t, R_t), bank $j = 1$ has the same choice as determined in Equation (30), (31) and (33). On the other hand, the choice for $j = -1$, the function $\mathbb{E}^{min}(Q_{-j,t})$ as determined in Equation (29) will be made to $\mathbb{E}^{min}(Q_{-j,t}) = 1$ due to absence of *counterparty risk*. As in Hugonnier & Morellec (2017) and to keep in line with the assumption before, we assume once bank $j = 1$ needs bailout, government will intervene and reconstruct the bank in a same way as in **Section 2.4**. Similarly, as the supporter for the bank $j = 1$, in the event of governmental intervention $E_{j=1,t} = 0$, the cost the government is responsible for is:

$$C_{G,j=1,t} = \left(K' + e_{j,-j,t}\right)(1 + \kappa) \tag{36}$$

Compared with Equation (23), when performing as bailout provider, the government will inject additional capital $K'(1 + \kappa)$ to reconstruct, while the bankruptcy cost is removed[21]. We also assume an equity issuance cost $\kappa K'$ in case of governmental bailout action. Thus, compared with Equation (23), the overall social cost deduction because of bailout is $c_{j=1}D_{j=1,t}(1 + r_d) - \kappa K'$. Since we assume an unconditional bailout policy to bank $j = 1$

results regarding the resulting the difference in loan investment and interbank lending can only attribute to the governmental bailout policy.

[20] To distinguish from the case when no governmental bailout policy is involved, we specify the bank with $j = 1$ or $j = -1$ in the subscripts respectively.

[21] The difference in Equation (23) and (36) indicates that government pays for the seed capital to rescue the bank to exchange for the bankruptcy costs $cD_{j,t}$ especially when the cost is high. However, the trade-off between capital injection and bankruptcy costs is not the focus of this paper. Instead, we aim to investigate banks' lending behaviour and interbank lending when under different bailout policies, and thus neglect the cause of bailout policy.

and thus whether to bailout or not is not the focus of this paper, we therefore assume for simplicity $c_{j=1}D_{j=1,t}(1+r_d) > \kappa K'$ to indicate it is socially optimal to rescue bank $j=1$. Afterwards, we will generalize our consideration of bailout to all banks.

3.4 Bank value, government payoff and social welfare

We denote *enterprise welfare* as a metric of bank efficiency, which can be represented by the sum of market value of bank equity plus the value of deposits net of cash balances, and plus the debts, which could calibrate banks' ability to create 'productive' intermediation[22]. Thus, the enterprise value $EV_j(x_t)$ of bank $j=\pm 1$ (without governmental bailout) could represent as follows:

$$EV_j(f_t) = E_j(f_t) + D_{j,t}(1+r_d)\big[1 - c\nabla_j(f_t)\big] - R_{j,t} \tag{37}$$

The payoff to the government $G(f_t)$, as the deposit insurer, is summarized as

$$G(f_t) = \sum_{j=\pm 1}\big[1-\nabla_j(x_t)\big]\cdot\big\{\varsigma\big(y_{j,t}\big) + \beta\mathbb{E}_j[G(x_{t+1})]\big\} - \nabla_j(f_t)\cdot C_{G,j,-j,t} \tag{38}$$

where $1-\nabla_j(f_t)$ indicates the solvency of the bank j under which circumstance the government will yield tax income $\varsigma\big(y_{j,t}\big)$ and the expected and discounted value of future tax proceeds. However, in the case of bankruptcy $\nabla_j(f_t)=1$, the government will pay for the related costs $C_{G,j,-j,t}$ that is defined in Equation (23). In addition, *social welfare* denotes the total value added to the economy due to banking activities, which can be represented by[23]

$$SW(f_t) = G(f_t) + \sum_{j=\pm 1} E_j(f_t) + D_{j,t}(1+r_d) - \nabla_j(f_t)\cdot K' \tag{39}$$

Thus, social welfare is the sum of government payoff $G(f_t)$, plus banks' equity value $E_j(f_t)$, deposits $D_{j,t}(1+r_d)$ and the newly injected capital $\nabla_j(f_t)\cdot K'$ for reconstructing banks when insolvent. In other words, the overall social welfare is the sum of values of banks' activities to all stakeholders. To differentiate from the case for governmental bailout, we assume the injected capital is paid by the bankers who plan to replace the failed one, and thus is not the cost of the government.

However, when considering governmental bailout policy, the above equations regarding welfare metrics will be modified. To feature the distress of bank $j=1$, we denote $\widetilde{\nabla_{j=1}} = 1$ as

[22] For the support of this calibration, see Gamba and Triantis (2008), Bolton *et al.* (2011) and De Nicolo *et al.* (2014).

[23] Since $R_{j=+1,t}$ and $R_{j=-1,t}$ cancels out each other, and we thus drop them off the Equation (39).

the indicator when its equity value is zero (i.e. when bank $j = 1$ needs bailout). The enterprise value $\widehat{EV}_{j=\pm 1}(f_t)$ [24]will be

$$\widehat{EV}_{j=\pm 1}(f_t) = \begin{cases} E_j(f_t) + D_{j,t}(1 + r_d) - R_{j,t} & if\ j = 1 \\ E_j(f_t) + D_{j,t}(1 + r_d)[1 - c\nabla_j(f_t)] - R_{j,t} & if\ j = -1 \end{cases} \tag{40}$$

and

$$\hat{G}(f_t) = [1 - \nabla_{j=-1}(f_t)] \cdot \{\varsigma(y_{j=-1,t}) + \beta \mathbb{E}_{j=-1}[G(f_{t+1})]\} - \nabla_{j=-1}(f_t) \cdot C_{G,j,-j,t} + [1 - \widetilde{\nabla_{j=1}}(f_t)] \cdot \{\varsigma(y_{j=1,t}) + \beta \mathbb{E}_{j=1}[G(f_{t+1})]\} - \widetilde{\nabla_{j=1}}(f_t) \cdot C_{G,j=1,t} \tag{41}$$

where $C_{G,j,-j,t}$ and $C_{G,j=1,t}$ are defined by Equations (23) and (36) respectively for capturing governmental losses. Moreover,

$$\widehat{SW}(f_t) = G(f_t) - \nabla_{j=-1}(f_t) \cdot K' + \sum_{j=\pm 1} E_j(f_t) + D_{j,t}(1 + r_d) \tag{42}$$

indicating the overall social welfare expressed as the sum of governmental costs $G(f_t)$, the cost of injecting equity $\nabla_{j=-1}(f_t) \cdot K'$ to reconstruct a new bank in the case of insolvency of bank $j = -1$, the total amount of equity $E_j(f_t)$ and the book value of current deposits $D_{j,t}(1 + r_d)$. Note that $R_{j=+1,t}$ and $R_{j=-1,t}$ cancels out each other, and we thus drop them off the Equation (42).

4. Regulations in a Simplified Version of the Model

To illustrate some trade-offs on bank optimal policies with interbank market, we introduce a simplified version of our proposed model within in which there are only three periods: t, $t + 1$ and $t + 2$. The model starts at time t, and banks will make decisions on time $t + 1$, and ends with the final date $t + 2$. All the two banks starts with the same balance sheet, denoted by $L_t = D_t + E_t$, and thus interbank lending will only be available at time $t + 1$. There are no taxes, equity adjustment costs and deposit managing cost, $\sigma = 0, r_i = \epsilon R_{t+1}^{\varphi-1}$ and the shareholder discount rate is $\beta \leq (1 + r_d)^{-1}$. There are no idiosyncratic credit risk $Z_{r,j} = 1, \tau = 0$ and systemic credit risk $Z_{p,t+2} = Z_{p,t+1} \cdot e^{\varepsilon_Z}$, where $\varepsilon_Z\ i.i.d. N(0, \sigma_Z^2)$. Deposit amount follows with a two-point distribution with probability of $1/2$ at $D_{t+1+i} = D_{t+i} \cdot \theta_D$, and probability of $1/2$ at $D_{t+1+i} = D_{t+i}/\theta_D$, where $\theta_D > 1$ and $i = 0, 1$. For simplicity, the worst-case credit risk $Z_d = e^{-2\sigma_Z} L_{t+1}^{1-\alpha}$, $D_d = D_{t+1}/\theta_D$ and $0 < \varpi < Q_{j,-j,t} = \mathbb{E}^{min}(Q_{-j,t}) = \curlyvee < 1$. Under these assumptions, the collateral constraint, capital requirement

[24] We add a hat to distinguish with the analysis without bailout policy.

and liquidity requirement respectively specified in Equation (30), (31) and (33) can be simplified to

$$R_{t+1} \geq \frac{1}{\Upsilon(1+r_d)}\left[1 + r_d - \frac{1}{\theta_D}\right] D_{t+1} - \frac{1+e^{-2\sigma_Z}}{\Upsilon(1+r_d)} L_{t+1} \tag{43}$$

For simplicity, we assume σ_Z is large enough, Υ and θ_D are small enough such that the condition $L_t + R_t \geq D_t$ is easy to be satisfied.

Moreover, the capital and liquidity requirements are simplified as

$$R_{t+1} \geq D_{t+1} - (1-k)L_{t+1} \tag{44}$$

$$R_{t+1} \geq \frac{l}{\Upsilon(1+r_d)}\left[1 + r_d - \frac{1}{\theta_D}\right] D_{t+1} - \frac{e^{-2\sigma_Z}}{\Upsilon(1+r_d)} L_{t+1} \tag{45}$$

We now turn to the analysis at time $t+1$, the decision time, and we discuss the decision process for liquidity surplus bank $D_{t+1} = D_t \cdot \theta_D$ and liquidity deficit bank $D_{t+1} = D_t / \theta_D$, respectively.

Liquidity Surplus Bank:

The cash flow to shareholders is $e_{s,t} = W_t + L_t - R_{t+1} - L_{t+1} + (\theta_D - 1)D_t$ if $e_{s,t} > 0$, and $e_{s,t}(1+\kappa)$ if $e_{s,t} < 0$, we assume in this simplified model that liquidity surplus bank's deposit is high enough such that its cash flow is positive, and thus the surplus bank's (the interbank market lender) maximization function at time $t+1$, will be

$$E_{s,t} = e_{s,t} + \beta \mathbb{E}_t\left[e_{s,t+1}\right] = [W_t + L_t - R_{t+1} - L_{t+1} + (\theta_D - 1)D_t] + \beta \max\Big\{ Z_{p,t+1} \cdot e^{0.5\sigma_Z^2} L_{t+1}^{\alpha} + \left(1 + \epsilon R_{t+1}^{\varphi-1}\right)\Upsilon R_{t+1} + L_{t+1} + \frac{1}{2}[\theta_D{}^2 - 2(2+r_d)\theta_D + 1]D_t, 0\Big\} \tag{46}$$

Subject to

$$R_{t+1} \geq 0,\;\; L_{t+1} \geq 0 \tag{47}$$

$$R_{t+1} \geq \frac{1}{\Upsilon\left(1+\epsilon R_{t+1}^{\varphi-1}\right)}[(1+r_d)\theta_D - 1]D_t - \frac{1+e^{-2\sigma_Z}}{\Upsilon\left(1+\epsilon R_{t+1}^{\varphi-1}\right)} L_{t+1} \tag{48}$$

$$R_{t+1} \geq \theta_D D_t - (1-k)L_{t+1} \tag{49}$$

$$R_{t+1} \geq \frac{l}{\Upsilon\left(1+\epsilon R_{t+1}^{\varphi-1}\right)}[(1+r_d)\theta_D - 1]D_t - \frac{e^{-2\sigma_Z}}{\Upsilon\left(1+\epsilon R_{t+1}^{\varphi-1}\right)} L_{t+1} \tag{50}$$

Liquidity Deficit Bank:

Similarly, the cash flow to the liquidity deficit bank is as follows:

$$E_{d,t} = e_{d,t} + \beta \mathbb{E}_t\left[e_{d,t+1}\right] = \left[W_t + L_t + R_{t+1} - L_{t+1} + \left(\frac{1}{\theta_D} - 1\right) D_t\right](1+\gamma\kappa) + \beta \max\Big\{ Z_{p,t+1} \cdot e^{0.5\sigma_Z^2} L_{t+1}^{\alpha} - \left(1 + \epsilon R_{t+1}^{\varphi-1}\right) R_{t+1} + L_{t+1} + \frac{1}{2\theta_D{}^2}[\theta_D^2 - 2(2+r_d)\theta_D + 1]D_t, 0\Big\} \tag{51}$$

Subject to $$R_{t+1} \geq 0,\ \ L_{t+1} \geq 0 \tag{52}$$

$$R_{t+1} \leq \frac{1+e^{-2\sigma_Z}}{1+\epsilon R_{t+1}^{\varphi-1}} L_{t+1} - \frac{1}{\left(1+\epsilon R_{t+1}^{\varphi-1}\right)\theta_D^2}[(1+r_d)\theta_D - 1]D_t \tag{53}$$

$$R_{t+1} \leq (1-k)L_{t+1} - \frac{1}{\theta_D} D_t \tag{54}$$

$$R_{t+1} \leq \frac{e^{-2\sigma_Z}}{1+\epsilon R_{t+1}^{\varphi-1}} L_{t+1} - \frac{l}{\left(1+\epsilon R_{t+1}^{\varphi-1}\right)\theta_D^2}[(1+r_d)\theta_D - 1]D_t \tag{55}$$

We now turn to the analysis for loan investment L_{t+1} and interbank lending R_{t+1} respectively for the above two banks before they enter the interbank market, at which point interbank lending amount is just proposed by banks and is subject to change due to unmatched lending and borrowing. To distinguish this mismatch, we denote $\widehat{R_{t+1}}$ as the amount that banks originally proposed and R_{t+1} as the amount that is finally settled in the market.

Firstly, for the liquidity surplus bank, the Lagrange equation with respect to L_{t+1} and R_{t+1} are:

$$\frac{\partial E_{s,t}}{\partial R_{t+1}} = -1 - \beta\Upsilon\left(1+\epsilon\varphi R_{t+1}^{\varphi-1}\right) + \zeta_1^R + \zeta_2^R + \zeta_3^R + \zeta_4^R = 0 \tag{56}$$

$$\frac{\partial E_{s,t}}{\partial L_{t+1}} = -1 + \beta[ϡ(L_{t+1}) + 1] + \zeta_1^L + \zeta_2^L + \zeta_3^L + \zeta_4^L = 0 \tag{57}$$

where $\zeta_1^R \sim \zeta_4^R$ and $\zeta_1^L \sim \zeta_4^L$ are the Kuhn-Tucker multipliers for Equations (47)~(50) respectively for L_{t+1} and R_{t+1}. In addition, $ϡ(L_{t+1}) = \beta\alpha\, Z_{p,t+1} \cdot e^{0.5\sigma_Z^2} L_{t+1}^{\alpha-1}$, and we can show that $ϡ(L_{t+1})$ is strictly decreasing with L_{t+1}, and $\epsilon\varphi R_{t+1}^{\varphi-1}$ is strictly decreasing with R_{t+1}. For simplicity, we assume $-1 + \beta\Upsilon\left(1+\epsilon\varphi R_{t+1}^{\varphi-1}\right) = 0$ for some values and thus liquidity surplus bank will have positive amount to borrow without binding the constraint conditions. Thus, under this assumption, $\zeta_1^R \sim \zeta_4^R$ and $\zeta_1^L \sim \zeta_4^L$ all equal to zero, reducing the above equations to

$$\frac{\partial E_{s,t}}{\partial R_{t+1}} = -1 + \beta\Upsilon\left(1+\epsilon\varphi R_{t+1}^{\varphi-1}\right) = 0 \tag{58}$$

$$\frac{\partial E_{s,t}}{\partial L_{t+1}} = -1 + \beta[1 + ϡ(L_{t+1})] = 0 \tag{59}$$

Thus, the optimal amount of $L_{s,t+1}$ and $\widehat{R_{s,t+1}}$ before entering interbank market are determined by Equations (58) and (59). However, after the settlement of interbank market, the final interbank lending/borrowing is $R_{t+1} \leq \widehat{R_{s,t+1}}$.

Then, for the liquidity deficit banks, we first analyse the case when the constraint does not bind, i.e. $\varsigma_1^R \sim \varsigma_4^R$ and $\varsigma_1^L \sim \varsigma_4^L$ all equal to zero, which means:

$$\frac{\partial E_{d,t}}{\partial R_{t+1}} = 1 + \gamma\kappa - \beta\left(1 + \epsilon\varphi R_{t+1}^{\varphi-1}\right) > 0 \tag{60}$$

$$\frac{\partial E_{d,t}}{\partial L_{t+1}} = -(1 + \gamma\kappa) + \beta[\text{ƛ}(L_{t+1}) + 1] \leq 0 \tag{61}$$

Equation (60) indicates that in our calibration $\gamma\kappa > \beta\epsilon\varphi R_{t+1}^{\varphi-1}$, that is the refinancing cost is always higher than the cost of interbank borrowing, otherwise the bank will cope with the liquidity shocks by raising capital instead of borrowing through the interbank market. However, the condition of Equation (61) will not be positive, otherwise the bank will continuously raise capital to increase the loan investment, until it becomes an equality. Thus, we pay more attention to the case when the constraint binds. The Lagrange equation with respect to L_{t+1} and R_{t+1} are rewritten as:

$$\frac{\partial E_{d,t}}{\partial R_{t+1}} = 1 + \gamma\kappa - \beta\left(1 + \epsilon\varphi R_{t+1}^{\varphi-1}\right) + \varsigma_1^R - \varsigma_2^R - \varsigma_3^R - \varsigma_4^R = 0 \tag{62}$$

$$\frac{\partial E_{d,t}}{\partial L_{t+1}} = -(1 + \gamma\kappa) + \beta[\text{ƛ}(L_{t+1}) + 1] + \varsigma_1^L + \varsigma_2^L + \varsigma_3^L + \varsigma_4^L = 0 \tag{63}$$

where $\varsigma_1^R \sim \varsigma_4^R$ and $\varsigma_1^L \sim \varsigma_4^L$ are the Kuhn-Tucker multipliers for Equations (52)~(55) respectively for L_{t+1} and R_{t+1}. Comparing Equation (58) and (62), we can notice that interbank supply/demand surplus is largely dependent on the stringency of requirement constraints.

Proposition 1. ***(Interbank Market Borrowing/Lending.)*** *The surplus of interbank lending/borrowing depends on the stringency of the requirement constraints. Normally a stricter requirement will constraint deficit bank's interbank borrowing and thus result in an interbank lending surplus. On the contrary, a loose requirement will realize an interbank borrowing surplus.*

This Proposition implies that due to the fact that liquidity deficit bank will be more likely to bind the requirement constraint, its interbank borrowing will significantly be affected by the stringency of the requirements. Moreover, the loan investment of the liquidity deficit bank will also be influenced by the requirement constraints, from Equation (63) we can notice that once the requirement constraint binds, the optimal loan investment will be reduced if refinancing cost γ is too high or the constraint is too strict which limits the access of raising capital from interbank borrowing. In addition, when we turn to the analysis of banks' loan adjustment behaviours when the interbank supply/demand is not fully satisfied, we can notice the following results. Due to the marginal return on loan investment $\beta[\lambda(L_{t+1}) + 1] = 1$, the liquidity surplus bank will not be willing to increase loan investment as the marginal return will be below than that of distributing to shareholders, the return of which is 1, if further loan investment is added. However, the liquidity deficit bank need to raise external funds at the cost of $1 + \gamma\kappa$ if interbank borrowing is not fully satisfied, while the marginal revenue of investing in loans is $\beta[\lambda(L_{t+1}) + 1] = 1 + \gamma\kappa - \varsigma_n^L < 1 + \gamma\kappa$. Thus, the bank will never raise capital to expand or even maintain the loan investment scale if the interbank borrowing is not satisfied. That is to say, the liquidity deficit bank will be prone to reduce the loan investment as in the adjustment after interbank settlement. Appendix A gives an alternative proof for liquidity deficit bank's reduction in loan investment after interbank settlement.

Proposition 2. ***(Unmatched interbank market.)*** *The unmatched interbank supply and demand will not increase liquidity surplus banks' loan investment due to its lower marginal return, and it will distribute the money to the shareholders. However, due to the high cost of raising external capital, the liquidity deficit bank will generally reduce loan investment if the interbank demand is not fully satisfied.*

Our proposition suggests that in order to maintain the loan investment scale for economy growth, the central bank should use intervention by lending to the liquidity deficit bank to prevent it from curtailing loan investment once the interbank demand is not fully satisfied. Moreover, we can notice that liquidity deficit banks are more likely to bind the requirement constraints, and from the Equations (56) ~ (61) the idiosyncratic liquidity shocks, although will trigger liquidity deficit bank's borrowing by introducing a negative current cash flow, will not affect banks' interbank lending/borrowing position while it is the counterparty risk effect and refinancing costs that determine the banks' position.

5. Simulation Results

The parameters we will use for simulation is summarized in Table 1. The time period is set to one year in order to reflect the fact that corporate tax is levied once a year. However, some of the pioneering work, like Gourio (2012), set the time period as one quarter, and in order to adopt their parameter values, parameter moderation (introduced in Online Appendix) is conducted.

<Insert Table 1 here>

The persistence and standard deviation of transitory shocks are adopted from Gourio (2012). Based on the moderation method described in the Online Appendix, we can thus set $\rho = 0.25$. The choice of standard deviation of transitory risk is set at $\sigma_r = 0.144$, which is close to the average transitory risk standard deviation adopted by Hajda (2017). The annual persistence and standard deviation of deposits are from De Nicolo *et al.* (2014) who use annual data for analysis, and we use their parameters for aggregate deposits simulation. Following the moderation method as described before, the drift $\tau = 0.02$ and standard deviation $\sigma_p = 0.04$ of the permanent shock are transformed from the parameters from Gourio (2012) whose values are quarterly. Similarly, the mean and standard deviation of additional transitory shocks when in recessions are set at $\mu_\varphi = -0.14$ and $\sigma_\varphi = 0.105$, using the data from Gourio (2012) and assuming the original persistence of transitory shocks is at 0.71.

The mean and standard deviation of additional deposit shocks is set at $\mu_{\text{ƕ}} = -0.0028$ and $\sigma_{\text{ƕ}} = 0.0180$ respectively, which closely mimics the estimates from Albuquerque & Schroth (2015). Meanwhile, in order to follow Gourio (2012), the adopted value for mean and standard deviation of the additional permanent shock in bad times are at $\mu_\emptyset = -0.028$ and $\sigma_\emptyset = 0.184$. The correlation between deposits and permanent risks $\theta = -0.85$ are from De Nicolo *et al.* (2014). The mean and standard deviation of idiosyncratic deposit fluctuation is set at $\mu_d = 0.48$ and $\sigma_d = 0.105$ respectively. The adoption of these values follows the estimates of core deposit fluctuation among banking sectors by Cornett *et al.* (2011). The conditional probability of switching to bad times from good times p and persistence of bad times q are both adopt from Repullo & Suarez (2012) which utilizes Markov process to indicate the expected duration of recessions and booms are 2.8 and 5 years, respectively. The return to loan investment $\alpha = 0.9$ are adopted from Zhu (2008) and De Nicolo *et al.* (2014), along with the annual percentage of reimbursed loan $\sigma = 20\%$ to imply that the average maturity of outstanding loans is four years, which is line with Van den Heuvel (2009). As in Equation (13) and following the assumption with De Nicolo *et al.* (2014), we set the loan adjustment cost when $I_t > 0$ at $m = 0.03$. As in Hugonnier & Morellec (2017), we set the annual deposit managing costs per unit at $\vartheta = 0.003$, but to ease the computation the deposit rate is normalized to $r_d = 0\%$, as in De Nicolo *et al.* (2014).

Moreover, the equity floating rate is set at $\kappa = 0.08$ in order to keep in line with Altinkilic & Hansen (2000) for an early evidence and Hennessy & Whited (2005 & 2007) for a relative recent support. For simplicity, we adopt $\gamma = 1.5$, which means the liquidity deficit banks are suffering from an additional refinancing cost three halves as the liquidity surplus banks. The bankruptcy costs is adopted from Repullo (2013) who uses $c = 0.20$ for computation. Note that although based on Hennessy & Whited (2007) the costs related to U.S. nonfinancial firms is estimated at 0.104, this figure is from nonfinancial sectors and might only be able to treated as a lower bound for financial institutions (De Nicolo *et al.*, 2014). Accordingly, we double this estimate to ensure it is very close to the value that is used by Repullo (2013). The value for nominal rate on interbank lending is adopted at $r_i = 3.5\%$ that is very close to the estimation of Filipovic & Trolle (2013), but 100 basis point above the estimation of Corbae & D' Erasmo (2018), and following their data we adopt $\varphi = 0.95$ for the simulation. Worst-case probability of counterparty default is set at $\varpi = 0.97$, which follows the estimation conducted by Arora *et al.* (2012) from using the bankruptcy survey results during the recent financial crises around 2009. The time discount factor is set at $\beta = 0.99$, equals to that used by Zhu (2008) and Cooley & Quadrini (2001). As in De Nicolo *et al.* (2014), the corporate tax rate for positive and negative earnings are at $\epsilon^+ = 15\%$ and $\epsilon^- = 0\%$, respectively. Lastly, the parameters for banking regulation is set at $k = 8\%$ and $h = 20\%$ for capital and liquidity requirements, respectively (Repullo & Suarez, 2013 and De Nicolo *et al.*, 2014).

5.1 Simulation Results

In this section, we present our baseline results for banks which are unregulated, are under capital requirement and are under liquidity requirement. For the ease of comparison and display, we show them respectively in the subsequent subsections.

5.1.1 Impulse Responses

<Insert Figures 4 and 5 here>

We firstly display the impulse responses of interbank trading volume and loan investment to the exogenous shocks, including the permanent shock $Z_{p,t}$, transitory shocks $Z_{r,j,t}$ and deposit amount shock $D_{j,t}$. The results are reported in Figures 4 and 5, respectively for the scenarios when under capital and liquidity requirements. The responses are similar for both banks across the regulation regimes, while the permanent shock causes a notable effect on banks' loan investment which hardly dies away even after the 30th period due to the shock's permanent impact. When considering idiosyncratic liquidity shocks, we can notice that exogenous shocks, especially the permanent shock, will cause a similar impact to liquidity surplus/deficit bank's loan investment, but they will create opposite impacts on interbank lending. To be specific, interbank market will exert a negative effect on the liquidity surplus bank, while a positive effect on the deficit bank. Moreover, when comparing with these two different regulations, we can notice that banks' reactions are more significant when under capital requirement (maximum at around 3 standard deviation changes) than the liquidity requirement (maximum at 0.2 standard deviation changes) as the result of one standard deviation changes in permanent shocks. The changes in loan investment are also smoother when under the liquidity requirement regime. These results in a way suggests that liquidity requirement is more effective in stabilizing the economy during the financial fluctuations.

5.1.2 Unregulated Banks

The simulated results for unregulated banks are given in Table 2.

<Insert Table 2 here>

As shown in Table 2, the liquidity surplus banks normally invest more (2.84) in the loan market, with a lower standard deviation (i.e. volatility) in terms of the loan investment (1.89), compared with the liquidity deficit banks. More interestingly, as we point out in **Proposition 2**, due to the unmatched interbank borrowing/lending, all the banks reduce the final loan investment amount from 3.04 (2.76) to 2.84 (2.53) respectively for the liquidity surplus and deficit banks, after the interbank settlement. In both cases, the reason is the lower marginal revenue of investing additional unit of loan. Bank $j = 1$ and bank $j = -1$ have nearly the same portfolio for all the results, indicating the fact of the equal likelihood of encountering idiosyncratic liquidity shocks. From the row *Interbank (Before)* we can notice that under the no banking regulation, the overall interbank demand (absolute value of -0.79) is higher than the interbank supply (0.65), meaning that liquidity deficit banks need more interbank borrowing than the counterparty could provide. The final overall interbank market is settled at the averaged value of 0.42, with a standard deviation of 0.51. The value of the liquidity surplus banks is around 4.10, which is nearly double that of the liquidity deficit banks (2.01). The probability of the liquidity deficit banks is averaged at 3.68%, while it is nearly zero for the liquidity surplus banks. The unconditional averaged probability of default is around 1.84%. The overall social welfare is at 7.54, after aggregating the value of the two banks, the government tax revenue and payment for the bankruptcy costs and the depositors' principal and interests.

5.1.3 Capital Requirement

The simulated results for banks that are under capital requirements ($k = 8\%$) are presented in Table 3.

<Insert Table 3 here>

From Table 3, we can notice that the results under the capital requirements are similar to that of the banks under no regulation as in the **Table 2**. Liquidity surplus banks are holding a higher amount of loan investment, averaged at 2.85, than liquidity deficit banks (around 2.56), but with a lower volatility which is averaged at 1.91 (compared with the deficit counterpart at 2.08). The interbank market is as active as in the unregulated banks, with the average 0.42 borrowing/lending amount. Similarly, there exists an interbank demand surplus (the absolute value of -0.78), which means a shortage of interbank supply (to the value of 0.66). The bank value is marginally higher than the unregulated banks, and the probability of the default is slightly lower (averaged at 1.81% compared with 1.84% for the unregulated banks), especially for the liquidity deficit banks. The government value is nearly the same, while the total social value (7.60) is higher than that of the unregulated banks (7.54), which indicates that capital requirement will help to increase social welfare. Moreover, the total loan investment (averaged at 2.72) is higher than that of the unregulated banks (averaged at 2.70), and this result is highly consistent for other loan investment scenarios, including liquidity surplus/deficit banks before/after interbank settlement. Our results regarding social welfare and loan investment is in line with the De Nicolo *et al.* (2014), who suggest that after the introduction of capital requirement, banks will increase the loan investment, resulting in an overall social welfare increase although at an insignificant value[25].

5.1.4 Capital and Liquidity Requirements

The results for banks under both capital requirement ($k = 8\%$) and liquidity requirement ($h = 20\%$) are shown in Table 4 below.

<Insert Table 4 here>

Table 4 shows the simulated results for the banks subject to the capital and liquidity requirements. We can notice that after the introduction of the liquidity requirement, the average loan investment amount reduces to 2.63, from 2.70 (unregulated banks) and 2.72 (capital requirements). The average bank value reduces to 2.99, while the value of liquidity

[25] Refer to the Table 5 of De Nicolo *et al.* (2014) for details. It shows that social welfare increases from 12.52 to 12.58 after a 4% capital requirement regime is introduced and the increase trend of which is very similar to ours.

deficit bank is marginally improved by 0.01, compared with the capital requirement regime. If we combine this result with the probability of default, we can indicate that liquidity requirement will to some degree help to maintain liquidity deficit bank value by reducing its probability of bankruptcy. Social welfare is the lowest, at the value of 7.38, compared with other regimes. Our results in terms of the loan investment and social welfare are also in line with De Nicolo *et al.* (2014) who maintain that liquidity requirement unambiguously reduces lending and welfare.

Bankruptcy probability is the lowest among other regulation regimes and the main reason for this is that the liquidity deficit bank failure is significantly reduced to 3.15%. This result is in line with Hugonnier & Morellec (2017) who suggest liquidity requirement will reduce the likelihood of default. Interestingly, we can infer from **Table 4** that, unlike other regulation regimes discussed, after the introduction of liquidity requirement there is an excess of interbank supply to the value of 0.68, compared with the interbank demand at 0.59 (the absolute value of -0.59). The resulting interbank market is thus the least active, to the value of 0.37. This insight justifies our **Proposition 1**, that with a stricter regulation regime, i.e. liquidity requirement, there will be an overall interbank supply surplus due to liquidity deficit bank's more impaired interbank borrowing ability. Lastly, the interbank supply is nearly stable at around 0.66 for all regulation regimes, while the interbank demand notably reduces to -0.59 (capital & liquidity requirements) from -0.78 (no regulation), which indicates that liquidity deficit banks are more likely to be affected by the regulation regimes, especially in the interbank market.

5.2 Bailouts, counterparty risk and central bank interbank intervention

In this section, we present the results for banks that are under the government bailout policy and are subject to the central bank intervention for interbank markets. We give the results in Table 5 and Table 6 respectively.

<Insert Table 5 here>

Table 5 shows the results regarding the bailout policy to the banks when insolvent, as a response to **Section 3.3**. The results are given by banks under capital requirement only, and under both capital and liquidity requirements, both of which depict similar results. When bailout is exclusive to a certain bank (Bank $j = 1$), the average loan investment amount of the counterparty, e.g. Bank $j = -1$, significantly reduces from 2.72 (2.63) to 2.32 (2.49), under capital and capital & liquidity requirements respectively. This is because the interbank lending is a safer way for investment, as the counterparty risk for Bank $j = 1$ is removed due to the bailout policy. This can be verified by the significant increase in interbank lending for Bank $j = -1$, when conditional bailout policy is exclusively carried out with respect to the Bank $j = 1$. The bank's value is reduced due to the lesser amount invested in the loan market. The overall social welfare decreases to 6.89 and 7.26 for both scenarios. Interestingly, unlike with our baseline scenario, the liquidity requirement outperforms the capital requirement. The rationale behind this result is that the liquidity requirement dramatically restricts banks' ability to borrow, and thus limits interbank market lending activity, which stimulates the banks incentives to invest in loans. This can be verified by the facts that the overall loan investment amount is higher (2.61) under the liquidity requirement than under the capital requirement (2.45). However, when the bailout policy is unconditionally applied to all the banks, the overall loan investment scale further reduces to 2.04 (2.07) for capital (capital & liquidity) requirement regimes. The social welfare decreases further to 5.93 and 6.79 respectively. The interbank market is more active, with the trading volume around 0.52 and 0.47, implying that with the introduction of bailout policy and the removal of counterparty risk all the banks prefer to invest in the safer interbank market. Moreover, the liquidity requirement outperforms the capital requirement in terms of the social welfare, due to a higher loan investment amount around 2.07 than under the capital requirement (at 2.04). This insight indicates that under certain circumstances, liquidity requirement will help to improve social welfare by sustaining bank lending.

<Insert Table 6 here>

Table 6 gives the results for government intervention in the interbank market. Firstly, we investigate the case when the intervention was exclusively provided to liquidity deficit banks. When only capital requirement is implemented, loan investment of liquidity deficit banks increases substantially from 2.56 to 3.62, making the average loan investment amount 3.67 (compared with that of 2.72 for our baseline results). Liquidity surplus banks also increase their loan investment, due partially to the increase in interbank settlement from 0.42 to 0.63, which encourages banks to invest instead of distributing to shareholders. The social welfare increases to 10.92 as the result of the increased loan investment, although the bankruptcy probability doubles to 3.82% due to a higher share of risky loan investment within banks' asset portfolio. When liquidity requirement is added, the social welfare increases further to 11.73, while the loan investment volumes marginally increase to 3.74 (compared with 3.67

when intervention is only offered to liquidity deficit banks). The marginal increase lies in the fact that liquidity surplus banks are less affected by the loan investment reduction once the interbank lending is not satisfied. When under the liquidity requirement regime, the result is similar, although the changes are less pronounced because of the strict regulation that highly constrains banks' borrowing or lending ability from the interbank market or from the central bank intervention. Consequently, we can conclude that intervening in the interbank market will help to sustain the overall loan investment activity and thus contribute to the social welfare, and the effect of intervening in the liquidity deficit banks is more significant. Although the social welfare also increases when liquidity surplus banks are helped, this effect is limited if the central bank intervention is costly (e.g. if the intervention costs the central bank an additional fee to inject funds into banks). This can be seen from the result that central bank intervention volume increases notably from 0.49 (0.26) to 1.20 (0.77) under capital (capital & liquidity) requirement. That is to say, when central bank intervention is costly, providing assistance exclusively to liquidity deficit banks will be more efficient.

5.3 Additional tests

In this section, we conduct some additional tests, including sensitivity analysis, in order to investigate the effects of different parameters on our simulated results. We present our results in Table 7 and Table 8, respectively.

5.3.1 Regulatory regimes

<Insert Table 7 here>

Table 7 shows the results for banks under different regulation regimes, for different level of these regulations. In our baseline analysis, the capital requirement and liquidity requirement are adopted at $k = 8\%$ and $h = 20\%$ respectively. We then run separate simulation procedures when capital requirement is under $k = 4\%$ and $k = 12\%$, in order to investigate banks' behaviours when they are subject to a looser and a stricter capital requirement. The first half of Table 7 shows the results. Social welfare is at 7.20 and 7.06 when $k = 4\%$ and $k = 12\%$. The probability of default is respectively at 3.80% and 3.60%, which indicates that a stricter capital requirement will help to reduce banks' probability of default. The overall interbank market demonstrates a demand surplus for all level of capital requirements. Interestingly, similarly to De Nicolo *et al.* (2014), our results also demonstrates an inverted

U-shaped relationship between capital requirement and welfare. The welfare is highest in our baseline results, when $k = 8\%$, decreasing to lower values when $k = 4\%$ and $k = 12\%$.

On the other hand, for the liquidity requirement, the inverted U-shaped relationship is less pronounced. The welfare term is highest when $h = 10\%$, standing at the value of 7.78, while this value is lowest when $h = 50\%$. The reason behind this is that the imposed liquidity requirement largely limits banks' borrowing/lending volume when faced with liquidity shocks, and thus banks will be prone to reducing the overall loan investment. Moreover, this result indicates there should an optimal level of liquidity requirement, $h = 10\%$ in our calibration, which improves the social welfare (at the value of 7.78) compared with no liquidity requirement (baseline result at 7.60).

5.3.2 Sensitivity analysis

<Insert Table 8 here>

Table 8 demonstrates some additional tests for banks under capital and liquidity requirements when varying some key parameters. We firstly investigate the effects of permanent and transitory shocks to the overall banking system. We increase the volatility of these two shocks in turn while keeping the total volatility constant, as in Hajda (2017). From the results in Table 8, we can identify that with the increase in the risk component of permanent and transitory shocks, the overall loan investment amount improves, because with the increase in the volatility the expected loan investment return increases. The impacts of transitory shocks are higher, given the fact the volatility increase ratio is the same as with the persistent shocks. Moreover, the increase in the transitory shock volatility notably decreases the interbank market activity: the overall interbank market lending/borrowing amount is only around 0.08 for both capital and capital & liquidity requirement regimes, while this amount is not pronounced for the permanent shocks. The explanation for this lies in the fact that transitory shocks are idiosyncratic and banks will have less dependency on each other through the interbank market, while the changes in permanent shocks are systemic and thus banks are more connected with each other through the interbank, making the trading volume 0.03 higher than our baseline case.

In the case of the idiosyncratic liquidity shocks, we find that when these are more volatile, the overall loan investment amount reduces, due partially to the fact that the interbank market cannot fully resolve this idiosyncratic shock and thus banks have to reduce the loan investment, which in turn impairs social welfare. As expected, the decrease in this value is more pronounced when under liquidity requirement regime, which largely disables bank's borrowing ability when facing extreme liquidity shocks. When the refinancing cost increases, it is more costly for all the banks to raise equity, and the liquidity surplus bank becomes more cautious about lending, due to the existence of counterparty risk. Thus, we can justify our proposition from the finding that the difference in interbank demand and supply before the interbank settlement rises from $0.14\ (= 0.78 - 0.66)$ and $-0.09\ (= 0.59 - 0.68)$ to $0.32\ (= 0.82 - 0.50)$ and $-0.02\ (= 0.63 - 0.65)$ for banks under capital and capital & liquidity requirement. This result confirms that when equity refinancing cost increases, liquidity deficit banks are more eager to borrow while liquidity surplus banks are less motivated to lend. Consequently, social welfare decreases under both regulation regimes.

When the duration of the expected recession increases, banks suffer from a lower loan investment return, and thus the resulting social welfare reduces notably. The probability of default increases for both banks and for both regulation regimes. Interestingly, in this scenario, the liquidity requirement outperforms the capital requirement, in terms of social welfare 6.53 (6.06). The reason behind this is that the liquidity requirement further limits banks' participation in the interbank market, and thus banks have to maintain loan investment in order to obtain revenue. We can justify our conjecture by using the highlighted results in **Table 8**, which show that the overall amount of bank lending is maintained at around 2.60, compared with 2.45 for the baseline result, when under the liquidity requirement regime. However, for the capital requirement regime, the loan investment amount only averages at 2.27, although the average loan investment is at around 2.72 in our baseline result. This insight suggests that, under some extreme cases such as financial crises, liquidity requirement might outperform the capital requirement by helping to maintain loan investment scale and thus stabilize social welfare. This result shares a similar trend for the case regarding the higher loan adjustment costs. As highlighted in Table 8, social welfare is higher (at 7.43) for banks under liquidity requirement than that of capital requirement (averaged at 7.09). The rationale behind this is similar: liquidity requirement helps to stabilize loan investment volume (at 2.67), higher than 2.56 for the capital requirement. This finding indicates that when adjusting loan amount is costly, banks are more likely to maintain the loan investment even though the expected loan investment return is not high enough. In addition, the liquidity requirement further boosts this situation by limiting banks' choice in interbank market, which in turn discourages banks from moving funding from loan market to interbank market. Thereby, the loan investment scale and social welfare is maintained. The significant increase in the probability of default for liquidity surplus banks when under the liquidity requirement regime might be attributed to the fact that liquidity surplus banks invest more in loans, which will cause more loss to the banks, especially in the financial crisis. However, this notable increase in the probability of bankruptcy does not impair social welfare but increase the welfare instead. This result suggests that the liquidity requirement will help to stabilize loan investment during the financial crisis to boost economic growth. Finally, in order to investigate the impacts of financial crises, we reduce the drift of loan investment revenue and find that with an impaired economy situation the interbank market is deactivated. This helps to explain the cause of the breakdown of the interbank market during the recent financial crisis, from 2007-2009. However, when referring to the case of transitory shock volatility we can conclude that there might be a novel reason to explain the failure of the interbank market, namely transitory shocks. As before, the social welfare is higher under liquidity requirement, indicating that liquidity requirement outperforms the capital requirement when in recessions.

5.4 Summary

In Section 5, we conducted a series of tests to investigate the effects of different levels of regulation regimes and parameters on the overall interbank activity, loan investment and the resulting social welfare. We firstly compared the results for different regulation regimes and found that capital requirement outperformed other regimes, which is in line with some existing literature. We also found an unbalanced interbank supply and demand, where there is an interbank demand surplus under the mild requirement (capital requirement) and an interbank supply surplus under the stricter requirement (liquidity requirement).

We have contributed to the literature by finding that bailout policy will discourage banks from investing in the loan market as the potential rescue by the government removes the counterparty risks within the interbank, and thus more investment flows into the safer interbank market. Central bank intervention in the interbank market will help to sustain the overall loan investment amount and as a result raise the social welfare. The intervention in the liquidity deficit banks will be more efficient if the interbank intervention is costly.

Moreover, we have identified the existence of the inverted U-shaped relationship between social welfare and the capital requirement, which is consistent with the findings of existing literature; however, this U-shaped relationship is less pronounced under the liquidity requirement. We have also revealed that liquidity requirement is not always suboptimal; it will outperform the capital requirement in certain situations, such as in extreme events such as financial crises. More interestingly, we found that increase in the portion of transitory risk volatility would noticeably deactivate the interbank market activity, though lacking in empirical support, suggesting the breakdown of interbank market during the financial crises might because the shocks are mainly transitory, not permanent, which will die away after couple of years. This finding offers a novel way of interpreting the interbank market failure: The transitory risk component increases and thereby results in the interbank market breakdown.

6. Conclusion

In this paper, we consider an economy in which banks use the interbank market to manage idiosyncratic liquidity shocks, and are subject to the same source of permanent shock but specific transitory shocks. Banks are operated under different regulatory regimes and choose optimal level of loan investment and interbank trading volume. We evaluate different requirements' impact to social welfare and reveal the merits and limitations of governmental bailout policy and central bank intervention in the interbank market.

We link banks' interbank activity with loan investment decisions and demonstrate that failure to satisfy interbank lending/borrowing demand will unambiguously discourage banks from lending, and this effect is more pronounced for liquidity deficit banks. The interbank activities are highly contingent on the regulation regimes: under mild requirement regime (i.e. the capital requirement), there is an interbank demand surplus; under strict regime (i.e. the liquidity requirement) there arises an interbank supply surplus. Bailout policy will divert banks to invest more in the interbank market, resulting in a reduction in loan investment and social welfare income. Central bank intervention in the interbank will encourage banks to lend, especially in the case of the liquidity deficit banks, and thus contribute to the social welfare growth. Normally, the liquidity requirement will reduce the social welfare by limiting interbank borrowing and loan lending but will make banks safer. However, under some extreme scenarios, such as recessions, the liquidity requirement will help to stabilize the loan lending and thus outperform the capital requirement in terms of the welfare metric.

Our work illuminates a way forward for future empirical studies. These could focus on the relationship between interbank trading activities and the loan investment market, especially for the banks that benefit from the interbank relationship lending that enables them to obtain liquidity faster than from the bond issuance. This will test our findings and thus will link our theoretical model with empirical studies. Moreover, future empirical studies should investigate the changes in the component of permanent and transitory risk during financial crises, testing whether our new interpretation of interbank market breakdown is plausible or not. We conclude our paper by conducting the limitations of our paper and provide some extensions for future research. Bond issuance should be considered to make the model more realistic and multiple bank analysis should also be conducted: In our paper there are only two banks. Moreover, considering the effects of systemic importance will further generalize our model and be in line with the implementation of the Basel III Accord, which regards Global *Systemically Important Financial Institutions* (SIFI) as the main concerns (BIS, 2011).

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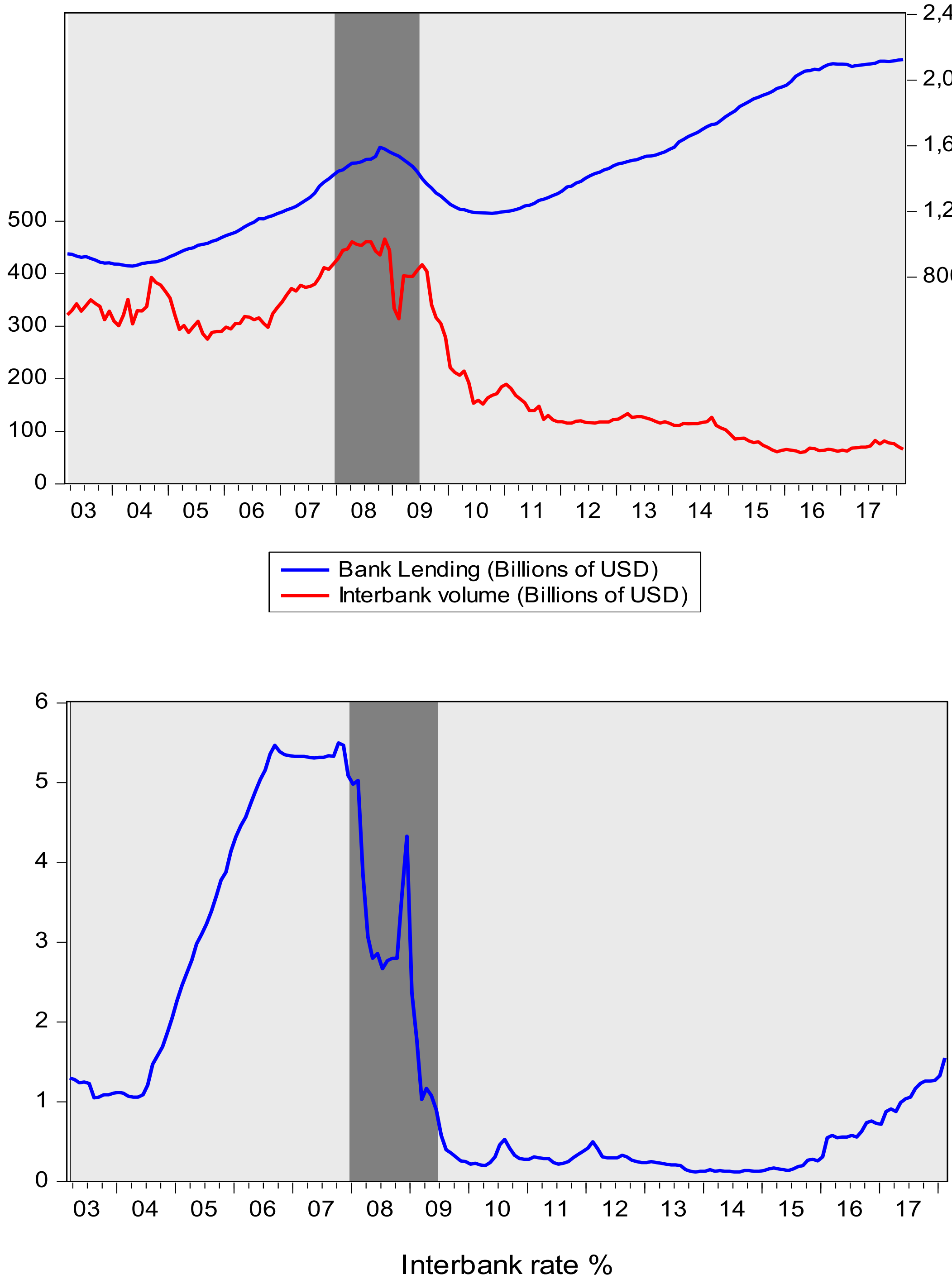
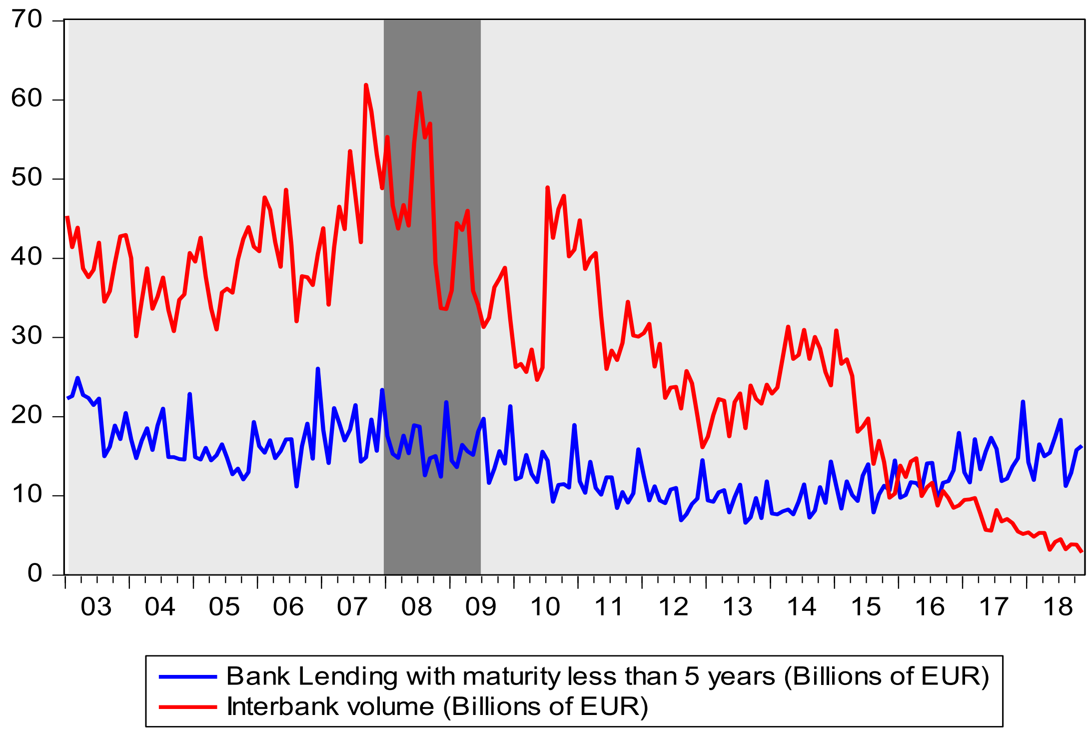


Figure 1 US banking lending, interbank volume and interbank rate
The figure shows the US market statistics, which is collected from the dataset of Federal Reserve Bank of St. Louis and the Federal Reserve Bank System. The data is calibrated monthly and ranges from March 2003 to February 2018 due to data constraint and to keep in line with the data horizon of Euro-zone, and the interbank rate is the 1 month rate. The shaded area indicates the financial recessions within the time horizon, which is from 2007-12-01 to 2009-06-01, as in the NBER recession data.



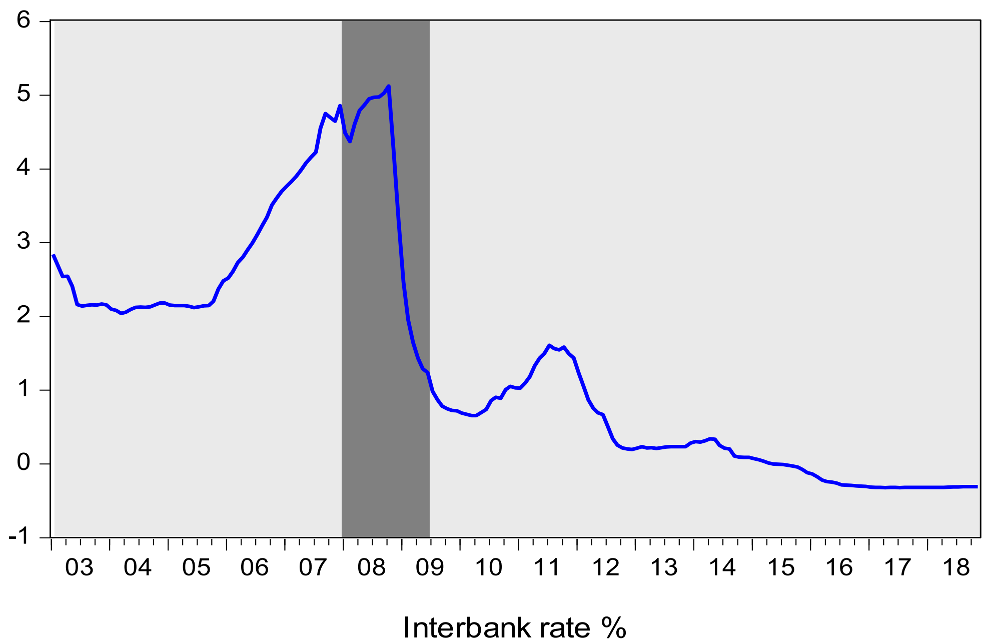


Figure 2 Euro-Zone banking lending, interbank volume and interbank rate
The figure shows the Euro-zone market statistics, which is collected from the dataset of European Central Bank. The data is calibrated monthly and ranges from January 2003 to November 2018 due to data constraint and to keep in line with the data horizon of US market, and the interbank rate is the 1 month rate. The shaded area indicates the financial recessions within the time horizon, which is from 2007-12-01 to 2009-06-01, as in the NBER recession data.

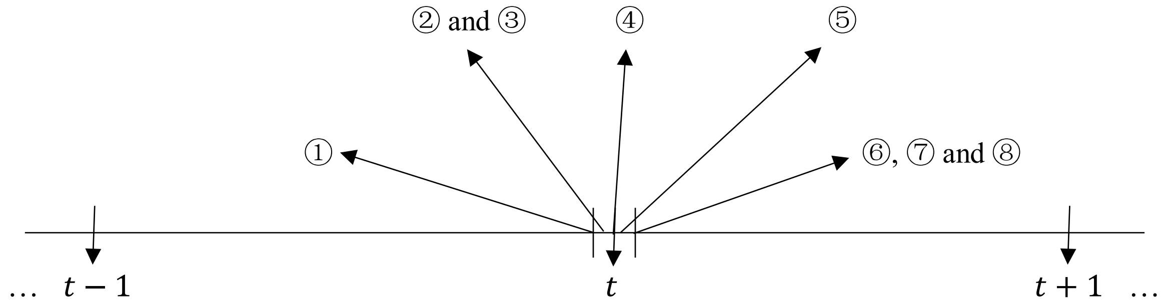


Figure 3
Banks' dynamic
Valuation of banks' each period cash flow with exogenous credit shock Z_t, liquidity shock D_{t+1} and investment strategies (L_{t+1}, R_{t+1}), assuming banks are solvent. The numbers in the figure indicates the order of the event sequence.

Time Sequence:

① Investment revenue $Z_{j,t}$ realized, interbank lending matured and deposit interest $r_d D_{j,t}$ got paid.

② Bankruptcy is uncertain as banks can rely on interbank.

③ Time t corporate tax $\varsigma(y_{j,-j,t})$ levied.

④ New deposits $D_{j,t+1}$ realized, causing liquidity shock if $D_{j,t+1} - D_{j,t} < 0$.

⑤ New investment strategies (L_{t+1}, R_{t+1}) determined.

⑥ Cash Flow e_t realizes.

⑦ Additional equity cost will be occurred if $e_t < 0$.

⑧ Bankruptcy if interbank lending insufficient and $E_t = 0$.

Table 1
Baseline parameters

Notations	Description	Value
ρ	Annual persistence of the log of transitory shocks	0.25
σ_r	Annual conditional standard deviation of the log of transitory shocks	0.144
ω_D	Annual persistence of the log of deposits	0.98
σ_D	Annual conditional standard deviation of the log of deposits	0.0209
$\overline{D}$	Unconditional average of deposits	£2
σ_p	Annual conditional standard deviation of log of permanent shocks	0.04
τ	Annual unconditional drift of the log of permanent shocks	0.02
μ_φ	Mean of the shocks to the log of transitory shocks in bad times	-0.14
σ_φ	Standard deviation of shocks to the log of transitory shocks in bad times	0.105
$\mu_{\text{ƕ}}$	Mean of the shocks to the log of deposits in bad times	-0.0028
$\sigma_{\text{ƕ}}$	Standard deviation of shocks to the log of deposits in bad times	0.0180
$\mu_\emptyset$	Mean of the shocks to the log of permanent shocks in bad times	-0.028
$\sigma_\emptyset$	Standard deviation of shocks to the log of permanent shocks in bad times	0.184
θ	Correlation between log-deposit and permanent shocks	-0.85
μ_d	Mean of the idiosyncratic deposit fluctuation	0.48
σ_d	Standard deviation of the idiosyncratic deposit fluctuation	0.105
p	Conditional probability of switching to bad times from good times	0.20
q	Persistence of bad times	0.64
α	Return to scale for loan investment	0.90
σ	Annual percentage of reimbursed loan	20%
m	Constant loan adjustment cost	0.03
r_d	Annual rate on deposits	0%
ϑ	Annual deposit managing costs	0.003
κ	Equity flotation costs	0.08
c	Bankruptcy costs	0.20
r_i	Nominal rate on interbank borrowing/lending	3.5%
ϖ	Worst-case probability of counterparty default	0.97
β	Time discount factor	0.99
ϵ^+	Corporate tax rate for positive earnings	15%
ϵ^-	Corporate tax rate for negative earnings	0%
k	Capital requirement ratio	8%
h	Liquidity requirement ratio	20%

Note: The distribution of transitory shocks is truncated to negative values, as in Gourio (2012) and Nakamura *et al.* (2013). The simulation and approximation for this truncated normal distribution is described in the Appendix.

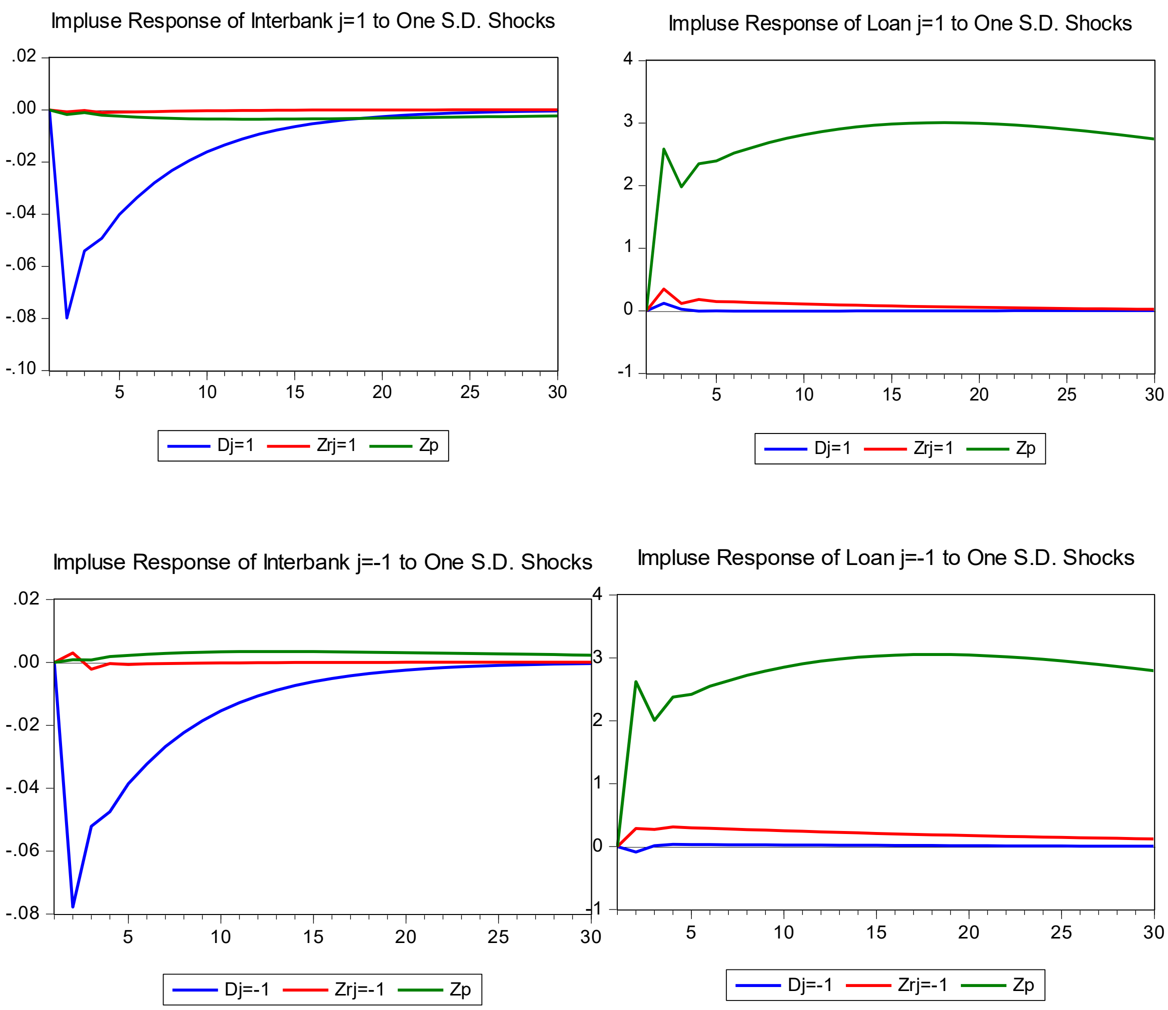


Figure 4 (a): Capital requirement and impulse response I

The figure shows the impulse response of bank $j = 1$ and bank $j = -1$, when subject to capital requirement, due to the permanent shock (labelled as Z_p) and respective deposit amount shock (labelled as $Z_{rj=\pm 1}$) and transitory shock (labelled as $D_{j=\pm 1}$). The data is from the simulated series. The shocks happen at time 0, with one standard deviation change, and the responses are calibrated with standard deviation changes from the 'steady state' after the shocks. All the parameters are adopted from Table 1.

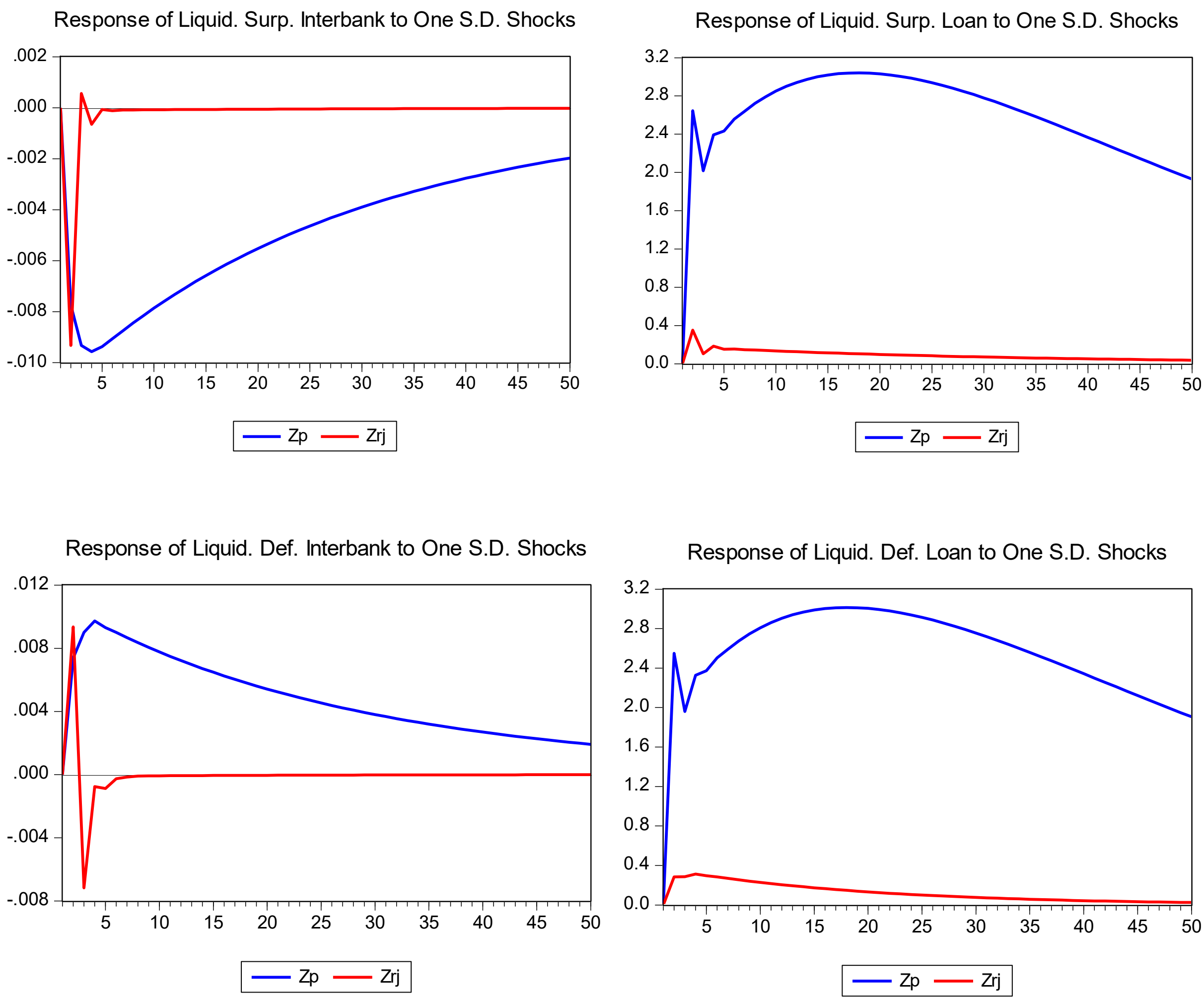


Figure 4 (b): Capital requirement and impulse response II

The figure shows the impulse response of liquidity surplus banks and liquidity deficit banks, when subject to capital requirement, due to the permanent shock (labelled as Z_p) and transitory shock (labelled as Z_{rj}). The data is from the simulated series. The shocks happen at time 0, with one standard deviation change, and the responses are calibrated with standard deviation changes from the 'steady state' after the shocks. All the parameters are adopted from Table 1.

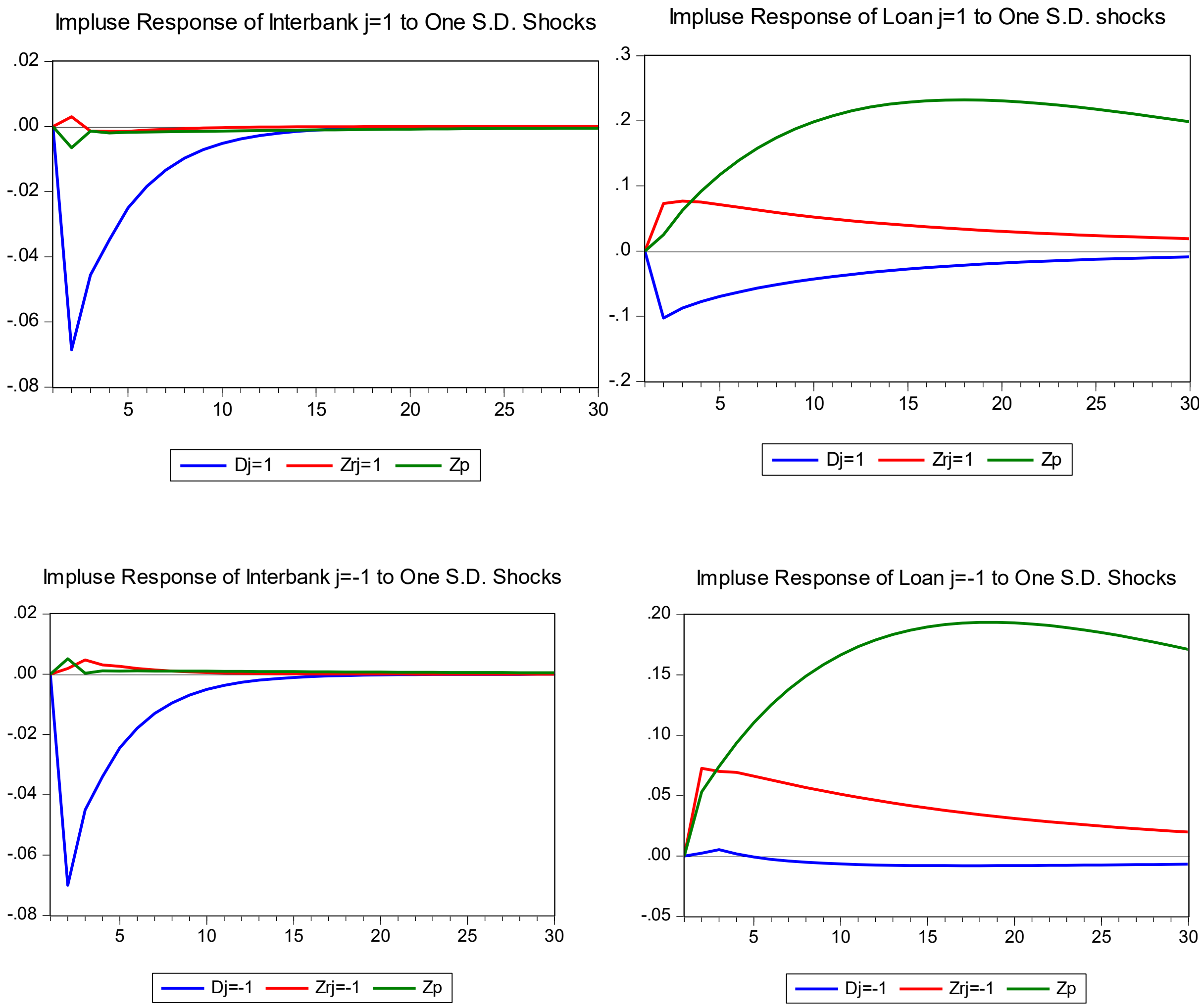


Figure 5 (a): Liquidity requirement and impulse response I
The figure shows the impulse response of bank $j = 1$ and bank $j = -1$, when subject to capital and liquidity requirements, due to the permanent shock (labelled as Z_p) and respective deposit amount shock (labelled as $Z_{rj=\pm1}$) and transitory shock (labelled as $D_{j=\pm1}$). The data is from the simulated series. The shocks happen at time 0, with one standard deviation change, and the responses are calibrated with standard deviation changes from the 'steady state' after the shocks. All the parameters are adopted from Table 1.

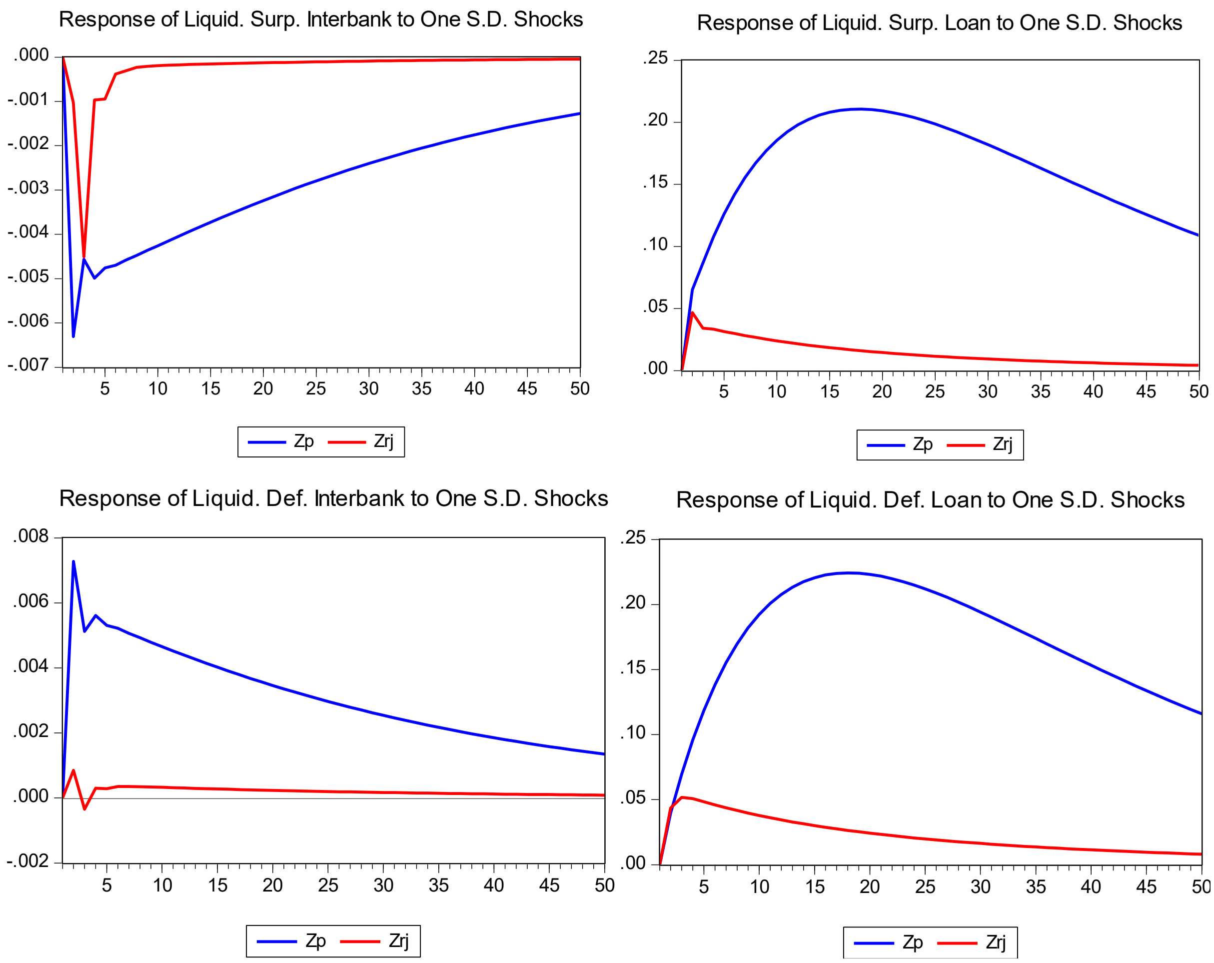


Figure 5 (b): Liquidity requirement and impulse response II
The figure shows the impulse response of liquidity surplus banks and liquidity deficit banks, when subject to capital and liquidity requirements, due to the permanent shock (labelled as Z_p) and transitory shock (labelled as Z_{rj}). The data is from the simulated series. The shocks happen at time 0, with one standard deviation change, and the responses are calibrated with standard deviation changes from the 'steady state' after the shocks. All the parameters are adopted from Table 1.

Table 2
Unregulated banks

The table presents the results of the banks under no regulation, but are subject to collateral constraints. The results are obtained using the value function in Equation (25)and the simulation steps are described in the Appendix B, using the parameter values in Table 1. The *Liquid. Def. Bank* and *Liquid. Surp. Bank* represents the liquidity deficit banks (whose idiosyncratic liquidity shock is positive) and liquidity surplus banks (whose idiosyncratic liquidity shock is negative) respectively, which is adopted from Bank $j = \pm 1$. In order to drop the extreme values of Z_p due to its instability and to highlight our interest, we disregard the observations where the de-trended *Social Welfare* Value are above 100 and are below 0.1 and when the liquidity deficit banks are in the interbank supply. After this truncation, we have 98687 observations left, which means around one fifth of the simulated observations are obtained for the investigation. Note that in the *Interbank (Before & After)* column we report the absolute value of the interbank lending/borrowing for Bank $j = \pm 1$ Average, instead of the real value the sum of which is nearly zero. The results of this table are the averages across the simulated results of the time-series averages of the cross-sectional averages. All the results are divided by the concurrent log $D_t/Z_{p,t}$ to remove the dependency of $Z_{p,t}$.

Unregulated			
	Liquid. Def. Bank	Liquid. Surp. Bank	Bank $j = \pm 1$ Average
Loans (Before)	2.76	3.04	2.91
Loans (After)	2.53	2.84	2.70
Std. Dev. Loan (After)	2.10	1.89	1.99
Interbank (Before)	-0.79	0.65	0.72
Interbank (After)	-0.42	0.42	0.42
Std. Dev. Interbank (After)	0.51	0.51	0.51
Bank Value	2.01	4.10	3.06
Bankruptcy Prob.	3.68%	0.02%	1.84%
Government Value		1.06	
Other Sector Value		-0.01	
Social Welfare		7.54	

Table 3
Banks under capital requirement

The table presents the results of the banks under the capital regulation only, at the level of $k = 8\%$. The results are obtained using the value function in Equation (25) and the simulation steps are described in the Appendix B, using the parameter values in Table 1. The *Liquid. Def. Bank* and *Liquid. Surp. Bank* represents the liquidity deficit banks (whose idiosyncratic liquidity shock is positive) and liquidity surplus banks (whose idiosyncratic liquidity shock is negative) respectively, which is adopted from Bank $j = \pm 1$. In order to drop the extreme values of Z_p due to its instability and to highlight our interest, we disregard the observations where the de-trended *Social Welfare* Value are above 100 and are below 0.1 and when the liquidity deficit banks are in the interbank supply. After this truncation, we have 97262 observations left, which means around one fifth of the simulated observations are obtained for the investigation. Note that in the *Interbank (Before & After)* column we report the absolute value of the interbank lending/borrowing for Bank $j = \pm 1$ Average, instead of the real value the sum of which is nearly zero. The results of this table are the averages across the simulated results of the time-series averages of the cross-sectional averages. All the results are divided by the concurrent $\log D_t / Z_{p,t}$ to remove the dependency of $Z_{p,t}$.

Capital Requirement ($k = 8\%$)			
	Liquid. Def. Bank	Liquid. Surp. Bank	Bank $j = \pm 1$ Average
Loans (Before)	2.78	3.05	2.93
Loans (After)	2.56	2.85	2.72
Std. Dev. Loan (After)	2.08	1.91	2.00
Interbank (Before)	-0.78	0.66	0.71
Interbank (After)	-0.42	0.42	0.42
Std. Dev. Interbank (After)	0.50	0.50	0.50
Bank Value	2.03	4.13	3.08
Bankruptcy Prob.	3.63%	0.02%	1.81%
Government Value		1.07	
Other Sector Value		-0.01	
Social Welfare		7.60	

Table 4
Banks under capital requirement and liquidity requirement

The table presents the results of the banks under the capital and liquidity regulation, at the level of $k = 8\%$ and $h = 20\%$ respectively. The results are obtained using the value function in Equation (25) and the simulation steps are described in the Appendix B, using the parameter values in Table 1. The *Liquid. Def. Bank* and *Liquid. Surp. Bank* represents the liquidity deficit banks (whose idiosyncratic liquidity shock is positive) and liquidity surplus banks (whose idiosyncratic liquidity shock is negative) respectively, which is adopted from Bank $jj = \pm 1$. In order to drop the extreme values of Z_p due to its instability and to highlight our interest, we disregard the observations where the de-trended *Social Welfare* Value are above 100 and are below 0.1 and when the liquidity deficit banks are in the interbank supply. After this truncation, we have 101329 observations left, which means around one fifth of the simulated observations are obtained for the investigation. Note that in the *Interbank (Before & After)* column we report the absolute value of the interbank lending/borrowing for Bank $j = \pm 1$ Average, instead of the real value the sum of which is nearly zero. The results of this table are the averages across the simulated results of the time-series averages of the cross-sectional averages. All the results are divided by the concurrent $\log D_t / Z_{p,t}$ to remove the dependency of $Z_{p,t}$.

Capital Requirement ($k = 8\%$) & Liquidity Requirement ($h = 20\%$)			
	Liquid. Def. Bank	Liquid. Surp. Bank	Bank $j = \pm 1$ Average
Loans (Before)	2.71	2.97	2.84
Loans (After)	2.51	2.78	2.63
Std. Dev. Loan (After)	2.07	1.89	1.98
Interbank (Before)	-0.59	0.68	0.63
Interbank (After)	-0.37	0.37	0.37
Std. Dev. Interbank (After)	0.43	0.43	0.43
Bank Value	2.04	3.94	2.99
Bankruptcy Prob.	3.15%	0.02%	1.59%
Government Value		1.04	
Other Sector Value		-0.01	
Social Welfare		7.38	

Table 5
Bailouts and counterparty risk
The table presents the results of the banks when government bailout policy is anticipated in the case of the bankruptcy, when they are under capital requirements and capital and liquidity requirements respectively. The *Baseline* results is the case when there is no government bailout, as in Table 3 and Table 4. The column *Bailout to Bank* $j = 1$ refers to the scenario when only Bank $j = 1$ will be bailed out when it fails and the column *Bailout to all banks* presents the results when all the banks are sponsored by the government. For the ease of comparison, we display the results for Bank $j = 1$ and Bank $j = -1$ and the average of both. The column *Std. Dev. Loan (After)* stands for the standard deviation of loans after interbank settlement, *Std. Dev. Interbank (After)* represents the standard deviation of interbank lending/borrowing after the interbank settlement, and *Bankruptcy Prob.* is the bankruptcy probability of the banks. The results for *Interbank (Before & After)* is the absolute value for the interbank lending/borrowing which is introduced to feature the vitality of the interbank, while *Interbank Real (Before)* is included to record the actual interbank lending/borrowing amount in order to feature the banks' interbank net position. All the simulation results are truncated within the results whose *Social Welfare* Value are above 100 and are below 0.1 and when the liquidity deficit banks are in the interbank supply to remove the influence of the extreme values of $Z_{p,t}$. The results of this table are the averages across the simulated results of the time-series averages of the cross-sectional averages. All the results are divided by the concurrent log $D_t/Z_{p,t}$ to remove the dependency of $Z_{p,t}$.

Capital Requirement ($k = 8\%$)	Baseline			Bailout to Bank $j = 1$			Bailout to all banks		
	Bank $j = 1$	Bank $j = -1$	$j = \pm 1$ Average	Bank $j = 1$	Bank $j = -1$	$j = \pm 1$ Average	Bank $j = 1$	Bank $j = -1$	$j = \pm 1$ Average
Loans (Before)	2.90	2.95	2.93	2.78	2.68	2.73	2.30	2.27	2.29
Loans (After)	2.68	2.72	2.70	2.58	2.32	2.45	2.06	2.01	2.04
Std. Dev. Loan (After)	2.05	1.95	2.00	1.94	2.11	2.03	2.03	2.04	2.03
Interbank (Before)	0.73	0.69	0.71	0.83	0.91	0.87	0.82	0.83	0.82
Interbank Real (Before)	0.02	-0.06	-0.04	-0.19	-0.02	-0.11	-0.08	-0.04	-0.06
Interbank (After)	0.42	0.42	0.42	0.42	0.42	0.42	0.52	0.52	0.52
Std. Dev. Interbank (After)	0.50	0.50	0.50	0.53	0.53	0.53	0.53	0.53	0.53
Bank Value	3.05	3.11	3.08	2.67	2.91	2.79	2.01	1.94	1.96
Bankruptcy Prob.	1.86%	1.77%	1.81%	0.00%	2.66%	1.33%	0.00%	0.00%	0.00%
Government Value		1.07			0.97			0.87	
Other Sector Value		-0.01			-0.01			0.00	
Social Welfare		7.60			6.89			5.93	

Capital & Liquidity Requirements ($k = 8\%, h = 20\%$)	Baseline			Bailout to Bank $j = 1$			Bailout to all banks		
	Bank $j = 1$	Bank $j = -1$	$j = \pm 1$ Average	Bank $j = 1$	Bank $j = -1$	$j = \pm 1$ Average	Bank $j = 1$	Bank $j = -1$	$j = \pm 1$ Average
Loans (Before)	2.84	2.83	2.84	2.86	2.77	2.82	2.33	2.30	2.32
Loans (After)	2.66	2.63	2.63	2.73	2.49	2.61	2.09	2.05	2.07
Std. Dev. Loan (After)	2.02	1.94	1.98	1.86	2.05	1.96	1.99	2.00	2.00
Interbank (Before)	0.64	0.62	0.63	0.58	0.68	0.63	0.68	0.66	0.68
Interbank Real (Before)	0.07	-0.02	0.03	-0.06	0.16	0.05	0.10	0.03	0.07
Interbank (After)	0.37	0.37	0.37	0.39	0.39	0.39	0.40	0.40	0.40
Std. Dev. Interbank (After)	0.43	0.43	0.43	0.44	0.44	0.44	0.47	0.47	0.47
Bank Value	2.97	3.03	2.99	2.81	3.08	2.95	2.36	2.33	2.34
Bankruptcy Prob.	1.54%	1.59%	1.57%	0.00%	2.06%	1.03%	0.00%	0.00%	0.00%
Government Value		1.04			1.02			0.84	
Other Sector Value		-0.01			-0.01			0.00	
Social Welfare		7.38			7.26			6.79	

Table 6
Government intervention in interbank market

The table presents the results of the banks when central bank intervention in interbank is anticipated, when they are under capital requirements and capital and liquidity requirements respectively. The *Baseline* results is the case when there is no central bank intervention, as in Table 3 and Table 4. The column *Provide to Deficit Banks* refers to the scenario when central bank only provide interbank lending when liquidity deficit bank's demand is not fully satisfied from the interbank market and the column *Provide to all banks* presents the results when all the banks are intervened once the interbank market fails to satisfy any supply or demand. For the ease of comparison, we display the results for Liquidity Deficit Bank (represented by *Def. Bank*), Liquidity Surplus Bank (represented by *Surp. Bank*) and the average of both (represented by *Bank Average*). The column *Std. Dev. Loan (After)* stands for the standard deviation of loans after interbank settlement, *Std. Dev. Interb. (After)* represents the standard deviation of interbank lending/borrowing after the interbank settlement, and *Bankruptcy Prob.* is the bankruptcy probability of the banks. *Central Bank Interv.* refers to the total cash provided by the central bank to satisfy the uneven supply/demand through the interbank, and in order to capture the total volume sponsored by the central bank we report this result in an absolute value. All the simulation results are truncated within the results whose *Social Welfare* Value are above 100 and are below 0.1 and when the liquidity deficit banks are in the interbank supply to remove the influence of extreme values of $Z_{p,t}$. The results of this table are the averages across the simulated results of the time-series averages of the cross-sectional averages. All the results are divided by the concurrent log $D_t/Z_{p,t}$ to remove the dependency of $Z_{p,t}$.

Capital Requirement ($k = 8\%$)	Baseline			Provide to Deficit Banks			Provide to all banks		
	Def. Bank	Surp. Bank	Bank Average	Def. Bank	Surp. Bank	Bank Average	Def. Bank	Surp. Bank	Bank Average
Loans (Before)	2.78	3.05	2.93	4.03	4.27	4.15	4.01	4.22	4.12
Loans (After)	2.56	2.85	2.72	3.62	3.72	3.67	3.69	3.79	3.74
Std. Dev. Loan (After)	2.08	1.91	2.00	2.25	2.27	2.26	2.18	2.19	2.18
Interbank (Before)	-0.78	0.66	0.71	-1.18	0.80	0.99	-1.18	0.90	1.04
Interbank (After)	-0.42	0.42	0.42	-0.63	0.63	0.63	-0.70	0.70	0.70
Std. Dev. Interb. (After)	0.50	0.50	0.50	0.86	0.86	0.86	0.88	0.88	0.88
Bank Value	2.03	4.13	3.08	3.00	4.56	3.78	3.30	4.95	4.13
Bankruptcy Prob.	3.63%	0.02%	1.81%	5.69%	1.94%	3.82%	5.02%	1.30%	3.16%
Central Bank Interv.		0.00			0.49			1.20	
Government Value		1.07			1.70			1.83	
Other Sector Value		-0.01			-0.02			-0.02	
Social Welfare		7.60			10.92			11.73	

Capital & Liquidity Requirements ($k = 8\%, h = 20\%$)	Baseline			Provide to Deficit Banks			Provide to all banks		
	Def. Bank	Surp. Bank	Bank Average	Def. Bank	Surp. Bank	Bank Average	Def. Bank	Surp. Bank	Bank Average
Loans (Before)	2.71	2.97	2.84	3.19	3.36	3.23	3.15	3.41	3.28
Loans (After)	2.51	2.78	2.63	2.81	2.97	2.89	2.93	3.09	3.01
Std. Dev. Loan (After)	2.07	1.89	1.98	2.18	2.12	2.15	2.16	2.09	2.13
Interbank (Before)	-0.59	0.68	0.63	-0.77	0.74	0.75	-0.77	0.80	0.78
Interbank (After)	-0.37	0.37	0.37	-0.48	0.48	0.48	-0.50	0.50	0.50
Std. Dev. Interb. (After)	0.43	0.43	0.43	0.77	0.77	0.77	0.78	0.78	0.78
Bank Value	2.04	3.94	2.99	3.07	3.92	3.50	3.42	4.34	3.88
Bankruptcy Prob.	3.15%	0.02%	1.59%	4.91%	0.53%	2.72%	4.22%	0.26%	2.24%
Central Bank Interv.		0.00			0.26			0.77	
Government Value		1.04			1.23			1.36	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.38			8.66			9.59	

Table 7
Capital and liquidity requirement

The table presents the results of the banks under different capital and liquidity regulation regimes. The first column depicts the results under the baseline regulations as in Table 3 and Table 4. The second and third column shows a looser and stricter regulation compared with our baseline regulation regimes to compare the effects of these regulations. The results are obtained using the value function in Equation (25) and the simulation steps are described in the Appendix B, using the parameter values in Table 1. In order to drop the extreme values of Z_p due to its instability and to highlight our interest, we disregard the observations where the de-trended *Social Welfare* Value are above 100 and are below 0.1 and when the liquidity deficit banks are in the interbank supply. Note that in the *Interbank (Before & After)* column we report the absolute value of the interbank lending/borrowing for Bank Average, instead of the real value the sum of which is nearly zero. The results of this table are the averages across the simulated results of the time-series averages of the cross-sectional averages. All the results are divided by the concurrent log $D_t/Z_{p,t}$ to remove the dependency of $Z_{p,t}$.

Capital Requirement	$(k = 8\%, h = 0\%)$			$(k = 4\%, h = 0\%)$			$(k = 12\%, h = 0\%)$		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.78	3.05	2.93	2.66	2.95	2.81	2.62	2.91	2.77
Loans (After)	2.56	2.85	2.72	2.43	2.74	2.59	2.39	2.70	2.54
Std. Dev. Loan (After)	2.08	1.91	2.00	2.10	1.91	2.01	2.08	1.90	1.99
Interbank (Before)	-0.78	0.66	0.71	-0.78	0.61	0.70	-0.78	0.60	0.70
Interbank (After)	-0.42	0.42	0.42	-0.41	0.41	0.41	-0.41	0.41	0.41
Std. Dev. Interbank (After)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Bank Value	2.03	4.13	3.08	1.92	3.92	2.92	1.86	3.86	2.86
Bankruptcy Prob.	3.63%	0.02%	1.81%	3.80%	0.02%	1.91%	3.60%	0.01%	1.79%
Government Value		1.07			1.01			0.99	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.60			7.20			7.06	

Capital & Liquidity Requirements	$(k = 8\%, h = 20\%)$			$(k = 8\%, h = 10\%)$			$(k = 8\%, h = 50\%)$		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.71	2.97	2.84	2.84	3.09	2.96	2.71	2.92	2.81
Loans (After)	2.51	2.78	2.60	2.67	2.92	2.79	2.39	2.70	2.54
Std. Dev. Loan (After)	2.07	1.89	1.98	2.01	1.84	1.92	2.10	1.92	2.02
Interbank (Before)	-0.59	0.68	0.63	-0.52	0.66	0.61	-0.59	0.74	0.66
Interbank (After)	-0.37	0.37	0.37	-0.31	0.31	0.31	-0.40	0.40	0.40
Std. Dev. Interbank (After)	0.43	0.43	0.43	0.38	0.38	0.38	0.52	0.52	0.52
Bank Value	2.04	3.94	2.99	2.23	4.08	6.31	1.87	3.86	2.86
Bankruptcy Prob.	3.15%	0.02%	1.59%	2.75%	0.01%	1.39%	3.90%	0.02%	1.96%
Government Value		1.04			1.09			0.99	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.38			7.78			7.07	

Table 8
Sensitivity analysis
The table presents the results for the sensitivity analysis when banks are under capital and capital & liquidity requirements respectively. The results are obtained using the value function in Equation (25) and the simulation steps are described in the Appendix B, using the parameter values in Table 1. For the ease of comparison, the first column of each row is the results of our baseline analysis, when capital requirement ($k = 8\%$) or capital and liquidity requirements ($k = 8\%, h = 20\%$) are imposed respectively. The first test is for the *Higher permanent shock volatility* which is conducted to make $\sigma_p = 0.48$ and $\sigma_\emptyset = 0.22$ (all multiplied by 1.2 with our baseline parameter). To rule out the effect of the total volatility, we also change the parameter for the transitory shock parameters to make $\sigma_{TOTAL} = \sqrt{\sigma_P^2 + \sigma_T^2}$ constant. The column *Higher transitory shock volatility* is conducted by using $\sigma_r = 0.17$ and $\sigma_\varphi = 0.126$ (all multiplied by 1.2 with our baseline parameter), and the parameters for the permanent shocks are also modified to ensure $\sigma_{TOTAL} = \sqrt{\sigma_P^2 + \sigma_T^2}$ is a constant. The test entitled *Higher idiosyncratic liquidity volatility* changes the volatility of the idiosyncratic liquidity shocks from 0.105 (baseline parameter) to 0.126, and keeps the drift of the idiosyncratic liquidity shocks constant. The test *Higher refinancing cost* is conducted by doubling $\kappa = 0.08$ in our baseline analysis to $\kappa = 0.16$. *Longer recession duration* test changes q, the persistence of bad times, from 0.64 to $q = 0.80$. As in Repullo & Suarez (2012), the expected recession period time is defined as $(1 - q)^{-1}$, which means the expected bad time period is changed from 2.8 years to 5 years. The test *Higher loan adjustment cost* is finished by altering $m = 0.03$ (in our baseline analysis) to $m = 0.06$. The term *Lower revenue drift in normal times* refers to the case when the permanent shock drift τ is set to 0.00 (reduced by 0.02 compared with the baseline parameter $\tau = 0.02$). Similarly, the term *Lower revenue drift in bad times* presents the results when $\mu_\emptyset = -0.084$, compared with the baseline parameter $\mu_\emptyset = -0.028$, the decreased value is set to ensure the expected value of the drift decrease is the same as the case *Lower revenue drift in normal times*, after considering the expected probability of encountering bad times to 0.36. In order to drop the extreme values of Z_p due to its instability and to highlight our interest, we disregard the observations where the de-trended *Social Welfare* Value are above 100 and are below 0.1 and when the liquidity deficit banks are in the interbank supply. Note that in the *Interbank (Before & After)* column we report the absolute value of the interbank lending/borrowing for Bank $j = \pm 1$ Average, instead of the real value the sum of which is nearly zero. The results of this table are the averages across the simulated results of the time-series averages of the cross-sectional averages. All the results are divided by the concurrent log $D_t/Z_{p,t}$ to remove the dependency of $Z_{p,t}$.

Capital Requirement ($k = 8\%$)	Baseline			Higher permanent shock volatility			Higher transitory shock volatility		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.78	3.05	2.93	2.79	3.06	2.94	3.21	3.33	3.27
Loans (After)	2.56	2.85	2.72	2.56	2.84	2.72	3.08	3.24	3.16
Std. Dev. Loan (After)	2.08	1.91	2.00	2.10	1.93	2.02	1.47	1.27	1.37
Interbank (Before)	-0.78	0.66	0.71	-0.82	0.66	0.74	-0.44	0.03	0.25
Interbank (After)	-0.42	0.42	0.42	-0.45	0.45	0.45	-0.08	0.08	0.08
Std. Dev. Interbank (After)	0.50	0.50	0.50	0.47	0.47	0.47	0.42	0.42	0.42
Bank Value	2.03	4.13	3.08	2.00	4.19	3.09	3.20	4.38	3.79
Bankruptcy Prob.	3.63%	0.02%	1.81%	3.72%	0.01%	1.87%	1.58%	0.00%	0.79%
Government Value		1.07			1.07			1.35	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.60			7.64			9.33	

Capital & Liquidity Requirements ($k = 8\%, h = 20\%$)	Baseline			Higher permanent shock volatility			Higher transitory shock volatility		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.71	2.97	2.84	3.26	3.31	3.28	3.44	3.47	3.45
Loans (After)	2.51	2.78	2.60	3.10	3.21	3.16	3.34	3.43	3.39
Std. Dev. Loan (After)	2.07	1.89	1.98	1.84	1.80	1.82	1.21	1.10	1.16
Interbank (Before)	-0.59	0.68	0.63	-0.58	0.89	0.74	-0.34	0.10	0.22
Interbank (After)	-0.37	0.37	0.37	-0.41	0.41	0.41	-0.08	0.08	0.08
Std. Dev. Interbank (After)	0.43	0.43	0.43	0.36	0.36	0.36	0.34	0.34	0.34
Bank Value	2.04	3.94	2.99	2.57	4.59	3.58	3.48	4.71	4.10
Bankruptcy Prob.	3.15%	0.02%	1.59%	1.46%	0.01%	0.74%	0.58%	0.00%	0.29%
Government Value		1.04			1.27			1.47	
Other Sector Value		-0.01			-0.01			-0.00	
Social Welfare		7.38			8.85			10.08	

Capital Requirement	Baseline			Higher idiosyncratic liquidity volatility			Higher refinancing cost		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.78	3.05	2.93	2.76	3.03	2.91	2.68	3.05	2.87
Loans (After)	2.56	2.85	2.72	2.53	2.82	2.65	2.34	2.84	2.59
Std. Dev. Loan (After)	2.08	1.91	2.00	2.09	1.92	2.01	2.09	1.95	2.02
Interbank (Before)	-0.78	0.66	0.71	-0.81	0.65	0.69	-0.82	0.50	0.66
Interbank (After)	-0.42	0.42	0.42	-0.44	0.44	0.44	-0.36	0.36	0.36
Std. Dev. Interbank (After)	0.50	0.50	0.50	0.53	0.53	0.53	0.55	0.55	0.55
Bank Value	2.03	4.13	3.08	1.97	4.13	3.05	2.03	4.05	3.04
Bankruptcy Prob.	3.63%	0.02%	1.81%	3.76%	0.01%	1.88%	4.40%	0.10%	2.25%
Government Value		1.07			1.06			1.05	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.60			7.54			7.53	

Capital & Liquidity Requirements	Baseline			Higher idiosyncratic liquidity volatility			Higher refinancing cost		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.71	2.97	2.84	3.01	3.28	3.15	2.63	3.00	2.81
Loans (After)	2.51	2.78	2.60	2.43	2.68	2.56	2.49	2.68	2.59
Std. Dev. Loan (After)	2.07	1.89	1.98	2.14	2.04	2.19	2.17	2.07	2.12
Interbank (Before)	-0.59	0.68	0.63	-0.53	0.72	0.69	-0.63	0.65	0.64
Interbank (After)	-0.37	0.37	0.37	-0.33	0.33	0.33	-0.32	0.32	0.32
Std. Dev. Interbank (After)	0.43	0.43	0.43	0.44	0.44	0.44	0.49	0.49	0.49
Bank Value	2.04	3.94	2.99	1.99	3.68	2.84	1.98	3.83	2.91

Bankruptcy Prob.	3.15%	0.02%	1.59%	4.84%	0.06%	2.45%	3.48%	0.04%	1.76%
Government Value		1.04			1.03			1.03	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.38			7.14			7.13	

Capital Requirement	Baseline			Longer recession duration			Higher loan adjustment cost		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.78	3.05	2.93	2.34	2.68	2.52	2.63	2.93	2.78
Loans (After)	2.56	2.85	**2.72**	2.09	2.44	**2.27**	2.40	2.73	**2.56**
Std. Dev. Loan (After)	2.08	1.91	2.00	2.08	1.91	2.00	1.97	1.79	1.88
Interbank (Before)	-0.78	0.66	0.71	-0.76	0.50	0.63	-0.77	0.61	0.69
Interbank (After)	-0.42	0.42	0.42	-0.38	0.38	0.38	-0.40	0.40	0.40
Std. Dev. Interbank (After)	0.50	0.50	0.50	0.52	0.52	0.52	0.50	0.50	0.50
Bank Value	2.03	4.13	3.08	1.57	3.36	2.46	1.87	3.88	2.88
Bankruptcy Prob.	3.63%	0.02%	1.81%	4.32%	0.01%	2.17%	3.79%	0.01%	1.90%
Government Value		1.07			0.83			0.99	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.60			**6.06**			**7.09**	

Capital & Liquidity Requirements	Baseline			Longer recession duration			Higher loan adjustment cost		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.71	2.97	2.84	2.73	3.03	2.86	2.78	3.07	2.93
Loans (After)	2.51	2.78	**2.60**	2.31	2.60	**2.45**	2.52	2.81	**2.67**
Std. Dev. Loan (After)	2.07	1.89	1.98	2.09	1.96	2.03	1.97	1.84	1.91
Interbank (Before)	-0.59	0.68	0.63	-0.51	0.66	0.59	-0.52	0.73	0.63
Interbank (After)	-0.37	0.37	0.37	-0.32	0.32	0.32	-0.35	0.35	0.35
Std. Dev. Interbank (After)	0.43	0.43	0.43	0.41	0.41	0.41	0.40	0.40	0.40
Bank Value	2.04	3.94	2.99	1.82	3.46	2.64	2.11	3.90	3.01
Bankruptcy Prob.	3.15%	0.02%	1.59%	4.25%	1.97%	3.11%	3.40%	1.18%	2.29%
Government Value		1.04			0.88			1.03	
Other Sector Value		-0.01			-0.02			-0.01	
Social Welfare		7.38			**6.53**			**7.43**	

Capital Requirement	Baseline			Lower revenue drift in normal times			Lower revenue drift in bad times		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.78	3.05	2.93	1.91	2.29	2.10	1.92	2.30	2.11
Loans (After)	2.56	2.85	2.72	1.66	2.03	1.85	1.67	2.03	1.85
Std. Dev. Loan (After)	2.08	1.91	2.00	1.57	1.39	1.48	1.59	1.41	1.50

Interbank (Before)	-0.78	0.66	0.71	-0.71	0.40	0.56	-0.72	0.42	0.57
Interbank (After)	-0.42	0.42	0.42	-0.33	0.33	0.33	-0.35	0.35	0.35
Std. Dev. Interbank (After)	0.50	0.50	0.50	0.45	0.45	0.45	0.48	0.48	0.48
Bank Value	2.03	4.13	3.08	1.01	2.59	2.31	1.00	2.66	1.83
Bankruptcy Prob.	3.63%	0.02%	1.81%	4.61%	0.04%	2.33%	4.70%	0.03%	2.37%
Government Value		1.07			0.58			0.59	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.60			4.39			4.45	

Capital & Liquidity Requirements	Baseline			Lower revenue drift in normal times			Lower revenue drift in bad times		
	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average	Liquidity Deficit Bank	Liquidity Surplus Bank	Bank Average
Loans (Before)	2.71	2.97	2.84	2.03	2.39	2.21	2.04	2.40	2.22
Loans (After)	2.51	2.78	2.60	1.81	2.16	1.99	1.81	2.16	1.99
Std. Dev. Loan (After)	2.07	1.89	1.98	1.54	1.34	1.44	1.60	1.40	1.50
Interbank (Before)	-0.59	0.68	0.63	-0.50	0.51	0.51	-0.53	0.52	0.53
Interbank (After)	-0.37	0.37	0.37	-0.30	0.30	0.30	-0.32	0.32	0.32
Std. Dev. Interbank (After)	0.43	0.43	0.43	0.37	0.37	0.37	0.40	0.40	0.40
Bank Value	2.04	3.94	2.99	1.16	2.74	1.95	1.18	2.79	1.98
Bankruptcy Prob.	3.15%	0.02%	1.59%	3.96%	0.02%	1.99%	4.10%	0.03%	2.07%
Government Value		1.04			0.64			0.65	
Other Sector Value		-0.01			-0.01			-0.01	
Social Welfare		7.38			4.75			4.83	

Appendix

Alternative proof for liquidity deficit bank in Proposition 2

For unregulated banks, suppose the liquidity deficit banks bind the constraint before entering the interbank market. Thus, the following equation should be satisfied:

$$\widehat{R_{t+1}} = \frac{1+e^{-2\sigma z}}{1+r_d} L_{t+1} - \frac{1}{(1+r_d)\theta_D{}^2}[(1+r_d)\theta_D - 1]D_t$$

Once the interbank lending is not satisfied, namely $R_{t+1} < \widehat{R_{t+1}}$, the following constraint as determined by Equation (53) is satisfied. We then turn to analyse whether the loan investment L_{t+1} will be adjusted even though the constraint is satisfied. The FOC of Equation (51) with respect to L_{t+1} is as follows:

$$\beta\lambda'\left(L_{t+1}^{d,c,after}\right) = (1+\gamma\kappa) - \beta - \frac{1+e^{-2\sigma z}}{1+r_d}\mathrm{q}$$

where q is the Kuhn-Tucker multiplier for the condition $R_{t+1} \leq \frac{1+e^{-2\sigma z}}{1+r_d} L_{t+1} - \frac{1}{(1+r_d)\theta_D{}^2}[(1+r_d)\theta_D - 1]D_t$, where now R_{t+1} is the constant, have been settled down by the interbank market. Suppose banks will not reduce the loan investment, thus $\mathrm{q} = 0$ because the constraint will not bind. Comparing it with the pre-interbank settlement loan amount,

$$\beta\lambda'\left(L_{t+1}^{d,c}\right) = \left[1 - \frac{1+e^{-2\sigma z}}{1+r_d}\right](1+\gamma\kappa) + \beta e^{-2\sigma z}$$

we can notice that $\beta\lambda'\left(L_{t+1}^{d,c,after}\right) - \beta\lambda'\left(L_{t+1}^{d,c}\right) = \frac{1+e^{-2\sigma z}}{1+r_d}[1+\gamma\kappa - \beta(1+r_d)] > 0$, which means $L_{t+1}^{d,c,after} < L_{t+1}^{d,c}$, contradicting to the our assumption made before that banks will not reduce loan lending. Thus, banks will unambiguously reduce loan lending if the interbank lending is not fully satisfied. However, whether the condition $R_{t+1} = \frac{1+e^{-2\sigma z}}{1+r_d} \widetilde{L_{t+1}} - \frac{1}{(1+r_d)\theta_D{}^2}[(1+r_d)\theta_D - 1]D_t$ will bind again with the new loan lending amount $\widetilde{L_{t+1}}$ is undetermined because Equation (63) and the above equation will not contradict each other if $\mathrm{q} \geq 0$ and if $L_{t+1}^{d,c,after} < L_{t+1}^{d,c}$. This result also keeps in line with the banks that are under capital or liquidity requirement.

Online Appendix

NOT FOR PUBLICATION

A. Model Solution

A.1 Permanent Risk and Deposit Shock Discretization

Since we assume that permanent risk and deposit amount are negatively related, we can put the dynamic of $(\log Z_{p,t}, \log D_{t+1})$ in a VAR model, which can be shown as:

$$X_{j,t} = \bar{X} + PX_{t-1} + \xi_t + \chi_{j,U>0.5}\nabla_t \quad \text{(OA1)}$$

where

$$X_t = \begin{pmatrix} \log Z_{p,t} \\ \log D_{j,t+1} \end{pmatrix}, \qquad \bar{X} = \begin{pmatrix} \tau \\ (1-\omega_D)\log \bar{D} \end{pmatrix}, \qquad P = \begin{pmatrix} 1 & 0 \\ 0 & \omega_D \end{pmatrix}$$

and

$$\xi_t = \begin{pmatrix} \varepsilon_{p,t} + \emptyset_t x_t \\ \varepsilon_{D,t} + \text{ƕ}_t x_t \end{pmatrix}, \qquad \nabla_t = \begin{pmatrix} 0 \\ \xi_{d,t} \end{pmatrix}, \qquad \theta_j = \{ \begin{matrix} 1 & if\ j=1 \\ -1 & if\ j=2 \end{matrix}$$

$$\mathbb{E}_{t-1}[\xi_t \cdot \xi'_t] = \mathbb{E}_{t-1}\begin{pmatrix} \sigma_p^2 + x_t\sigma_\emptyset^2 & \theta\sqrt{\sigma_D^2 + x_t\sigma_{\text{ƕ}}^2}\sqrt{\sigma_p^2 + x_t\sigma_\emptyset^2} \\ \theta\sqrt{\sigma_D^2 + x_t\sigma_{\text{ƕ}}^2}\sqrt{\sigma_p^2 + x_t\sigma_\emptyset^2} & \sigma_D^2 + x_t\sigma_{\text{ƕ}}^2 \end{pmatrix} = \Sigma$$

The above equation indicates the correlation matrix between the error term of permanent risks and deposit shocks is conditional upon the realization of x_t, which can be predicted based on the realization of x_{t-1}. Since $x_t = 0,1$, we can show that $x_t^2 = x_t$ for both values and we drop the squared mark for simplicity. To achieve the simulation of the above two shocks, we follow Lkhagvasuren & Galindev (2008) to decompose them into two independent process[26]. Note that the idiosyncratic liquidity shock happens with symmetric image and the liquidity surplus/deficit occurs with equal probability within each banks in each period, which implies that banks cannot effectively cope with the idiosyncratic liquidity shock in advance although the distribution of this shock is known. Moreover, since the term $\xi_{d,t}$ is memoryless and thus cannot be a part of a AR(1) process, which means this error term will not be considered for discrete procedure. Accordingly, only the part $X_t = \bar{X} + PX_{t-1} + \xi_t$ in Equation (OA1) will be approximated to a discrete process. Denote $\propto_t = \varepsilon_{p,t} + \emptyset_t x_t \in N\left[x_t\left(\mu_\emptyset - \frac{1}{2}\sigma_\emptyset^2\right), x_t\sigma_\emptyset^2 + \sigma_p^2\right]$, with $\mu_{\propto,t} = x_t\left(\mu_\emptyset - \frac{1}{2}\sigma_\emptyset^2\right), \sigma_{\propto,t} = \sqrt{x_t\sigma_\emptyset^2 + \sigma_p^2}$, and $\text{ƚ}_t = \varepsilon_{D,t} + \text{ƕ}_t x_t \in N\left[x_t\left(\mu_{\text{ƕ}} - \frac{1}{2}\sigma_{\text{ƕ}}^2\right), x_t\sigma_{\text{ƕ}}^2 + \sigma_D^2\right]$, with $\mu_{\text{ƚ},t} = x_t\left(\mu_{\text{ƕ}} - \frac{1}{2}\sigma_{\text{ƕ}}^2\right), \sigma_{\text{ƚ},t} = \sqrt{x_t\sigma_{\text{ƕ}}^2 + \sigma_D^2}$ which means[27]:

[26] From Lkhagvasuren & Galindev (2008), this discretization method outperforms the Tauchen (1986) method for highly persistent VAR(1) process. Alternatively, De Nicolo *et al.* (2014) cope with this problem by utilizing the least squared solution of over-identified equation system (in their Appendix B) to generate equivalent VAR with uncorrected error terms. However, the accuracy of this method cannot be guaranteed when the number of equations is marginally larger than the unknown parameters (as in their example) and the iteration stopping criterion is not strict.

[27] This transformation is equivalent to the decomposition conducted by Equation (12) and (13) of Lkhagvasuren & Galindev (2008). The proof is put in the Online Appendix.

$$\xi_t = \begin{pmatrix} \propto_t \\ Ɨ_t \end{pmatrix} = \begin{pmatrix} \mu_{\propto,t} \\ \mu_{Ɨ,t} \end{pmatrix} + \begin{pmatrix} \sigma_{\propto,t} & 0 \\ 0 & \sigma_{Ɨ,t} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \theta & \sqrt{1-\theta^2} \end{pmatrix} \begin{pmatrix} \varepsilon 1_t \\ \varepsilon 2_t \end{pmatrix}$$

$$= \begin{pmatrix} \mu_{\propto,t} \\ \mu_{Ɨ,t} \end{pmatrix} + \begin{pmatrix} \sigma_{\propto,t} & 0 \\ \theta\sigma_{Ɨ,t} & \sigma_{Ɨ,t}\sqrt{1-\theta^2} \end{pmatrix} \begin{pmatrix} \varepsilon 1_t \\ \varepsilon 2_t \end{pmatrix}$$

Thus, the VAR with related error terms can be transformed using the above equation within which the two correlated error terms $(\propto_t,\ Ɨ_t)$ can be linearly represented by two independent white noise processes $(\varepsilon 1_t, \varepsilon 2_t)$ both with zero mean and standard deviation one, while the correlation coefficient between $(\propto_t,\ Ɨ_t)$ is still at θ. To simulate, we adopt seven points for $\log D_{j,t+1}$, before considering idiosyncratic liquidity risks. The transition matrix construction for $\log D_{j,t+1}$ will be introduced in **Part A.2**. However, since $\log Z_{p,t}$ follows a random walk, we simulate the error term that follows the normal distribution $N\left[\tau + x\left(\mu_{\emptyset} - \frac{1}{2}\sigma_{\emptyset}^2\right), \sigma_p^2 + x\sigma_{\emptyset}^2\right]$, conditional on the realization of bad times x on the current time. The realization of idiosyncratic liquidity risk $\chi_{j,U_{>0.5}}\xi_{d,t}$ for bank j is respectively determined from the value $\beth$ (to determine $\xi_{d,t}$) draws from simulated normal distribution $N(\mu_d - \frac{1}{2}\sigma_d^2, \sigma_d^2)$, and for each period $\chi_{j,U_{>0.5}} = \pm 1$ is conditional on the realization of the value draws from a uniform distribution $U[0,1]$.

A.2 Deposit Amount Discretization

For current period, once $\chi_{j,U>0.5}\xi_{d,t}$ is determined, this period's deposit amount $\log D_{j,t+1}$ is finalized for each bank j. However, in order to approximate next period deposit, we should disregard the idiosyncratic deposit amount $\chi_{j,U>0.5}\xi_{d,t}$. To approximate, adopt 5 points to discrete its realization. Since the persistence of the log of the deposits is above 0.90, we thus follow the methodology utilized by Rouwenhorst (1995) for approximation since this method performs better for highly persistent process (Kopecky & Suen, 2010). From Equation (7), we can notice that $\log D_{t+1}$ is governed by two independent normal-distributed random variables if in recessions, and one random variable if in booms. When in booms, the transitory shock can be written as

$$\log D_{t+1} = (1-\omega_D)\log \bar{D} + \omega_D \overline{\log D_t} + \varepsilon_{D,t}$$

where $\varepsilon_{D,t}\ i.i.d.\ N(0,\sigma_D^2)$. Whenever in recessions, the aggregate deposit amount is as follows:

$$\log D_{t+1} = (1-\omega_D)\log \bar{D} + \omega_D \overline{\log D_t} + \varepsilon_{D,t} + ƕ_t x_t$$

where $ƕ_t \in N\left(\mu_{ƕ} - \frac{1}{2}\sigma_{ƕ}^2, \sigma_{ƕ}^2\right)$. Given the fact that $ƕ_t$ and $\varepsilon_{D,t}$ are i.i.d. and are mutually independent, we can assume $\aleph_{j,t} = \varepsilon_{D,t} + ƕ_t$, where $\aleph_{j,t} \in N\left(\mu_{ƕ} - \frac{1}{2}\sigma_{ƕ}^2, \sigma_D^2 + \sigma_{ƕ}^2\right)$. Since the persistence is fixed at ω_D, from Rouwenhorst (1995) method the transition matrix within each financial situation will thus remain the same for both good times and bad times. We denote $\log \overline{D_g}^N$ and $\log \overline{D_b}^N$ for the realizations of $\log D_{t+1}$ for good and bad times respectively, and $N = 1,2,\ldots,5$. It is straightforward to show that

$$\log \overline{D_g}^j = \log \bar{D} + \left[-1 + \frac{2(j-1)}{N-1}\right]\sqrt{N-1}\sigma_D$$

where $N = 5$ and $j = 1,2,\ldots,5$.

$$\log \overline{D_b}^i = \log \bar{D} + \frac{\mu_{ƕ} - \frac{1}{2}\sigma_{ƕ}^2}{1-\omega_D} + \left[-1 + \frac{2(i-1)}{N-1}\right]\sqrt{N-1}\sqrt{\sigma_D^2 + \sigma_{ƕ}^2}$$

where $N = 5$ and $i = 1,2,\ldots,5$. We thus assume $\boldsymbol{P}_D$ a $N \times N$ matrix determined by Rouwenhorst (1995). We next consider the transition matrix when financial situation changes. When financial situation changes from good times to bad times, the cross-situational transition matrix can be defined as

$$p_{ji}^{\log\overline{D_{g\to b}}} = Pr\left[\log\ \overline{D_b}^{i} - w^{i} \leq (1-\omega_D)\log\overline{D} + \omega_D\log\overline{D_g}^{j} + \aleph_{j,t} \leq \log\ \overline{D_b}^{i} + w^{i}\right]$$
$$= F\left(\frac{\log\ \overline{D_b}^{i} + w^{i} - \mu_b - (1-\omega_D)\log\overline{D} - \omega_D\log\overline{D_g}^{j}}{\sqrt{\sigma_D^2+\sigma_{\text{ƕ}}^2}}\right) - F\left(\frac{\log\ \overline{D_b}^{i} - w^{i} - \mu_b - (1-\omega_D)\log\overline{D} - \omega_D\log\overline{D_g}^{j}}{\sqrt{\sigma_D^2+\sigma_{\text{ƕ}}^2}}\right)$$

otherwise,

$$p_{j1}^{\log\overline{D_{g\to b}}} = F\left(\frac{\log\ \overline{D_b}^{1} + w^{i} - \mu_b - (1-\omega_D)\log\overline{D} - \omega_D\log\overline{D_g}^{j}}{\sqrt{\sigma_D^2+\sigma_{\text{ƕ}}^2}}\right) \tag{OA2}$$

$$p_{jN}^{\log\overline{D_{g\to b}}} = 1 - F\left(\frac{\log\ \overline{D_b}^{N} + w^{i} - \mu_b - (1-\omega_D)\log\overline{D} - \omega_D\log\overline{D_g}^{j}}{\sqrt{\sigma_D^2+\sigma_{\text{ƕ}}^2}}\right) \tag{OA3}$$

where $w^{i} = \frac{\sqrt{\sigma_D^2+\sigma_{\text{ƕ}}^2}}{\sqrt{N-1}}$ and $\mu_b = \mu_{\text{ƕ}} - \frac{1}{2}\sigma_{\text{ƕ}}^2$. Similarly, we can construct the cross-situational transition matrix when the situation is from bad times to good times:

$$p_{ij}^{\log\overline{D_{b\to g}}} = Pr\left[\log\ \overline{D_g}^{j} - w^{j} \leq (1-\omega_D)\log\overline{D} + \omega_D\log\overline{D_b}^{i} + \varepsilon_{D,t} \leq \log\ \overline{D_g}^{j} + w^{j}\right]$$
$$= F\left(\frac{\log\ \overline{D_g}^{j} + w^{j} - (1-\omega_D)\log\overline{D} - \omega_D\log\overline{D_b}^{i}}{\sigma_D}\right) - F\left(\frac{\log\ \overline{D_g}^{j} - w^{j} - (1-\omega_D)\log\overline{D} - \omega_D\log\overline{D_b}^{i}}{\sigma_D}\right)$$

otherwise,

$$p_{i1}^{\log\overline{D_{b\to g}}} = F\left(\frac{\log\ \overline{D_g}^{1} + w^{j} - (1-\omega_D)\log\overline{D} - \omega_D\log\overline{D_b}^{i}}{\sigma_D}\right) \tag{OA4}$$

$$p_{iN}^{\log\overline{D_{b\to g}}} = 1 - F\left(\frac{\log\ \overline{D_g}^{N} - w^{j} - (1-\omega_D)\log\overline{D} - \omega_D\log\overline{D_b}^{i}}{\sigma_D}\right) \tag{OA5}$$

where $w^{j} = \frac{\sigma_D}{\sqrt{N-1}}$. We thus denote the matrix $\boldsymbol{P}_{D,g\to b}$ and $\boldsymbol{P}_{D,b\to g}$ that are constructed based on Equation (OA2), (OA3), (OA4) and (OA5), respetively. Moreover, the conditional probability of transition regarding the financial situations are defined as:

$$\begin{pmatrix} x_t = 1 \\ x_t = 0 \end{pmatrix} = \begin{pmatrix} q & 1-q \\ p & 1-p \end{pmatrix}\begin{pmatrix} x_{t-1} = 1 \\ x_{t-1} = 0 \end{pmatrix}$$

Thus, to summarize, if the current state is good time/no disasters, the expected transitory shock for next period $E[D_g]$ is calculated as

$$E[D_g] = \left[(1-p)e^{\overrightarrow{\mathbf{log}\,\boldsymbol{D}_g}}\boldsymbol{P}_D' + pe^{\overrightarrow{\mathbf{log}\,\boldsymbol{D}_b}}\boldsymbol{P}_{D,g\to b}'\right]\overrightarrow{\boldsymbol{V}_{D,g}}$$

where $\boldsymbol{P}_D'$ and $\boldsymbol{P}_{D,g\to b}'$ denotes the transpose of $\boldsymbol{P}_D$ and $\boldsymbol{P}_{D,g\to b}$, respectively. The term $\overrightarrow{\boldsymbol{V}_{D,g}}$ is a $N \times 1$ vector denoting the current realization/state, and $\overrightarrow{\mathbf{log}\,\boldsymbol{D}_{s=b,g}}$ is a $1 \times N$ vector which stores the distribution of log $\overline{D_{s=b,g}}^{N}$, while $e^{\overrightarrow{\mathbf{log}\,\boldsymbol{D}_{s=b,g}}}$ is a $1 \times N$ vector which stores the distribution of $\overline{D_{s=b,g}}^{N}$. Similarly, we can compute the expected realization $E[D_b]$ for the scenario when the current situation is in bad times/disasters[28].

[28] Danthine & Donaldson (1999) and Bai *et al.*(2018) use an alternative method to incorporate the likelihood of disasters; however, their consideration are mainly suitable for rare catastrophes and will limit the law of motion of the disasters by only allowing one-way switch from disasters to recovery state, while by disabling the possible situation changes from recovery state to a disaster. Thus, our model seems better to reflect the reality by generalizing this consideration.

$$E[D_b] = \left[q e^{\overrightarrow{\log D_b}} \boldsymbol{P}'_D + (1-q) e^{\overrightarrow{\log D_g}} \boldsymbol{P}'_{D,b\to g}\right] \overrightarrow{\boldsymbol{V}_{D,b}}$$

where $\overrightarrow{\boldsymbol{V}_{D,b}}$ is a $N \times 1$ vector denoting the current realization/state, and $\boldsymbol{P}'_{D,b\to g}$ denotes the transpose of $\boldsymbol{P}_{D,b\to g}$.

A.3 Truncated transitory shock approximation

As in Gourio (2012) and Nakamura *et al.* (2013), we truncate the realization of transitory shocks to $(-\infty, 0]$. To keep in line with our previous analysis, we still use Rouwenhorst (1995) method to approximate $\log Z_{r,j,t-1}$, although Tauchen (1986) method can be used for this process, as the persistence of it is not high (which is below 0.8, where the approximation errors become pronounced (Tauchen, 1986)). We should adopt more points for approximation as positive points will be dropped out for the assumption. We use 9 points for each situation (Normal times and Disasters) of the process (before truncation) and drop the points once $\log \overline{Z_{s=b,g}}^{N=i,j} > 0$. The law of motion of $\log Z_{r,j,t}$ is as follows:

When in booms, the transitory shock can be written as

$$\log Z_{r,j,t} = \rho \log Z_{r,j,t-1} + \varepsilon_{r,j,t}$$

where $\varepsilon_{r,j,t}\ i.i.d.\ N(0, \sigma_r^2)$. Whenever in recessions, the transitory shocks is as follows:

$$\log Z_{r,j,t} = \rho \log Z_{r,j,t-1} + \varepsilon_{r,j,t} + \varphi_{j,t} - \emptyset_t$$

Suppose there are $G(B)$ points for the realization of $\log \overline{Z_{r,g}}^{j}$ when in good times (bad times) after truncation. Based on the assumption and characteristic of $\log Z_{r,j,t}$, $G = 5$ in our calibration, while the actual number of $B \geq G$ is subject to the parameters. Using Rouwenhorst (1995) method, we can obtain:

$$\log \overline{Z_{r,g}}^{j} = \left[-1 + \frac{2(j-1)}{N-1}\right] \sqrt{N-1}\sigma_r$$

where $N = 9$ and $j = 1,2,\ldots,G$.

$$\log \overline{Z_{r,b}}^{i} = \frac{\mu_\varphi - \mu_\emptyset - \frac{1}{2}\sigma_\varphi^2 + \frac{1}{2}\sigma_\emptyset^2}{1-\rho} + \left[-1 + \frac{2(i-1)}{N-1}\right] \sqrt{N-1} \sqrt{\sigma_r^2 + \sigma_\varphi^2 + \sigma_\emptyset^2}$$

where $N = 9$ and $i = 1,2,\ldots,B$.

To construct the adjusted in-sectional transition matrix $\widetilde{\boldsymbol{P}}_{r,g}$ and $\widetilde{\boldsymbol{P}}_{r,b}$, we should adopt the original transition matrix $\boldsymbol{P}_{r,g}$ and $\boldsymbol{P}_{r,b}$, and adopt the first $G(B)$ rows and first $G(B)$ columns, respectively for good times (bad times) for the truncation purpose. Suppose $P_{r,s=g(b)}^{k,l}$ is the value stored in the kth row and lth column, where $l \leq G(B)$, in the adopted matrix, and the adjusted transition probability (for each row) to be stored in the transition matrix $\widetilde{\boldsymbol{P}}_{r,g}$ and $\widetilde{\boldsymbol{P}}_{r,b}$ is:

$$\tilde{P}_{r,s=g(b)}^{k,l} = \frac{P_{r,s=g(b)}^{k,l}}{\sum_{i=1}^{G(B)} P_{r,s=g(b)}^{k,i}} \quad \text{(OA6)}$$

This manipulation in the above equation, designed to adjust for truncation, will help to make the sum of the probability of each row equal to one. For the cross-sectional transition matrix construction, we firstly construct the original transition matrix, which are as follows:

$$p_{ji}^{\log \overline{Z_{r,g\to b}}} = Pr\left[\log \overline{Z_{r,b}}^{i} - w^i \leq \rho \overline{Z_{r,g}}^{j} + \varepsilon_{r,j,t} + \varphi_{j,t} - \emptyset_t \leq \log \overline{Z_{r,b}}^{i} + w^i\right]$$
$$= F\left(\frac{\log \overline{Z_{r,b}}^{i} + w^i - \mu_{r,b} - \rho \overline{Z_{r,g}}^{j}}{\sqrt{\sigma_r^2 + \sigma_\varphi^2 + \sigma_\emptyset^2}}\right) - F\left(\frac{\log \overline{Z_{r,b}}^{i} - w^i - \mu_{r,b} - \rho \overline{Z_{r,g}}^{j}}{\sqrt{\sigma_r^2 + \sigma_\varphi^2 + \sigma_\emptyset^2}}\right) \tag{OA7}$$

otherwise,

$$p_{jB}^{\log \overline{D_{g\to b}}} = F\left(\frac{-\mu_{r,b} - \rho \overline{Z_{r,g}}^{j}}{\sqrt{\sigma_r^2 + \sigma_\varphi^2 + \sigma_\emptyset^2}}\right) - F\left(\frac{\log \overline{Z_{r,b}}^{B} - w^i - \mu_{r,b} - \rho \overline{Z_{r,g}}^{j}}{\sqrt{\sigma_r^2 + \sigma_\varphi^2 + \sigma_\emptyset^2}}\right)$$

where $w^i = \frac{\sqrt{\sigma_r^2 + \sigma_\varphi^2 + \sigma_\emptyset^2}}{\sqrt{B-1}}$ and $\mu_{r,b} = \frac{\mu_\varphi - \mu_\emptyset - \frac{1}{2}\sigma_\varphi^2 + \frac{1}{2}\sigma_\emptyset^2}{1-\rho}$, and

$$p_{ij}^{\log \overline{Z_{r,b\to g}}} = Pr\left[\log \overline{Z_{r,g}}^{j} - w^j \leq \rho \overline{Z_{r,b}}^{i} + \varepsilon_{r,j,t} \leq \log \overline{Z_{r,g}}^{j} + w^j\right]$$
$$= F\left(\frac{\log \overline{Z_{r,g}}^{j} + w^j - \rho \overline{Z_{r,b}}^{i}}{\sigma_r}\right) - F\left(\frac{\log \overline{Z_{r,g}}^{j} - w^j - \rho \overline{Z_{r,b}}^{i}}{\sigma_r}\right) \tag{OA8}$$

otherwise,

$$p_{iG}^{\log \overline{D_{b\to g}}} = F\left(\frac{-\rho \overline{Z_{r,b}}^{i}}{\sigma_r}\right) - F\left(\frac{\log \overline{Z_{r,g}}^{G} - w^j - \rho \overline{Z_{r,b}}^{i}}{\sigma_r}\right)$$

where $w^j = \frac{\sigma_r}{\sqrt{G-1}}$. Once obtaining the original cross-sectional matrix $\boldsymbol{P}_{r,g\to b}$ and $\boldsymbol{P}_{r,b\to g}$ using Equation (OA7) and (OA8), respectively, we can construct the adjusted cross-sectional matrix $\widetilde{\boldsymbol{P}}_{r,g\to b}$ and $\widetilde{\boldsymbol{P}}_{r,b\to g}$ as in Equation (OA6), and for these adjusted matrix the sum of the probability of each row is normalized to one. Note that $\widetilde{\boldsymbol{P}}_{r,g\to b}$ and $\widetilde{\boldsymbol{P}}_{r,b\to g}$ might not be square matrices as $B \geq G$ in our assumption. Lastly, the expected value of transitory shocks can thus be determined, conditional on the realization of financial situation.

A.4 Transforming the problem

The process $\log Z_{p,t}$ is non-stationary as it has a unit root, and we thus need to de-trend the variables by $Z_{p,t}$ to make them stationary and reduce the dimension of the state space (Gourio, 2012). Given the homogeneity of the value function, and conditional on the realization of bad times x_t at each period, we can rewrite $E_j(f)$ in Equation (26) for bank j as

$$E_j(f) = E_j\big(L, R, D, Z_p, Z_r\big) = Z_p g(l, r, d, Z_r)$$

where $l = L/Z_p$, $r = R/Z_p$, $d = D/Z_p$, $d' = D'/Z_p$. Thus, from the definition of $E_j(x)$ in Equation (26), the function $g(l, r, d, Z_r)$ can be expressed as:

$$g(l, r, d, Z_r) = \max\left\{0, \max_{(l',r')\in\Delta(d')}\left\{e_j(f, d', l', r') + \beta\mathbb{E}\big[E_j(f')\big]\right\}\right\}$$

Additionally, in Equation (25), we can write that $E_j(f') = Z_p g\big(l', r', d'', Z'_{j,r}\big)$, where

$$l' = \frac{L'}{Z'_p} = \frac{L'}{Z_p}\frac{Z_p}{Z'_p} = \frac{L'}{Z_p}\exp -\left(\tau + x'\mu_\emptyset + \varepsilon'_1\sqrt{\sigma_p^2 + x'\sigma_\emptyset^2}\right)$$
$$r' = \frac{R'}{Z'_p} = \frac{R'}{Z_p}\frac{Z_p}{Z'_p} = \frac{R'}{Z_p}\exp -\left(\tau + x'\mu_\emptyset + \varepsilon'_1\sqrt{\sigma_p^2 + x'\sigma_\emptyset^2}\right)$$
$$d'' = \frac{D''}{Z'_p} = \frac{D''}{Z_p}\frac{Z_p}{Z'_p}$$
$$= \frac{D'^{\omega_D}}{Z_p} e^{-\tau + (1-\omega_D)\log \bar{D}} e^{\varepsilon'_1\left[\theta\left(\sqrt{\sigma_D^2 + x'\sigma_{\mathrm{hv}}^2}\right) - \left(\sqrt{\sigma_p^2 + x'\sigma_\emptyset^2}\right)\right]} e^{\varepsilon'_2\sqrt{1-\theta^2}\sqrt{\sigma_D^2 + x'\sigma_{\mathrm{hv}}^2}} e^{x'\left[\left(\theta + \sqrt{1-\theta^2}\right)\mu_{\mathrm{hv}} - \mu_\emptyset\right]}$$

where ε_1' and ε_2' are independent standard normal distributions. Again, note that from **Figure 1**, deposits D_{t+1} and revenues $Z_{j,t}$ has one period difference, and thus we denote $D = D_t$, $D' = D_{t+1}$, $D'' = D_{t+2}$.

The resulting problem is reduced to (Note that both the control variables l' and r' are de-trended by the Z_p', which allows us to choose the discretized grids of points for the control variables without calculating expected value for the term $e_j\big(l, l', r, r', d', d, Z_{j,r}\big)$):

Value function

$$
\begin{aligned}
&g_j(l, r, d, Z_r) \\
&= \max\left\{0, \max_{(l',r')\in\Delta(d')}\left\{e_j\big(l, l', r, r', d', d, Z_{j,r}\big)\right.\right. \\
&\left.\left.+\,\beta\,\mathbb{E}_{Z_{j,r}',\varepsilon_1',\varepsilon_2'}\left[e^{\tau + x'\mu_\emptyset + \varepsilon_1'\sqrt{\sigma_p^2 + x'\sigma_\emptyset^2}}\, g_j\left(\frac{L'}{Z_p}, \frac{R'}{Z_p}, \frac{D^{\omega_D}}{Z_p'} e^{-\tau + (1-\omega_D)\log\bar{D}} e^{\varepsilon_1'\theta\sqrt{\sigma_D^2 + x'\sigma_{\text{ƕ}}^2}} e^{\varepsilon_2'\sqrt{1-\theta^2}\sqrt{\sigma_D^2 + x'\sigma_{\text{ƕ}}^2}}, Z_{j,r}'\right)\right]\right\}\right\}
\end{aligned}
\tag{OA9}
$$

subject to

Current period cash flow

$$
\begin{aligned}
e_j\big(&l, l', r, r', d', d, Z_{j,r}\big) \\
&= \max\big\{(1-\epsilon)\big\{Z_{j,r}L^\alpha + \big[(1+r_i)Q_{-j} - 1\big]r - (r_d + \vartheta D^4)d\big\} + rQ_{-j} + (d' - d) \\
&\quad - r' - (l' - l) - Z_p \cdot M\langle|l' - l(1-\sigma)|\rangle, 0\big\} \\
&\quad + \min\big\{(1-\epsilon)\big\{Z_{j,r}L^\alpha + \big[(1+r_i)Q_{-j} - 1\big]r - (r_d + \vartheta D^4)d\big\} + rQ_{-j} + (d' - d) \\
&\quad - r' - (l' - l) - Z_p \cdot M\langle|l' - l(1-\sigma)|\rangle, 0\big\}\,(1+\kappa)
\end{aligned}
$$

Adjusted collateral constraint

$$
\begin{aligned}
\text{ч}(d') = \Bigg\{(l', r') \,\Big|\, &\frac{l' - Z_p \cdot M\langle -l'(1-\sigma)\rangle + d_d'' + z_d' L'^\alpha (1-\epsilon)}{1 + (r_d + \vartheta D^4)(1-\epsilon)} + r' \\
&\cdot \frac{\epsilon + (1+r_i)(1-\epsilon)\cdot \mathbb{E}^{min}\big(Q_{-j}'\big)}{1 + (r_d + \vartheta D^4)(1-\epsilon)} \ge d', r' < 0\Bigg\} \cup \{r' > 0\}
\end{aligned}
$$

where $z_d' = Z_{p,d}' Z_{r,d}' / Z_p$, and ϵ denotes the tax rate conditional on the worst-case scenario EBT for the next period. The indicator Q_{-j} (Q_{-j}'), which represents for current (next) period, equals to zero if the counterparty bank $-j$ fails and $r > 0$ ($r' > 0$); otherwise, equals to one.

Adjusted capital requirement

$$
\text{л}(d') = \big\{(l', r') \,\big|\, (1-k)l' + r' \ge d'\big\}
$$

Adjusted liquidity requirement

$$
\text{ж}(d') = \left\{(l', r') \,\Big|\, \frac{\sigma l' + h d_d'' + z_d' L^\alpha (1-\epsilon)}{h + (h-\epsilon)(r_d + \vartheta D_t^4)} + r' \cdot \frac{\epsilon + (1-\epsilon)(1+r_i)\cdot \mathbb{E}^{min}\big(Q_{-j}'\big)}{h + (h-\epsilon)(r_d + \vartheta D_t^4)} \ge d'\right\}
$$

Law of motion of shocks

$$
\text{Log}\, Z_{j,r}' = \rho \log Z_{r,j} + \varepsilon_{r,j}'
$$

$$
\varepsilon_{r,j}' \sim i.i.d.\ N\left[\left(\mu_\varphi - \mu_\emptyset - \frac{1}{2}\sigma_\varphi^2 + \frac{1}{2}\sigma_\emptyset^2\right)x', \sigma_r^2 + \big(\sigma_\varphi^2 + \sigma_\emptyset^2\big)x'\right]
$$

$$
\varepsilon_1' \sim i.i.d.\ N(0,1),\ \ \varepsilon_2' \sim i.i.d.\ N(0,1)
$$

Note that the approximation of Log $Z'_{j,r}$ will use the method described in **Part B.1**. Using the equivalent representation of the problem, showed in Equation (OA9), we solve the problem within bounded state-space and stationary simulation.

A.5 Compact feasible set

As in De Nicolo *et al.* (2014), we can confirm the existence of the compactness of the feasible set of the banks in question. Firstly, due to strict concavity of $\pi_j(L_t) = Z_{j,t}L_t^{\alpha}$, there exists an upper bound on loan investment amount $L_u > 0$ that satisfies $G(L_u) = \overline{\pi}_j(L_u) - rL_u = 0$, where r denotes the cost of marginal money raised either from deposits or interbank lending, and $\overline{\pi}_j(L_u)$ is the highest level of total shocks. We can show that $G'(L_t) = \alpha Z_{j,max}L_t^{\alpha-1} - r \gtreqless 0$ and $G''(L_t) = \alpha(\alpha-1)Z_{j,max}L_t^{\alpha-2} < 0$. Since $G(0) = 0$ and $G'(L_t) > 0$ when L_t is positive and is very close to zero, we can conclude there is only one unique positive L_u value that makes $G(L_u) = 0$. Thus, this condition $G(L_u) = 0$ determines an upper bound L_u on L and ensures any investment $L > L_u$ would be unprofitable, as the marginal costs would exceed the marginal revenues. Given the loan investment is always nonnegative, we can thus establish the feasible set/interval for loan investment $[0, L_u]$ once L_u is determined.

Then, we turn to the bounds on interbank lending $R_{j,t}$. As the upper bound on loan investment L_u is determined, a lower bound $R_l < 0$ (namely the upper bound for interbank borrowing volume) can be easily determined through conditions (30), (31) and ((33), whichever allows the lowest feasible $R_{j,t}$ value. To obtain an upper bound $R_u > 0$ on interbank borrowing, we assume that bank j offers to lend all the deposits D_t to the bank $-j$ in the form of interbank lending. Thus, the proceeds of this interbank lending is $1 + r_i(1 - \epsilon^+)$. To increase an additional interbank lending, bank j has to raise the equity at the rate of $1 + \kappa$ due to the equity issuance cost. Since $1 + \kappa > 1 + r_i(1 - \epsilon^+)$ in our calibration, which means the cost of investing in interbank lending exceeds the revenue, and thus banks are have no incentive to increase the investment in interbank lending beyond D_t. Thus, the existence of an upper bound on interbank lending $R_u = D_{max}$ is verified[29]. Accordingly, the feasible set/interval for interbank market volume is set as $[R_l, R_u]$. To summarize, the feasible set of the banks is assumed to be $[0, L_u] \times [R_l, R_u]$.

The above discussion theoretically proves the existence of feasible sets for banking activities that bank's choice will never bind under the maximization program if with appropriate bound values. Note that although the bounds/intervals discussed above is for the original value function, we can still adopt these intervals for the model described in Equation (25) because we can de-trend them by the lowest expected value for Z_p, which is usually assumed to be 1. Thus, the feasible set of the banks under the transformed Value Function in Equation (25)is adopted as $[0, L_u] \times [R_l, R_u]$. Finally, as the transformed Value Function is stationary, the maximization problem can be achieved within the feasible sets without binding the value boundaries.

A.6 Numerical solution and simulation of the valuation problem

Following **Part B.3**, equity value of the bank j is obtained numerically by a value iteration algorithm on a discrete state-space of $l', r', Z'_{j,r}$, following the de-trend consideration by Z_p. As discussed in **Part B.4**, the de-trended control variables (l', r') will range within $[0, L_u] \times [R_l, R_u]$ for our simulation. We discrete l' to obtain a grid of n_l points, and for each point

$$\widetilde{l'} = \{\widetilde{l'_s} = L_u(1-\sigma)^s \mid s = 1, \dots, n_l - 1\} \cup \{\widetilde{l'_{n_l}} = 0\}$$

[29] If we consider the counterparty risks and potential unmatched interbank market, the upper bound would be even lower.

The interval $[R_l, R_u]$ is discretized into n_r equally spaced values, which makes a set of $n_r + 1$ points of $\widetilde{r'}$. However, to find the real value for each variable without de-trending, we should multiply the values by Z_p realized at each period. Yet, these values are non-stationary and thus cannot be analysed directly, we thus discuss de-trended variables only.

For the parameters in Table 1, we use $L_u = 20,\ R_l = -7$ and $R_u = 7$ to ensure the optimal choice of loans and interbank lending never hits the lower/upper thresholds. To discretize, and as mentioned before, we use nine points for transitory risks (before truncation), five points for deposit amount (before adding idiosyncratic components) respectively for each bank and for each financial situation. The permanent risk is generated using a single normal distribution, without discretization, and is applicable for both banks. However, we need more points for control variable discretization: we choose $n_l = 31$ and $n_r = 40$ for loan and interbank lending. For the calculation of the expected continuation value (as in the equation below), we use linear interpolation method as in Hajda (2017) to extend ε_1' and ε_2' to 120 points to make the results more accurate.

$$\mathbb{E}_{Z_{j,r}',\varepsilon_1',\varepsilon_2'}\left[e^{\tau+x'\mu_\emptyset+\varepsilon_1'\sqrt{\sigma_p^2+x'\sigma_\emptyset^2}}g_j\left(\frac{L'}{Z_p},\frac{R'}{Z_p},\frac{D^{\omega_D}}{Z_p'}e^{-\tau+(1-\omega_D)\log\bar{D}}e^{\varepsilon_1'\theta\sqrt{\sigma_D^2+x'\sigma_{\text{ƕ}}^2}}e^{\varepsilon_2'\sqrt{1-\theta^2}\sqrt{\sigma_D^2+x'\sigma_{\text{ƕ}}^2}},Z_{j,r}'\right)\right]$$

Given the optimal solution in the above equation and **Assumption 7**, we can determine the optimal loan and interbank lending/borrowing for each period. We generate 10,000 pair of banks for 100 periods (years). In particular, we start with $x_{t=0} = 0$ and $Z_{j,r}'(0) = 1$ for $j = 1,2, Z_p(0) = 1$, and $D(0) = D_d$. For the settings of the initial choice, we adopt $R(0) = 0$ and $L_j(0) = D_u$ for $j = \pm 1$ (so the initial bank capital for both banks is $D_u - D_d$). Recursively, we apply the transition function as in Equation (27) once the bank fails, in which case the depositors will be paid in full and the bankruptcy costs will be credited to the government and then a new bank will be born with a seed capital $D_u - D_d$ and an initial loan investment at $L(0) = D_u$ reconstructed by the government to stabilize the loan market. Afterwards, this new bank will follow the same path by operating under the optimal policy. To ensure the realized results does not depend on the initial settings, we drop the first fifty steps for each path.

B. Simulation of financial situations

We follow Adda & Cooper (2003) to draw x_t from uniform [0,1] distribution. To incorporate the financial situation changes, the process is simulated based on the previous period. Firstly, we generate a series of N values drawn from uniform [0,1] distribution in a vector U_t and predetermine the initial state of $x_{t=1}$, which is assumed to be $x_{t=1} = 0$. The iterative method to determine x_t is as follows:

If $x_{t-1} = 0$ and $U_t < p, x_t = 1$; otherwise, $x_t = 0$.
If $x_{t-1} = 1$ and $U_t < q, x_t = 1$; otherwise, $x_t = 0$.

The iteration process continues until $t = N$.

C. Simulation of shocks

As in Adda & Cooper (2003) and Terry & Knotek (2011), we simulate the shocks via draws u_t from the uniform [0,1] distribution, where t stands for the sequence of the generated variables. Suppose at each time t after the financial situation x_t is determined as in previous section, the current state S_t switches from previous state $S_{t-1} = S_i$, via the inner-situation transition matrix (if financial situation remains) or cross-situation matrix (if financial situation changes). Consider the chosen transition matrix as $\boldsymbol{P}$, and given S_i and u_t, and denote a new matrix as $\overline{\boldsymbol{P}}_{i,j} = \sum_{m=1}^{j} P_{i,m}$, where $P_{i,m}$ stands for the value stored in the ith row and mth column of the matrix $\boldsymbol{P}$, and similarly $\overline{P}_{i,j}$ denotes the value stored in the ith row and jth column of the matrix $\overline{\boldsymbol{P}}$. If $u_t \in (\bar{P}_{i,j-1}, \bar{P}_{i,j}]$, it implies $S_t = S_j$ (and $S_t = S_1$ if $u_t \leq \bar{P}_{i,1}$). The simulation of the states is initialized at the mean value which belongs to state set $\boldsymbol{S} = \{S_s | s = 1,2, \dots, N\}$ where N represents the total number of the feasible states.

The uniform shocks u_t can be directly used to simulate $\log Z_{r,j,t}$ using the method described above since it is not in the VAR. However, some transformation is needed to simulate $\log Z_{p,t}$ and $\log D_{t+1}$ (with aggregate liquidity shocks only) as their error terms are correlated. To solve this, we simulate two independent standard normal distribution ε_{1t} and ε_{2t}, both of which are with zero mean and with a variance of one. Then we construct $\varepsilon_{3t} = \rho\varepsilon_{1t} + \sqrt{1-\rho^2}\varepsilon_{2t}$ to make $(\varepsilon_{1t}, \varepsilon_{3t})$ as the simulated error term for the VAR, where ρ denotes the correlation coefficient of the error terms. If we convert $(\varepsilon_{1t}, \varepsilon_{3t})$ to uniform $[0,1]$ distribution using Cumulative Distribution Function (cdf), we can thus turn to the method described in the previous paragraph to realize our simulation. Lastly, the deposit amount $\log D_{j,t+1}$ for individual bank j is determined by adding $\theta_j \xi_{d,t}$, where $\xi_{d,t}\ i.i.d.\ N(\mu_d - \frac{1}{2}\sigma_d^2, \sigma_d^2)$. Since $\xi_{d,t}$ is not a part of AR(1), it will not be considered for discretization, but be added after the aggregate liquidity shock $\log D_{t+1}$ is settled down.

D. Equivalent transformation to Lkhagvasuren & Galindev (2008)

This section proves the decomposition method described in Appendix **B.2** is equivalent to Lkhagvasuren & Galindev (2008) transformation. To save space, we use L&G to represent Lkhagvasuren & Galindev (2008) in the rest of this section. In the Page 13 of L&G, they propose that two independent AR(1) processes $u_{1,1,t}$ and $u_{2,2,t}$ can be simulated to represent two correlated AR(1) processes $x_{1,t}$ and $x_{2,t}$ by using the Equation (OA11) and (OA12).

$$x_{1,t} = \sqrt{1-\rho_1^2}u_{1,1,t} \tag{OA11}$$

$$x_{2,t} = v_{2,t} + \sqrt{1-\gamma^2}\sqrt{1-\rho_2^2}u_{2,2,t} \tag{OA12}$$

where $v_{2,t}$ can be represented by pre-generated series $\hat{u}_{1,1,t}$ using Equation (OA13)

$$v_{2,t} = \rho_2 v_{2,t-1} + \gamma\sqrt{1-\rho_2^2}\left(\hat{u}_{1,1,t} - \rho_1 \hat{u}_{1,1,t-1}\right) \tag{OA13}$$

where γ represents the correlation of the error term of $x_{1,t}$ and $x_{2,t}$, ρ_i is the persistence of $u_{i,i,t}$ and $\sigma_{u,i,i}^2 = 1/\left(1-\rho_i^2\right)$. It shows that the correlated AR(1) processes can respectively be represented by one AR(1) process $u_{1,1,t}$ (for $x_{1,t}$) and two AR(1) processes $v_{2,t}$ and $u_{2,2,t}$ (for $x_{2,t}$). It is straightforward to show that $\sigma_{x1}^2 = \sigma_{x2}^2 = 1$ and $\sigma_{v2}^2 = \gamma^2$. However, we decompose the error terms of the correlated AR(1) processes as follows:

$$y_{1,t} = \rho_1 y_{1,t-1} + \varepsilon_{1,t} \tag{OA14}$$

$$y_{2,t} = \rho_2 y_{2,t-1} + \gamma\varepsilon_{1,t} + \sqrt{1-\gamma^2}\varepsilon_{2,t} \tag{OA15}$$

To prove Equation (OA5) is equivalent to Equation (OA2), we introduce $Z_{1,t}$ and $Z_{2,t}$ to enable $y_{2,t}$ to be rewritten as

$$\begin{aligned} y_{2,t} &= \gamma Z_{1,t} + \sqrt{1-\gamma^2}\, Z_{2,t} \\ &= \gamma\left(\rho_2 Z_{1,t-1} + \varepsilon_{1,t}\right) + \sqrt{1-\gamma^2}\left(\rho_2 Z_{2,t-1} + \varepsilon_{2,t}\right) = \rho_2\left(\gamma Z_{1,t-1} + \sqrt{1-\gamma^2} Z_{2,t-1}\right) + \\ &\quad \gamma\varepsilon_{1,t} + \sqrt{1-\gamma^2}\varepsilon_{2,t} \end{aligned} \tag{OA16}$$

Thus, if we decompose $y_{2,t-1}$ into two parts and represents it as $y_{2,t-1} = \gamma Z_{1,t-1} + \sqrt{1-\gamma^2}Z_{2,t-1}$, we can claim that $y_{2,t}$ can be represented by two AR(1) processes $Z_{1,t}$ and $Z_{2,t}$, with $\sigma_{Z1}^2 = \sigma_{Z2}^2 =$

$1/(1-\rho_2^2)$, and $\sigma_{yi}^2 = 1/(1-\rho_i^2)$. To make the variances in Equation (OA4) and (OA5) equal to one as in Equation (OA1) and (OA2), we rescale the processes above and yield the following:

$$X_{1,t} = \sqrt{1-\rho_1^2}(\rho_1 y_{1,t-1} + \varepsilon_{1,t}) = \sqrt{1-\rho_1^2}y_{1,t} \quad \text{(OA17)}$$

$$X_{2,t} = \sqrt{1-\rho_2^2}y_{2,t} = \sqrt{1-\rho_2^2}\left(\gamma Z_{1,t} + \sqrt{1-\gamma^2}\, Z_{2,t}\right) = \gamma\sqrt{1-\rho_2^2}Z_{1,t} + \sqrt{1-\gamma^2}\sqrt{1-\rho_2^2}\, Z_{2,t} \quad \text{(OA18)}$$

Comparing Equation (OA17), (OA18) with (OA11), (OA12), we can notice that if we make $x_{2,t} = X_{2,t}$, $u_{1,1,t} = y_{1,t}$, $u_{2,2,t} = Z_{2,t}$ and $v_{2,t} = \gamma\sqrt{1-\rho_2^2}Z_{1,t}$, we can obtain $x_{i,t} = X_{i,t}$. Thus, this proves our transformation used in Equation (OA14), (OA15) and in **Appendix B.2** is equivalent to the L&G decomposition method. Our proof thus completes.

E. Moderating quarterly data to annual data.

Since the law of motion of the shocks follows the AR(1) process, we can write it as follows:

$$D_1 = \rho D_0 + \tau + \varepsilon_t$$

where D_n stands for the data for one quarter. If we write the equation for D_2, D_3 and D_4 using the recursive method and express D_4 only in terms of D_0, with assumption that ε_t is *i.i.d.* across the time period, we can obtain the following equation:

$$D_4 = \rho^4 D_0 + (\rho^2+1)(\rho+1)\tau + (\rho^2+1)(\rho+1)\varepsilon_t$$

We can thus reproduce $D_{4n}, n = 0,1,2$ as the annual data to replace the original quarterly data, and moderate the original parameters as appropriate. The new persistence is $\rho' = \rho^4$, the new drift is $\tau' = (\rho^2+1)(\rho+1)\tau$, the new error term is $\varepsilon_t' = (\rho^2+1)(\rho+1)\varepsilon_t$ with standard deviation $(\rho^2 + 1)(\rho+1)\sigma_\varepsilon$, where σ_ε is the standard deviation of ε_t.