The Effects of Capital and Liquidity Requirements in a Dynamic Model with an Interbank Market

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Abstract

This paper studies the quantitative impacts of Basel-style capital and liquidity requirements on bank lending, bank liquidity holdings and interbank trading activities. We develop a model in which banks are subject to business cycle variations, are financed by deposits and equity, and transform these liabilities into loans, liquid assets, and interbank lending. Banks are exposed to systematic credit and liquidity shocks and idiosyncratic credit and liquidity shocks, where the idiosyncratic shocks can be managed through the interbank market. Our novel findings show (1) adding banking requirements, especially the liquidity requirements, reduces the interbank rates, (2) the benefits of liquidity requirements are at the cost of lowered social welfare, and (3) there exists a U-shaped relationship between interbank trading volume (representing banks' reliance on the interbank market) and the liquidity requirements (for both *Liquidity Coverage Ratio* and *Net Stable Funding Ratio*), where the required ratios set around 65% reach the minimum. We then conclude that the current liquidity requirement ratio (100%) appears to be too strict to limit banks' reliance on the interbank market.

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1. Introduction

The Basel Committee on Banking Supervision (BCBS) has introduced several Basel Accords, known as Basel I, Basel II and Basel III, with the aim to strengthen the soundness and stability of the international banking system. The first two accords, i.e., Basel I and Basel II, mainly focus on banks' capital regulations. The latest version, Basel III[1], improves the capital requirements by stipulating that the ratio of banks' Tier-1 capital to banks' risk-weighted assets (RWA) should be at least 6%, where the minimum requirement is 4% from previous regimes. Basel III also introduces liquidity requirements in the form of Liquidity Coverage Ratio (LCR) and Net Stable Funding Ratio (NSFR) to mitigate banks' short-term and long-term liquidity issues, respectively. More importantly, unlike previous accords, Basel III also aims to address some banks' macro-prudential issues, e.g., penalising banks' excessive reliance on the interbank market, using the liquidity requirements (BCBS, 2011, Paragraph 33).

This raises some macro-prudential questions: how does these Basel-style requirements, especially Basel III, affect banks' behaviour and the interbank market activities? How do these requirements impact the real economy and social welfare? Has the target for mitigating macro-prudential issues been fulfilled as expected? To answer these questions, we build up a dynamic equilibrium model to investigate the impacts of those Basel-style banking requirements from a macro-prudential perspective. In our model, time horizon is infinite and there are a continuum of banks facing a same source of systematic credit shocks and aggregate deposit variations (source of liquidity shocks), and they are also subject to specific idiosyncratic credit shocks and idiosyncratic deposit variations. Both the idiosyncratic shocks are short-term and occur continuously and overnight while a variation in the mass of liquidity-deficit banks makes those

[1] A newer version of the Basel Accords, referred to as Basel IV, is now under discussion and is planned to be implemented by 2023. However, there is no official guidance on this new accord and, as we will mention in Section 5, the proposed changes to be introduced in Basel IV would not affect our model. Hence, we neglect the discussion of this accord in our paper.

banks become liquidity-surplus or liquidity-deficit banks. These assumptions of regarding the idiosyncratic shocks capture specific variations in credit revenues (the credit shocks) and in liquidity (deposit variations) among banks which cannot be predicted by them beforehand, usually occur within short periods (less than a few days), and can normally be managed through the interbank market. Therefore, our model mimics the *overnight* interbank market.

Unlike other studies which mainly focus on micro-prudential analyses, we incorporate some macro-prudential aspects by including several forces that are beyond a single bank, such as the interbank market and the heterogeneity among banks caused by idiosyncratic shocks. Our model generates the results of aggregate bank loans, liquid asset holdings, average interbank rate, and the aggregate interbank trading volume for each period (year), aiming to mimic the macroeconomic dynamics of the real economy. We then compare the results among all requirement regimes considered, such as when banks are under no regulation, under capital requirements, and under both capital and liquidity requirements, to evaluate the impacts of these requirements on banks, the interbank market, and the real economy (social welfare).

The first contribution of this paper is that we develop a quantitative equilibrium dynamic model to evaluate the impacts of the (Basel-style) capital and liquidity requirements on financial stability (banks' resilience) and social welfare from a macro-prudential angle, i.e., we evaluate their performance considering a system of banks. Unfortunately, this consideration is missing in the literature. Existing studies, such as Repullo and Suarez (2013), De Nicolo *et al.* (2014) and Hugonnier and Morellec (2017), merely evaluate these requirements micro-prudentially, i.e., from the perspective of a representative bank. Walther (2016) considers a macro-prudential analysis merely dealing with fire sales. Accordingly, our paper provides a more thorough evaluation for those requirements as more macro-prudential factors (e.g., banks' heterogeneity due to idiosyncratic shocks) are incorporated in our model.

The second contribution of this paper is that we evaluate the impacts of the Basel-style capital and liquidity requirements on the interbank market. Although extant studies, such as Freixas *et al.* (2011), Liu (2016), Corrado and Schuler (2017) and Davis *et al.* (2020), have considered interbank markets and to some degree investigated the impacts of the banking requirements on the interbank markets, they have not explicitly investigated the impacts on two factors: interbank rates and interbank trading volume. Our paper fills this gap. We calculate these two factors endogenously to investigate their changes across various requirement regimes. This consideration is important as one of the main motivations of the liquidity requirements in Basel III is to limit banks' excessive reliance on the interbank market (BCBS, 2011, Paragraph 33). We find that adding the liquidity requirement to the capital requirement would reduce the interbank rate and thus lower the price of liquidity in the interbank market, i.e., the cost of borrowing from counterpart banks, which implies these requirements would address some macro-prudential issues. Our findings also suggest the existence of a U-shaped relationship between the interbank trading volume (reflecting banks' reliance on the interbank market) and the liquidity ratio required (both for the LCR and NFSR requirements). This result, which has not yet been shown in the existing literature, indicates that the Basel committee's aim to limit banks' excessive reliance on the interbank market would not be achieved if higher liquidity is required.

The third contribution is the consideration of a 'two-stage' decision-making process for our quantitative equilibrium model analysis. Recent quantitative studies such as De Nicolo *et al.* (2014), Begenau and Landvoigt (2018), and Elenev *et al*. (2021), assume that banks' optimal decision choices to maximise their utility function are made simultaneously, i.e., all the decision choices are assumed to be made at the beginning of each period. This simplifying assumption seems to violate reality as some of banks' decision choices, e.g., in response to idiosyncratic deposit value variations, would be made at different points in time. We provide a solution to accommodate nonsynchronous events in our analysis, which could therefore help with the applicability of our quantitative equilibrium model to more complex analyses. In our model, both the discrete-time and continuous-time factors are incorporated, while we solve our model relying on a method designed for discrete-time models. Introducing several appropriate assumptions, e.g., aggregation methods, while no generality is lost, which supports the fact that our approach can also be seen as a methodological contribution.

The main results of our paper are as follows. We find that when banks are unregulated or are only under capital requirements (i.e., no liquidity requirements), their loan holdings are pro-cyclical, and their liquidity holdings are countercyclical. In other words, banks are more illiquid in the economic expansions under those requirement regimes. This liquidity issue can be remedied by liquidity requirements. Imposing liquidity requirements could lead to a lowered interbank rate, which means the liquidity requirement would help to lower the price of liquidity within the interbank market. This finding is in line with the empirical data of the US and European markets represented in Figure 1, which demonstrates a trend of reduction of both the interbank rates and the volume of interbank loans especially after 2010, the year when the liquidity requirements (introduced by Basel III) begin to be implemented.[2]

<Insert Figure 1 here>

We also find from our simulation results that there exists a U-shaped relationship between the interbank trading volume and the liquidity ratio required, which is in line with a simplified version of our model (provided in the Online Appendix). This result can be explained in two ways: 1) under a lower liquidity requirement, banks tend to have low liquidity and thus they would rely on the interbank market to obtain liquidity while raising the liquidity requirements would improve banks' liquidity and help to reduce their reliance on the interbank market

[2] This trend might also be explained as a response to the Global Financial Crisis occurring in 2007-08, which could possibly impact the trading volume and rate. However, there should exist a recovery process at some point before the end of the period represented in the plot (which does not happen given that they remain relatively low until the end of the sample period). This reasoning implies that the observed trend in Figure 1 could be largely due to the introduction of the liquidity requirements.

(captured by lowered interbank trading volume), until the requirement is strengthened to a proper level; however, 2) when liquidity requirements become stricter, banks would rely more on the interbank market to seek more liquidity to meet the stricter requirement. Our results show that liquidity ratios required (for both LCR and NSFR requirements) around 65% would result in lowest interbank trading volume, i.e., less reliance on the interbank market. This means that the current requirement set at 100% seems relatively high when it comes to the reduction of the reliance of banks on the interbank market. Lastly, we find that implementing capital requirements alone results in the highest value of social welfare as compared to other regimes considered. The benefits of imposing liquidity requirements are at the cost of lowered social welfare.

There are several policy implications of our paper. Our findings suggest that the Basel-style capital and liquidity requirements would have some macro-prudential impacts on the banking system, i.e., reducing interbank rates. Liquidity requirements could, in a way, mitigate banks' reliance on the interbank market to manage their liquidity issues *only* with an appropriate level of the required ratios. Our results imply that the current ratio (100%) required seems ineffective in addressing banks' reliance on the interbank market.

The rest of this paper is organised as follows. Section 2 summarises the related literature. Section 3 presents our model, which is solved in Section 4. Section 5 introduces the banking regulations, which will be applied as constraints in the simulation process. Section 6 reports the simulation analyses and results of our quantitative model while Section 7 concludes the paper. An Online Appendix presents our simulation method employed for the simulation, a simplified version of our model as a supplement to our analysis, and additional tables regarding our results.

2. Literature Review

This paper is closely related to the following literature. De Nicolo *et al*. (2014) build up a dynamic model and consider the effects of banks' capital and liquidity requirements from a micro-prudential perspective. They argue that liquidity requirements will unambiguously reduce social welfare, which is in line with our analysis, and they reveal that resolution policies, such as prompt corrective action, seem to dominate the regulations in efficiency and welfare terms. We extend this study by including some macro-prudential factors, such as the interbank market. Hugonnier and Morellec (2017) also establish a dynamic model to allow banks' equity refinancing decisions in case of their insolvency, which has not been considered by De Nicolo *et al.* (2014). Hugonnier and Morellec (2017) find that combining liquidity and capital requirements reduces both the probabilities of default and the related default loss. However, their analysis is also limited to micro-prudential concerns.

Our paper is also related to other literature in banking. Allen *et al.* (2009) develop a model within which the interbank market connects the banks suffering from idiosyncratic liquidity shocks. They conclude that when the interbank market cannot fully hedge banks' liquidity shocks, the market will be prone to higher volatility, and in such situation central banks should intervene. Freixas *et al.* (2011) model a scenario where idiosyncratic liquidity shocks and interbank market are present and they claim that to make banks hold enough liquid assets, the interbank rates should be set high enough, while the rates should be cut during financial crises to maintain financial stability. Acharya and Merrouche (2012) empirically find a 30% increase in the liquidity demand of banks following the 2007–08 subprime crises, causing over-night interbank rate to rise. This finding is in line with our results according to which the interbank rates are higher in economic downturns. 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. Walther (2016) investigates the interactions between banks' capital and liquidity requirements employing a model incorporating their projects' systematic and idiosyncratic risks. The findings of this study suggest that the requirements should be set in a time-varying manner and that the macro- and micro-prudential regulations are imperfect substitutes. Corrado and Schuler (2017) employ a dynamic model to analyse the effects of macro-prudential policies on the interbank market. They find that combining both the capital and liquidity requirements would help to lower welfare losses, thereby highlighting the importance of Basel III. Castiglionesi *et al.* (2019) investigate the impacts of financial integration, which allows banks in different regions to manage liquidity shocks by participating in the interbank market, on the stability of the financial system. They conclude that financial integration leads to more stable interbank interest rates in normal times but to higher interest rates in financial crises, and they also show that financial integration can increase the benefits of the liquidity requirements in a second-best world. Kim *et al.* (2020) build a static model incorporating banks and nonbanking sectors, and they find that despite that the interbank volume would increase when banks' reserves decline the existence of balance sheet costs may motivate banks to borrow from nonbanks instead of from the interbank market. Davis *et al.* (2020) investigate the impacts of liquidity requirements under a stylised interbank market environment by employing an experimental method. They find that adding liquidity requirements (both LCR and NSFR) hampers investment inefficiency and seems less effective than imposing a capital requirement alone in reducing bankruptcies. Elenev *et al.* (2021) propose a general equilibrium model in which both producers and bankers are financially constrained. They find that raising the capital requirements would reduce financial fragility, reduce the size of both financial and non-financial sectors, and lower banks' profits. They also find that a capital requirement set around 6% would maximise social welfare, and counter-cyclical capital requirements improve welfare.

3. The Model

Consider an economy where the horizon is infinite and is divided into a number of periods of unit length. There is a continuum of banks[3], aggregating to unit mass and a representative bank is indexed by $i \in [0,1]$. At the beginning of each period t, banks make decisions on loans and liquid asset holdings in response to a *systematic credit shock* Z_{t-1} and *aggregate deposit value* d_{t-1} to maximise their value function. These two exogenous shocks occur at the end of each period and are generic to all banks. During each period after decisions are made at time t, each bank i face *idiosyncratic credit shocks,* denoted by $f_{\omega,t+v}(i)$, and *idiosyncratic deposit value variations,* denoted by $f_{\psi,t+v}(i)$, where $v \in [0,1]$ denotes time intervals within each time period. Both the idiosyncratic shocks are exogenous[4] and are specific to each bank and these shocks occur continuously within each period and independently across periods.[5] An exogenous variation in the mass of liquidity-deficit banks, occurring at the beginning of the period and independent across periods, makes banks liquidity-surplus or liquidity deficit. As a response, each bank i will continuously choose to adjust its loans[6] and liquid asset holdings and borrow/lending thorough the interbank market with its counterparties (i.e., liquidity-surplus or liquidity-deficit banks) to maximise it value function.

The systematic credit shock $\boldsymbol{Z_t}$ captures the uncertainty of banks' loan revenues due to the variation in economic situations. It follows a first-order autoregressive process[7]

[3] This assumption enables us to divide banks in different groups (to be introduced later) and undertake aggregation of banks without considering their exact number.

[4] The idiosyncratic credit and liquidity shocks are introduced to target banks' probability of failure and interbank trading volume, respectively. Although the shocks are exogenous (i.e., can be seen as random variables, irrespective of banks' asset holdings), banks' loans and liquidity holdings are endogenously determined as the holdings are not purely dependent of the realisation of these shocks; therefore, the resulting banks' probability of failure and interbank volume are endogenous.

[5] The independency assumption of the idiosyncratic shocks across periods is similar to that in Elenev *et al.* (2021), where the authors assume the dispersion of the idiosyncratic shocks follows a Markov process. However, given the objective of our paper, the idiosyncratic shocks are assumed to be unexpected and cannot be managed by banks beforehand, we assume the dispersion of the idiosyncratic shocks is time-varying while the realisation of the dispersion is independent across time.

[6] Due to the fact of lacking in opportunities of investment in the middle of each period, we assume that increment of loans made by liquidity-surplus banks can only be bought from sales of loans by liquidity-deficit banks; this leads to a non-positive net loan increment constraint in our simulation, i.e., no new loans will be generated within each period.

[7] The autoregressive assumption is widely used in related literature, such as De Nicolo *et al.* (2014) and Elenev *et al.* (2021).

$$Z_t = (1 - \rho_Z)\bar{Z} + \rho_Z Z_{t-1} + \varepsilon_{Z,t}, \tag{1}$$

where ρ_Z is persistence of the systematic shock, $\bar{Z}$ is its long-term average, and $\varepsilon_{Z,t} \sim N(0, \sigma_Z^2)$ is the error term. The shareholders' stochastic discount factor (SDF), $M_{t-1,t}$, is then determined by

$$M_{t-1,t} = \beta e^{-g_{t-1}\varepsilon_{Z,t} - \frac{1}{2}g_{t-1}^2 \sigma_Z^2}, \tag{2}$$

where $g_{t-1} = \gamma_0 + \gamma_1 Z_{t-1}$, in which γ_0 and γ_1 are constant price and time-varying price of risk parameter. The term σ_Z is the time-invariant standard deviation of the error term $\varepsilon_{Z,t}$. Equation (2) ensures that $\mathbb{E}_{t-1}\left[M_{t-1,t}\right] = \beta e^{-\frac{1}{2}g_{t-1}^2\sigma_Z^2}\mathbb{E}_t[e^{-g_t \varepsilon_{Z,t}}] = \beta$, which implies the risk-free rate is $1/\beta - 1$. The assumption made in (2) is widely employed in asset pricing literature, such as Zhang (2005) and Jones and Tuzel (2013), indicating a countercyclical price of risk such that the SDF takes higher values during financial contractions while lower values in expansions.

The aggregate deposit value d_t banks receive also follows a first-order autoregressive process[8]

$$\log d_t = (1 - \rho_D)\log \bar{d} + \rho_D \log d_{t-1} + \varepsilon_{D,t},$$

where $\boldsymbol{\rho_D}$ is the persistence of deposits, $\boldsymbol{\bar{d}}$ is its long-term average, and $\boldsymbol{\varepsilon_{D,t} \sim N(0, \sigma_D^2)}$ is the error term. The error terms $\boldsymbol{\varepsilon_{D,t}}$ and $\boldsymbol{\varepsilon_{Z,t}}$ have a correlation coefficient $\boldsymbol{\theta < 0}$, as in De Nicolo *et al.* (2014).[9] The negative $\boldsymbol{\theta}$ suggests that when $\boldsymbol{\varepsilon_{Z,t} > 0}$, i.e., when banks receive a positive credit shock, deposit variations are likely to be negative as depositors might withdraw more than in other economic states to look for other profitable investment opportunities because the economy is booming. On the other hand, depositors would withdraw less when $\boldsymbol{\varepsilon_{Z,t} < 0}$ due to

[8] We adopt this assumption following De Nicolo *et al.* (2014).
[9] We show in Online Appendix A how this force is modelled in our simulations.

the lack of attractive investment opportunities.[10]

Idiosyncratic credit shocks[11] are *independent and identically distributed* (*i.i.d.*) across banks and time and are defined as $f_{\omega,t+v}(i) = \sigma_{\omega} dB_v$, where $v \in [0,1]$ and B_v is a Brownian motion. For notational simplicity and in line with the law of large numbers,[12] we drop the subscript i from the equations in the remainder of this paper. These shocks capture the uncertainty of banks' revenues from loans, occurring in banks' daily operations, due to individual factors such as operational costs and managers' skills. Idiosyncratic deposit value variations realise at the value of $f_{\psi,t+v} = d_t(\tau dv + \sigma_d dB_v)$, impacting on liquidity-surplus banks with $f_{\psi,t+v}$ and on liquidity-deficit ones with $-f_{\psi,t+v}$. These shocks reflect banks' individual short-term deposit value variations, normally lasting overnight or a couple of days, i.e., within $[t-v, t+v]$, where v represents a time interval. For a given period t, the mass of liquidity-deficit banks is $\lambda_t \sim N(1/2, \sigma_{\lambda}^2)$, where λ_t is truncated to $0 < \lambda_t < 1$, and the mass of liquidity-surplus banks is $1 - \lambda_t$.[13] This assumption implies that a representative bank has a probability of λ_t to become a liquidity-deficit bank and $1 - \lambda_t$ to become liquidity-surplus. The expected cumulative idiosyncratic deposit variation in one period is $\int_0^1 f_{\psi,t+v}\, dv = \tau d_t$, which means the expected cumulative variation in deposits of one representative bank in one period, conditional on the realisation of λ_t, is $\tau(1 - 2\lambda_t)d_t$. Given the properties we have assumed for λ_t, the expected cumulative idiosyncratic deposit value variation in bank i in one

[10] The existence of a negative θ is supported by our collected data of US chartered banks from 1995 to 2017. The results are available upon request.

[11] By the law of large numbers, idiosyncratic credit shocks will not affect banks' decision choices occurring at the beginning of each period. We thus assume the idiosyncratic credit shocks will only occur in each period (not across periods).

[12] As mentioned later by the aggregation problem, which is proved in Online Appendix B, we can investigate the investment choice of a representative bank for the aggregation of banks.

[13] This assumption captures the heterogeneity of liquidity among banks which leaves some banks surplus of liquidity looking for investment opportunities while causes other ones' shortage of liquidity seeking for an immediate liquidity aid. To focus on our objectives, we assume that an interbank market, which we will introduce later, is more efficient and less costly than a central bank's liquidity injection when absent an aggregate liquidity shortage (Liu, 2016). Since our focus in this paper is banks' behaviours and it is assumed that there are no severe aggregate liquidity shortages which may lead to interbank market breakdown, we thus disregard the central banks' intervention to inject liquidity in our analysis.

given period is zero.[14]

3.1 Bank Dynamics for Systematic Credit Shocks and Aggregate Deposit Variations

At the beginning of a representative period t, a representative bank makes investment choices in loans l_t and in liquid assets (such as risk-free government bonds) c_t and funds its investments with deposits d_t and its own capital k_t. This arrangement makes the balance sheet of the bank at the beginning of period t satisfy

$$l_t + c_t = d_t + k_t.$$

Loans l_t generate risky revenues (subject to the realisation of Z_t) and liquid assets c_t generate a risk-free return r_f. Note that $c_t < 0$ implies a negative position in risk-free assets, e.g., issuing bonds. The deposit rate of d_t is r_d.

The law of motion of l_t can be modelled as[15]

$$l_t = l_{t-1}(1-\sigma) + \Delta l_t,$$

where Δl_t is the new investment in loans for period t, and $\sigma \in (0, 1/2)$ is the portion of the existing loans matured at the end of the previous period, i.e., $t-1$. Δl_t can be positive if banks expand lending and negative if they liquidate their existing loans.[16] The loan management cost can be expressed as

$$M(l_t) = m\left(\frac{l_t}{\bar{d}_t} - 1\right)^2,$$

where m is the unit price for loan management cost and $\bar{d}_t = \upsilon d_t$ is introduced to target

[14] This assumption indicates that the idiosyncratic deposit value variations cannot be forecasted and be considered for investment decisions in advance. Such assumptions claiming that the idiosyncratic variations are unknown prior to their realisations are largely employed in the literature, for example Diamond and Dybvig (1983).

[15] As in Repullo and Suarez (2013) and De Nicolo *et al.* (2014), we implicitly assume that the amount of the existing loans will not be reduced if loans default. However, defaults of the loans are modelled in the realisations of the (systematic and idiosyncratic) credit shock, which affects loan returns as in (3). Hence, a lower loan return can represent a higher default rate of loans. For more details regarding modelling this force, refer to Repullo and Suarez (2013).

[16] As in De Nicolo *et al.* (2014), $\sigma < 1/2$ ensures that $1/\sigma - 1 > 1$. This assumption implies that the weighted average maturity of the existing loans is longer than one period, which implies their illiquid properties compared with the liquid assets. The weighted average maturity of existing loans at t is $\sum_{s=0}^{\infty} s\frac{\sigma l_{i,t+s}}{l_{i,t}} = \frac{1}{\sigma} - 1$, where the residual of outstanding loans at $t+s$ is $l_{i,t+s} = l_{i,t}(1-\sigma)^s$.

the average ratio of bank credit to deposits, observed from the relevant data.[17] This assumption implies that the management costs are higher if banks' loan holdings are above or below the average value $\bar{d}_t$, similar to De Nicolo *et al.* (2014), Hugonnier and Morellec (2017), and Elenev *et al.* (2021). This means that banks may need more labour and resources to manage and supervise the increased loans or banks may need to exert more efforts (e.g., advertising) to seek loan borrowers if banks' loan holdings are lower.

The loan revenue function $\pi(l_t)$ at t can be presented as

$$\pi(l_t) = Al_t^{\alpha}, \tag{3}$$

where $A > 0$ is the loan rate parameter, and α is the parameter of return to scale of loan revenues, and $0 < \alpha < 1$. We can show that $\pi(0) = 0$, $\pi(l_t) > 0$, $\partial\pi(l_t)/\partial l_t > 0$ and $\partial^2\pi(l_t)/\partial l_t^2 < 0$. The total loan revenues, represented by $\pi(l_t)Z_t$, are subject to the realisations of the credit shock Z_t, which is introduced in (1). Equation (3) implies banks' loan revenues are subject to a decreasing return to scale, following Holmstrom and Tirole (2001) and Acharya *et al.* (2010). This assumption guarantees banks' value function is concave, and thus ensures the existence of an upper bound of l_t for the simulation solution.

3.2 Bank Dynamics for Idiosyncratic Shocks

Within each period, idiosyncratic shocks occur to each bank continuously and independently, and for a representative time interval, for example $t + v$, banks can participate in the interbank market,[18] leading to an equilibrium interbank trading volume r_{t+v}^{j}, where $j = d, s$ indicates the bank is a liquidity-deficit and -surplus bank, respectively. Banks can also adjust their assets, i.e., loans and liquid assets, subject to an adjustment cost Φ,[19] which can be defined as

[17] The target is the average ratio of US banks' credit to deposits, which we will introduce in Section 7.1.

[18] As mentioned before, our model mimics the overnight interbank market. Hence, our results have a better implication for this particular market.

[19] The management cost includes transaction and underwriting costs of trading these assets as the trading occurs before the maturity of the assets, i.e., at the end of each period. This assumption implies that interbank borrowing or lending would incur lower costs in dealing with short-term funding needs.

$$\Phi_L\left(l_{t+v}^j\right) = \phi_L\left(\frac{\hat{l}_{t+v^-}^j}{l_t^j}\right) l_{t+v}^j, \tag{4}$$

$$\Phi_C\left(c_{t+v}^j\right) = \phi_C\left(\frac{\hat{c}_{t+v^-}^j}{c_t^j}\right) c_{t+v}^j, \tag{5}$$

where l_{t+v}^j and c_{t+v}^j are banks' adjustments in the asset holdings made at $t+v$, and $\hat{l}_{t+v^-}^j$ and $\hat{c}_{t+v^-}^j$ are the corresponding cumulative changes until $t+v^-$, where v^- denotes the previous time interval of v. We set the parameters $\phi_L > \phi_C$ to reflect the fact that it is more costly to trade loans than the liquid assets due to loans' higher illiquidity. Equations (4) and (5) indicate that the unit cost of adjustment, $\phi_L \hat{l}_{t+v^-}^j / l_t^j$ and $\phi_C \hat{c}_{t+v^-}^j / c_t^j$, depends on the deviations of their original position of asset holdings, which means that, as in Elenev *et al*. (2021), the adjustment costs are frictions of the banking system that penalise upward and downward deviations of banks' original position of asset holdings, at the beginning of each period.[20]

3.3 Timeline

The timeline of the events described previously and the collection of corporate tax $\varsigma(y_{i,t})$ occurred at the end of the period is summarised in Figure 2, in which we use a typical time period t and a representative bank for illustration.

<Insert Figure 2 here>

In case of bankruptcy, the government will take over the defaulting banks, repay their depositors in full and replace those banks with new ones, and endow new banks with the same value of deposits and capital as the surviving ones.[21] By the law of large numbers, we can obtain aggregation of banks' optimal choices by looking into a representative bank for the analysis and by investigating the problem from a representative time interval (for the decision

[20] As explained in Online Appendix B, the function forms assumed in Equations (4) and (5) also ensure the additivity of the first-order conditions in the aggregation, which makes $\int_0^1 \Phi_L'\left(L_{t+v}^j\right) dv \approx \Phi_L'\left(\hat{L}_{t+v}^j\right)$.

[21] This assumption ensures the total mass of banks is one (i.e., one unit) and banks' aggregate assets are unchanged after the replacement.

regarding the idiosyncratic shocks). We present the proof of the aggregation problem in Online Appendix B. Model solution is introduced in Section 4, where we use the capital letter of the corresponding variables as the notation to indicate that the solutions refer to the whole banking system, when considering the aggregation of individual banks.

4. Model Solution

Due to the characteristics of our model, we first introduce the analysis of idiosyncratic shocks and then introduce the analysis of systematic credit shocks and aggregate deposit variations.

4.1 Decisions for Idiosyncratic Shocks

Denote the original value of loans and liquid assets (i.e., at the beginning of t) held by the banking system as L_t and C_t, respectively, and deposit amount as D_t. We also use the following equations $L_t^d = \lambda_t L_t$ ($C_t^d = \lambda_t C_t$) and $L_t^s = (1-\lambda_t)L_t$ ($C_t^s = (1-\lambda_t)C_t$) to respectively represent the loan and liquid asset holdings of liquidity-deficit and liquidity-surplus banks at the beginning of period t, recalling that λ_t is the mass of liquidity-deficit banks. Given the different decision choices of the liquidity-deficit and liquidity-surplus banks, we will introduce them separately in the following subsections.

4.1.2 Liquidity-Deficit Banks

For the time interval $v \in [0,1]$, we write the liquidity-deficit banks' budget constraint as

$$I_{t+v}^d + L_{t+v}^d + C_{t+v}^d - R_{t+v^-}^d + q_t^R R_{t+v}^d \geq f_{\psi,t+v} - f_{\omega,t+v} + \Phi_L\left(L_{t+v}^d\right) + \Phi_C\left(C_{t+v}^d\right). \quad (6)$$

The above constraint shows that the liquidity-deficit banks face exogenous idiosyncratic shocks $-f_{\psi,t+v} + f_{\omega,t+v}$, and can choose to sell (trade) loans to obtain L_{t+v}^d subject to the adjustment cost $\Phi_L\left(L_{t+v}^d\right)$, sell (trade) liquid assets to obtain C_{t+v}^d by paying for the related costs $\Phi_C\left(C_{t+v}^d\right)$, borrow $q_t^R R_{t+v}^d$ from the interbank market, and repay $R_{t+v^-}^d$ borrowed from the previous time interval, i.e., v^-, or pay (negative) dividends I_{t+v}^d with the equity issuance cost η to make up for the liquidity shortage. Note that one can show that from this definition the interbank rate $r_t^p = 1/q_t^R - 1$.[22] We present a detailed simulation solution for the liquidity-deficit banks in Online Appendix C.1.1.

4.1.3 Liquidity-Surplus Banks

The budget constraint of the liquidity-surplus banks at time interval $v \in [0,1]$ is given by

$$I_{t+v}^s + L_{t+v}^s + C_{t+v}^s + q_t^R R_{t+v}^s \leq f_{\psi,t+v} + f_{\omega,t+v} - \Phi_L(L_{t+v}^s) - \Phi_C(L_{t+v}^s) + \left[1 - \eta_{\omega+\psi,t+v^-}^d\right] R_{t+v^-}^s. \tag{7}$$

Equation (7) implies that liquidity-surplus banks facing exogenous idiosyncratic shocks $f_{\psi,t+v} + f_{\omega,t+v}$ need to adjust their holdings of loans at the amount of L_{t+v}^s subject to the adjustment cost $\Phi_L(L_{t+v}^s)$, adjust the holdings of liquid assets at the amount of C_{t+v}^s, and pay for the related costs $\Phi_C(L_{t+v}^s)$, and retain dividends I_{t+v}^s to the shareholders. The banks can also participate in the interbank market to lend $q_t^R R_{t+v}^s$ to the liquidity-deficit ones and are repaid $\left[1 - \eta_{\omega+\psi,t+v^-}^d\right] R_{t+v^-}^s$ that is lent at the previous time interval, i.e., v^-, where $\eta_{\omega+\psi,t+v^-}^d$ indicates the probability of default of the liquidity-deficit banks at $t + v^-$, which thus captures the *counterparty risks* in the interbank market. Upon default, the government will step in and bail out the failed banks for the following time interval.[23] We present a detailed simulation solution for the liquidity-surplus banks in Online Appendix C.1.2.

4.1.4 Equilibrium of the Banking System

Given the realisations of $\{Z_{t-1}, D_t, \lambda_t, L_t, C_t, f_{t+v}(\psi), f_{t+v}(\omega)\}$, we define equilibrium values of the cumulative variables at the end of the period, i.e., at $t+1$, summarised as $\{\hat{L}_{t+1}^d, \hat{C}_{t+1}^d, \hat{R}_{t+1}^d\}$ for liquidity-deficit banks and $\{\hat{L}_{t+1}^s, \hat{C}_{t+1}^s, \hat{R}_{t+1}^s\}$ for liquidity-surplus banks in the following set of equations, which features the equilibrium of this model:

Loans:
$$\tilde{L}_t = \sum_{j=s,d} H_{\omega+\psi,t+1}^j \left(L_t^j + \hat{L}_{t+1}^{j=s} 1_{\{j=s\}} - \hat{L}_{t+1}^{j=d} 1_{\{j=d\}}\right), \tag{8}$$

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[22] For computational tractability, we assume the (overnight) interbank rate q_t^R is constant for a given t.

[23] We assume the defaulting banks are bailed out by the government, thus the mass of the liquidity-deficit and liquidity-surplus is unchanged and the total mass of the banks remains one.

Liquid assets: $\tilde{C}_t = \sum_{j=s,d} H^j_{\omega+\psi,t+1}\left(C^j_t + \hat{C}^{j=s}_{t+1} 1_{\{j=s\}} - \hat{C}^{j=d}_{t+1} 1_{\{j=d\}}\right),$ (9)

Interbank assets: $\hat{R}^d_{t+1} = \hat{R}^s_{t+1},$ (10)

Profits after taxes: $P_t = (1-\varphi)Y_t = (1-\varphi)\Big\{\pi(L_t)Z_t\tilde{L}_t + r_f\tilde{C}_t -$

$r_d \sum_{j=s,d} H^j_{\omega+\psi,t+1}[1+\tau(1-2\lambda_t)]D^j_t\Big\}.$ (11)

Equations (8) and (9) are the market clearing conditions for loans and liquid assets, where $H^j_{\omega+\psi,t+1} = 1 - \int_0^1 \eta^j_{\omega+\psi,t+v} dv$ denotes the mass of surviving banks $j = s, d$ at the end of the period and $\eta^j_{\omega+\psi,t+v}$ is the probability of default of bank $j = s, d$ at $t + v.$ Equation (10) is the clearing condition for interbank assets and (11) is the profit after corporate taxes, where corporate taxes are defined as $\varsigma(Y_t) = \varphi Y_t$. Note that the corporate taxes are levied according to a convex function of Earnings Before Taxes (EBT), i.e., Y_t , which means $\varphi = \varphi^+ \max\{Y_t, 0\}/Y_t + \varphi^- \min\{Y_t, 0\}/Y_t$. The assumption that $\varphi^- \leq \varphi^+$ reflects a reduced tax benefit from loss carryback or carryforward. We present a detailed implementation of the market clearance and of the whole model in Online Appendix C.2.

4.2 Decisions for Systematic Credit Shocks and Aggregate Deposit Variations

At the beginning of $t+1$ (after the realisation of Z_t and D_{t+1}), banks will maximise their equity value by choosing optimal loans L_{t+1} and liquid assets C_{t+1} for the coming period, according to the realisations of $\left(\tilde{L}_t, \tilde{C}_t, P_t, D_{t+1}, D_t\right)$, where $\left(\tilde{L}_t, \tilde{C}_t, P_t\right)$ are defined in (8), (9) and (11), respectively. Banks will be subject to requirement constraints, if any, and the following budget constraint

$$(1-\Phi_0)N_t + E_t - \Phi_E(E_t) - M(\Delta L_{t+1}) \geq L_{t+1} + C_{t+1} - D_{t+1} - \varrho C^2_{t+1} \cdot \chi_{C_{t+1}<0}, \quad (12)$$

where Φ_0 stands for the target pay-out ratio of dividends to equity. $N_t = [1 + (1-\varphi)\pi(L_t)Z_t]\tilde{L}_t + \left[1 + (1-\varphi)r_f\right]\tilde{C}_t - D_{t+1}$ represents the (market) equity value of banks prior to the decision choices. E_t and $\Phi_E(E_t)$ are the amount of equity issuance[24] and the relating issuing costs. $\Delta L_{t+1} = L_{t+1} - (1-\sigma)\tilde{L}_t$ and $M(\Delta L_{t+1})$ denotes the loan adjustments and the associated adjustment costs, respectively. The term $\varrho C_{t+1}^2 \cdot \chi_{C_{t+1}<0}$ captures the deposit insurance fee, and ϱ is the corresponding parameter, which will be incurred if banks have a negative position in liquid assets, i.e., when $C_{t+1} < 0$.[25] Equation (12) ensures that the retaining equity $(1-\Phi_0)N_t$ plus the newly issued equity $E_t - \Phi_E(E_t) - M(\Delta L_{t+1})$, net of the incurred costs, should be no less than the equity after the decision of new investments, i.e., $L_{t+1} + C_{t+1} - D_{t+1} - \varrho C_{t+1}^2 \cdot \chi_{C_{t+1}<0}$, considering the deposit insurance fee $\varrho C_{t+1}^2 \cdot \chi_{C_{t+1}<0}$. The equity issuance cost $\Phi_E(E_t)$ in (12) is defined as

$$\Phi_E(E_t) = \phi_E E_t^2, \tag{13}$$

where ϕ_E is the parameter of equity issuance cost. The equity issuance cost is considered with a view to targeting the ratio of banks' equity issuance to total book equity, as observed from our data. Thus, the net dividend pay-out I_t can be summarised as the sum of after-tax income P_t and dividend pay-out $\Phi_0 N_t$, deducting equity issuance E_t, and is expressed as:

$$I_t = P_t + (\Phi_0 + \Phi_1)N_t - E_t, \tag{14}$$

where Φ_1 is the ratio of banks' share repurchase to total equity, as observed from US data. The inclusion of (13) and (14) aims to match the observed banks' net equity issuance ratio and net dividend payout ratio, respectively. Equation (14) will then be used for the banks' equity valuation and will be introduced in Section 4.3.

4.3 Bank Equity Valuation and Bellman Equation

[24] In our analysis, a positive equity issuance indicates banks shareholders' retaining revenues as equity; while a negative equity issuance implies shareholders' selling their equity to new shareholders (equity issuance to new shareholders), a way of diluting their ownership of the banks.

[25] The inclusion of the deposit insurance fee aims to match the targeted ratio of bank loans to deposits (86%) for unregulated banks according to our collected data. We will present the respective comparison in Table 4. This assumption also set up a collateral constraint on banks which are in the negative position of liquid assets (bonds) to ensure their issued bonds are fully collateralised. This consideration thus has a function similar to Equation (10) in De Nicolo *et al.* (2014).

Let $E(x_t)$ denote the equity value of banks at time t. Given the realisations of the state $x_t = \{L_t, C_t, Z_t, D_t, \lambda_t\}$, we define $E(x_t)$ as

$$E(x_t) = \max_{\left\{\left(\mathcal{Q}_p, \mathcal{Q}_{p+v}^j\right), p=t,\dots,T, v\in[0,1]\right\}} \mathbb{E}_t \left\{ \sum_{p=t}^{T} \left[I_p\left(x_p, W_p\right) + \int_0^1 \left[-I_{p+v}^d\left(x_p, W_{p+v}^d\right) + I_{p+v}^s\left(x_p, W_{p+v}^s\right)\right] dv \right] \prod_{q=t}^{p} M_{q-1,q} \right\},$$

where $\mathbb{E}_t[\cdot]$ is the expectation with respect to t, which is employed to value the streams of banks' dividends $I_{p+v}^j\left(x_p, W_{p+v}^j\right)$, resulting from banks' optimal decision choices for the idiosyncratic shocks, and $I_p\left(x_p, W_p\right)$, from the optimal choices for systematic credit shocks and aggregate deposit variations. These dividends are defined in (6), (7) and (14), respectively, where W_{p+v}^j is the initial wealth of bank j upon $p+v$ and W_p is the initial wealth of banks at period p. $\mathcal{Q}_{p+v}^j$ is the decision choices of $\left\{I_{p+v}^j, L_{p+v}^j, C_{p+v}^j, R_{p+v}^j\right\}$ and $\mathcal{Q}_p$ is the decision choices of $\{L_t, C_t\}$ described in sections 4.1 and 4.2, respectively. $M_{q-1,q}$ is the discount factor as defined in (2). Note that $M_{q-1,q} = 1$ if $q = t$ as the valuation is calculated with respect to t. Since this model is stationary, it can be solved by Bellman Equation with involvement of two periods, e.g., current period and the next one. The value of banks' equity thus satisfies

$$E(x_t, W_t) = \max\left\{0, \max_{\{\mathcal{Q}_t, \mathcal{Q}_{t+v}, v\in[0,1]\}} \left\{ I_t(x_t, W_t) + \int_t^{t+1} \left[\sum_{j=d,s} I_{t+v}^j\left(x_t, W_{t+v}^j\right)\right] dv + \mathbb{E}_t\left[M_{t,t+1} E(x_{t+1}, W_{t+1})\right] \right\} \right\}. \tag{15}$$

Due to limited liability, equity value $E(x_t, W_t)$ is nonnegative and will be zero if banks are insolvent, at which point the government will bail out banks in distress. In Online Appendix C, we explain how Equation (15) is used in both decisions.

4.4 Bank Value and Social Welfare

Following De Nicolo *et al.* (2014), we define enterprise welfare of banks as a metric of their efficiency, which calibrates banks' ability to create 'productive' intermediation.[26] We define it as the sum of bank equity value and deposits netting of short-term investments (i.e., liquid assets), which play no role in contributing to production. The measurement is taken for the whole banking system at the end of each period. As per our definition, banks' enterprise value can be represented as

$$EV(x_t) = E(x_t) + D_t(1 + r_d)\{1 - cH(x_t)\} - C_t, \tag{16}$$

where c is the bankruptcy cost of banks' deposits and $H(x_t)$ is the portion of defaulting banks. *Social welfare* is measured as the value generated from banks' activities to government and the whole economy. We thus define social welfare as

$$SW(x_t) = E(x_t) + D_t(1 + r_d) - C_t + G(x_t), \tag{17}$$

where $G(x_t)$ is the net revenue of the government, which can be written as

$$G(x_t) = F(x_t)\{\varphi Y_t + \mathbb{E}_t[G(x_{t+1})M_{t,t+1}]\} - [1 - F(x_t)]\{c(1 + r_d)D_t + \varsigma(L_t + C_t)\}. \tag{18}$$

The first term of (18) is sum of the current tax revenues φY_t and the expected future tax revenues, $\mathbb{E}_t[G(x_{t+1})M_{t,t+1}]$, as long as banks are solvent. The second term of (18) shows the (negative) payoffs to the government in the form of bankruptcy costs $c(1 + r_d)D_t$ due to its role as the deposit insurer and recovery costs $\varsigma(L_t + C_t)$ paid for the defaulting banks.

5. Banking Regulations

In this section, we introduce Basel-style capital and liquidity requirements as the banking regulations, which will be inserted as the constraints in our simulations.[27]

5.1 Capital Requirements

In the Basel Accords requirements, the capital ratio refers to the ratio of bank capital to risk-

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

[27] In this paper, we consider capital and liquidity requirements from Basel III (BCBS, 2010, 2011, 2013 and 2014). Although a newer version, to be called as Basel IV (BCBS, 2017), is under discussion, the main amendments to be introduced, e.g., restoring creditability in the calculation of risk-weighted assets and improving the comparability of banks' capital ratios, will not affect our model. Thus, we use Basel III as the requirement regime in our analysis.

weighted assets, where we assume they are loans in our model. If banks are under the capital requirement, at least an amount of capital $\widetilde{K}_t = \kappa \tilde{L}_t$ is required to support its lending.[28] Therefore, the feasible set of optimal choices $\left(L_{t+v}^j, C_{t+v}^j, R_{t+v}^j\right)$ and (L_t, C_t), for both decision choices, under the capital requirement can be defined as

$$Л = \begin{cases} \left\{\left(L_{t+v}^j, C_{t+v}^j, R_{t+v}^j\right) \middle| (1-\kappa)L_{t+v}^j + C_{t+v}^j + R_{t+v}^j \geq f_{\omega+\psi,t+v}^j\right\} \\ \left\{(L_t, C_t) \middle| (1-\kappa)L_t + C_t \geq D_t\right\} \end{cases}, \tag{19}$$

where $f_{t+v}^j(\psi+\omega) = -f_{\psi,t+v}1_{\{j=d\}} + f_{\psi,t+v}1_{\{j=s\}} + f_{\omega,t+v}$ captures the idiosyncratic shocks faced by both groups of banks, where $1_{\{j=d\}}$ and $1_{\{j=s\}}$ are indicators equal to 1 when the condition of their subscripts is satisfied and equal to zero otherwise. Equation (19) thus summarises the capital requirement constraint for decisions regarding idiosyncratic shocks (the upper equation) and of credit and aggregate deposit variations (the lower equation), respectively.[29] Thus, for banks under the capital requirement, the feasible set of choice is $Л$.

5.2 Liquidity Requirements

Basel III regulation (BCBS, 2013) introduces the *Liquidity Coverage Ratio* (LCR) requirement for mitigating a 30-day liquidity distress, and *Net Stable Funding Ratio* (NSFR) requirement for a long-term liquidity management, such as one year. Based on our model, LCR better fits the analysis in Section 4.1 and NSFR matches the analysis in Section 4.2. Hence, we will model these two requirements for the analyses individually.

5.2.1 LCR Requirement

The LCR is defined as the ratio of *High-Quality Liquid Assets* (HQLAs) to *Net Cash Outflows* (NCOs). Following BCBS (2013) and Walther (2016), HQLAs are a weighted sum of bank

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[28] Since in our analysis loans are equally risky, this treatment for the risk-weighted loans as in the Basel Accords does not lose generality. Similarly, Shleifer and 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 amount of loan investment.

[29] Note that the requirement constraint for decisions of idiosyncratic shocks is set for the increment in the variables at $t+v$, which implicitly assumes that the requirement constraint holds before that time interval.

assets, where illiquid assets have low weights, while NCOs are weights of bank liabilities with a cash outflow within 30 days assigned with a higher weight. According to LCR and to fit the analysis described in Section 3.1, the ratio of HQLAs to NCOs at $t+v$ should be no less than ι_1, which means

$$\frac{h_S L_{t+v}+C_{t+v}+R_{t+v}^{j=s}-R_{t+v}^{j=d}}{\mu_d f_{\omega+\psi,t+v}^{j}} \geq \iota_1. \tag{20}$$

Equation (20) indicates that the HQLAs[30] are the sum of: 1) 'haircut' increment in loans, $h_S L_{t+v}$, where h_S is the haircut on loans; 2) increments in liquid assets C_{t+v}; and 3) net interbank market assets $R_{t+v}^{j=s} - R_{t+v}^{j=d}$.[31] NCOs are defined as the worst-case scenario of deposit outflow $\mu_d f_{\omega+\psi,t+v}^{j}$, due to the idiosyncratic deposit value variations. Accordingly, the feasible set $Ж_1$ of bank decision choices $\left(L_{t+v}^{j}, C_{t+v}^{j}, R_{t+v}^{j}\right)$ under the LCR liquidity requirement is

$$Ж_1 = \left\{\left(L_{t+v}^{j}, C_{t+v}^{j}, R_{t+v}^{j}\right) \middle| \frac{h_S}{\iota_1 \mu_d} L_{t+v}^{j} + \frac{1}{\iota_1 \mu_d} C_{t+v}^{j} + \frac{1}{\mu_d} R_{t+v}^{j=s} - \frac{1}{\mu_d} R_{t+v}^{j=d} \geq f_{\omega+\psi,t+v}^{j}\right\}. \tag{21}$$

Thus, if banks are subject to both the capital and the LCR liquidity requirement, the feasible set of choice is $Л \cap Ж_1$.

5.2.2 NSFR Requirement

The NSFR is defined as the ratio of *Available Stable Funding* (ASF) to *Required Stable Funding* (RSF). Following BCBS (2013) and Walther (2016), ASF is the weighted sum of bank liabilities and the ones which may cause liquidity shortfalls have low weights. RSF is the sum of bank assets according to their weights where illiquid assets are assigned with high weights. According to NSFR and to fit the analysis described in Section 3.2, the ratio should be no less

[30] For computational tractability, we neglect the tax effect on HQLAs. However, this treatment does not lose generality as HQLAs will be unambiguously reduced when the corporate tax is considered while NCOs are unchanged. Thereby, a higher l would offset this minor bias of neglecting the tax without affecting the characteristics of the LCR liquidity requirement.

[31] As in (19), we implicitly assume banks' asset positions satisfy the liquidity requirement before occurrence of the idiosyncratic shocks, i.e., we can transform the requirement constraints to the increments of the assets.

than ι_2, which means

$$\frac{L_t+C_t-D_t+h_D D_t}{L_t} \geq \iota_2,$$

where the numerator is the sum of equity $L_t + C_t - D_t$ and 'haircut' deposits $h_D D_t$ with a 'haircut' of h_D, while the denominator is the sum of illiquid assets, i.e., loans L_t. Accordingly, the feasible set Ж$_2$ of bank decision choices (L_t, C_t) under NSFR liquidity requirement is

$$Ж_2 = \left\{(L_t, C_t) \mid \frac{1-\iota_2}{1-h_D} L_t + \frac{1}{1-h_D} C_t \geq D_t\right\}. \tag{22}$$

Thus, if banks are subject to both the capital and the NSFR liquidity requirement, the feasible set of choice they are subject to is Л ∩ Ж$_2$.

6. Quantitative Analysis and Results

We use this section to present the simulation results of the model described in Sections 3, 4 and 5. We first introduce the parameters of the variables used in our simulations, and then present our baseline results.[32] We continue this section comparing the results generated by our model with empirical data. Lastly, we conduct some sensitivity analyses to better understand some key drivers of our results.

6.1 Parameters

The parameters we use for simulation are presented in Table 1. The time period is set to one year in order to reflect the fact that, in practice, corporate tax is levied once a year. The estimates are from US data or studies on the US market.

<Insert Table 1 here>

The persistence and standard deviation of the credit shock are estimated from the data of annual return on investments for all US banks, from 1984 to 2019. This leads to the values of the parameters as $\rho_Z = 0.81$ and $\sigma_Z = 0.00962$. The standard deviation of idiosyncratic credit

[32] A detailed simulation procedure is provided in Online Appendix D.

shocks is set at $\sigma_\omega = 0.045$ to match the average US bank failure rate of 0.739%, from the period from 1984 to 2019. Since the estimates of the autocorrelation process of (log) deposits indicate a unit root, we thus estimate its values using the HP-detrending algorithm, which leads to the value of $\rho_D = 0.88$ and $\sigma_D = 0.0145$. The unconditional value of deposits is set at $\overline{D} = 2$, according to the average value of (log) deposits, in trillion dollars, from 1984 to 2019. The correlation between (HP-detrended) deposits and systematic credit shock is set at $\theta = -0.66$, as in our data.

The loan rate parameter A, as defined in (3), is set at $A = 0.075$ to match the observed average loan rates, from 1984 to 2019. This figure is also close to the estimates given by De Nicolo *et al.* (2014). Based on their study, we also adopt the values of parameter of $\alpha = 0.90$. The persistence and standard deviation of idiosyncratic deposit value variations are set at $\tau = 0.12$ and $\sigma_\lambda = 0.005$, respectively, to match the observed mean ratio (5.8%) of interbank loans to deposits from 1984 to 2017[33] and the bank failure rate of 0.739% from the period of 1984 to 2019. The discount factor is set at the value of $\beta = 0.976$ to match the observed average real risk-free (Treasury bond) rate of 2.5% (thus $r_d = r_f = 2.5\%$) from 1984 to 2019. The constant price and time-varying price of risk parameter, defined in (2), are set at $\gamma_0 = 3.22$ and $\gamma_1 = -15.30$, following Jones and Tuzel (2013) and De Nicolo *et al.* (2014). The annual ratio of matured loans is $\sigma = 20\%$, following Van den Heuvel (2008) and De Nicolo *et al.* (2014), which implies that the average maturity of outstanding loans is four years.[34] The tax rates on positive and negative earnings are $\varphi^+ = 20\%$ and $\varphi^- = 0\%$, respectively, according to the average value of US corporate tax rates between 1984 and 2019.

The equity issuance cost $\eta = 0.09$ is adopted according to the average return on equity in the US market from 1984 to 2019. The bankruptcy cost follows Mendicino *et al.* (2018), who

[33] The curtailed observation period of this parameter is due to data availability. Likewise, this limitation also applies to other parameters the observation period of which does not span from 1984 to 2019.
[34] Based on the calculation, the average maturity is $1/\sigma - 1 = 4$.

provide an estimated value of $c = 0.30$. The recovery cost of defaulting banks' assets is $\varsigma = 0.03$, which comes from observed data on the ratio of overhead costs to total assets (at 3%) from 1996 to 2017. The targeted ratio of bank credit to deposits is set at $\upsilon = 1.12$ to match the observed data of US average ratio of bank credit to deposits of 112% from 1984 to 2019. The parameter of deposit insurance fee is set at $\varrho = 0.80$ to ensure the targeted ratio of bank loans to deposits is satisfied for banks which are in a negative position of liquid assets.[35] The pair of the adjustment costs of loans and liquid assets are set at $(\phi_L = 6, \phi_C = 2)$, respectively. These values are selected to match the observed data, from 1986 to 2018, of interbank rate of 4.13% and the standard deviation of the rate of 2.63%. The ratio of dividend pay-out $\Phi_0 = 6.8\%$ and the ratio of share repurchase to total equity $\Phi_1 = 3.8\%$ are based on the observed results from Elenev *et al.* (2021). According to this study, we also set the parameter of equity issuance cost $\phi_E = 4$ and the loan management cost $m = 7.8$ to target the observed average ratio of equity issuance to total equity of 4.8% and the average net dividend pay-out ratio of 5.8%, respectively.

The values of regulatory liquidity 'haircut' are 50% and 90%, respectively, for loans and deposits. They are selected from the documents of BCBS (2013) and BCBS (2014) according to the appropriate category of the respective asset. Lastly, the parameters for banking regulations are set at $\kappa = 6\%$[36] and $\iota_1 = \iota_2 = 100\%$ for the capital and liquidity requirement ratios, respectively (BCBS, 2011).

6.1 Baseline Results

6.1.1 Bank Lending, Equity Issuance and Dividend Pay-out

Our baseline results are reported in Table 2.

<Insert Table 2 here>

[35] In the case when banks' liquid bonds are in negative positions, we treat the bonds as deposits of the banks.
[36] The required ratio of 6% is set for the Tier 1 capital.

This table presents the results of the banks under various regulation regimes, namely when they are unregulated, are subject to capital requirement only, and are subject to both capital and liquidity requirements. The results are obtained using the value function in Equation (15), based on the parameter values in Table 1.

As shown in Table 2, bank lending rises from 1.896 (No regulation) to 2.177 when they are only under the capital requirements (slightly lowered to 2.158 when capital requirements are strengthened to 12%), while this figure falls to 1.949 when liquidity requirements are added to the capital requirements. This result is not surprising and is in line with De Nicolo *et al.* (2014), which implies that a mild capital requirement raises banks' resilience and encourages banks to raise their lending to secure potential profitability, while adding liquidity requirements unambiguously reduces bank lending as banks are required to hold more liquid assets.

The equity issuance ratio rises from –29.50% (unregulated) to 4.79% (capital and liquidity requirements) while the net pay-out ratio reduces from 29.50% (unregulated) to 5.81% (capital and liquidity requirements). This finding indicates that both the requirements would result in a higher equity issuance and a reduced dividend pay-out, thereby lowering banks' value.

6.1.2 Interbank Rate and Interbank Trading Volume

The interbank rate is reduced from 20.84% (unregulated) to 11.61% (capital requirement) and further reduced to 4.24% (capital and liquidity requirements). This finding implies that the requirements imposed raise the liquidity position of banks (reflecting their increased liquid asset holdings) and thus reduces the price of the liquidity within the interbank market. One can also see that with the strengthening of the LCR liquidity requirements (i.e., increasing the minimum ratio required) the interbank rate falls (i.e., reduction in the price of liquidity). The average rate lowers to 0.44% when $\iota_1 = 110\%$, while rises to 12.05% when $\iota_1 = 80\%$. However, this trend does not apply to the NSFR requirements, where the interbank rate falls to 3.68% when the requirement reduces to $\iota_2 = 80\%$, compared with our baseline results of

4.24% when $\iota_2 = 100\%$. This result suggests that LCR and NSFR would affect the interbank rate in different directions, which is not surprising as NSFR targets banks' longer-term liquidity issues and is less effective in affecting the function of the interbank market.

The interbank trading volume is higher at 0.192 when banks are unregulated, and the volume is reduced to 0.073 when capital requirements are added. This result is intuitive as banks are in a healthier condition with capital requirements regulated at the ratio of $\kappa = 6\%$, and their liquid holdings rise to -0.048 (compared with the unregulated banks of -0.427). The interbank trading volume is 0.107 ($\iota_1 = 100\%$) in our baseline result, rising to 0.112 when the LCR requirement $\iota_1 = 110\%$, while this figure reduces to 0.085 when $\iota_1 = 80\%$. The volume remains around 0.107 when the NSFR requirement ranges from $\iota_2 = 80\%$ to $\iota_2 = 110\%$. This result is expected as the NSFR requirement aims to address banks' longer-term liquidity issues and could be less effective in affecting the interbank trading volume. The trading volume reduces to 0.060 when $\iota_1 = \iota_2 = 50\%$, the figure is even lower than the results (0.073) when only the capital requirement is imposed. This result indicates that there is a U-shaped relationship between the interbank trading volume and the liquidity requirements, which is in line with our findings derived from a simplified model (provided in Online Appendix E). This result is not surprising as with mild liquidity requirements banks are in a good liquidity position and thus would not excessively rely on the interbank market to obtain liquidity. However, if the liquidity requirement become strict enough, banks would need to borrow more from the interbank market to satisfy the increased liquidity requirement. This result implies that Basel III's effort for limiting banks' excess reliance on the interbank market seems to have a limited (or even a converse) impact if the liquidity requirements are higher than the optimal level.

We then conduct an analysis by changing the ratios of the liquidity requirements (while keeping the LCR and NSFR requirements equal to each other, i.e., $\iota_1 = \iota_2$) to compare the changes in the interbank trading volume and in the interbank rate. We find that a ratio around

65% (for both LCR and NSFR requirements) would lead to the lowest interbank trading volume. These results are presented in Figure 3.[37] Figure 3 also presents an inverted U-shaped relationship between interbank rates and the liquidity ratio required, which is also in line with the results from the simplified model in Online Appendix E. As will be explained, this relationship is largely due to the fact that the NSFR requirement is not binding with a lower liquidity ratio required and banks thus mainly consume their retained liquidity to deal with the short-term liquidity shortage and to satisfy the LCR requirement (which is proved to be always binding in our model), driving up the price of their retained liquidity. However, if the liquidity requirements become stricter, which makes NSFR requirement constraint binding, banks are of higher liquidity in both longer- and shorter-terms, which thus lowers the price of the liquidity in the interbank market, i.e., the interbank rate reduces.

<Insert Figure 3 here>

6.1.3 Probability of Bank Failure, Bank Value and Social Welfare

The probability of bank failure decreases from 0.89% for unregulated banks to 0.00% when banking regulations are imposed. This result is in line with most of the literature, e.g., De Nicolo *et al.* (2014) and Hugonnier and Morellec (2017), confirming that the capital and liquidity requirements are effective in minimising bank failure. Bank equity value raises from 3.49 (unregulated) to 4.03 (capital requirement) but falls to 1.97 when both capital and liquidity requirements are in place. The pronounced reduction in bank value when the liquidity requirements are added is primarily owning to the fact that banks' dividends are lowered, and equity issuance is raised. Social welfare increases from 5.831 (unregulated) to 6.114 when banks are under capital requirement regimes, while reducing to 3.831 when both the capital

[37] A detailed result is presented in the Online Appendix, Table OA2.

and liquidity requirements are in place.[38] This result is in line with De Nicolo *et al.* (2014), who suggest that imposing capital requirements alone seems to result in the highest value of social welfare while the combination of the capital and liquidity requirements would result in lower social welfare. Similar to De Nicolo *et al.* (2014), we also find a U-shaped relationship between social welfare and the capital requirements, i.e., social welfare is at 5.831 when no capital requirements are imposed, and the welfare terms raises to 6.114 when $\kappa = 6\%$, but reduces to 6.035 when the requirement is improved to $\kappa = 12\%$. However, we cannot find this U-shaped relationship between liquidity requirements and social welfare, i.e., social welfare seems to be at the optimal value when no liquidity requirement is imposed. This result implies that the addition of liquidity requirement to the regulatory regimes would unambiguously reduce social welfare. Thus, our results suggest that regulators should consider whether it is optimal to exchange social welfare with bank liquidity, before implementing liquidity requirements.

6.1.4 Cyclical Variation Analysis

In this subsection, we present some cyclical analyses where we report our simulation results according to the realisations of the exogenous shocks, i.e., credit shock Z, aggregate deposit value D, and mass of liquidity-deficit banks λ, with the aim to investigate the changes in banks' behaviours among the variations in those shocks. The results are presented in Table 3.

<Insert Table 3 here>

From Table 3, we can see that banks' loan holdings are pro-cyclical, i.e., the ratios of loans to deposits are lower when the economy is in downturns ($Z = 0.98$), while banks'

[38] Combining this with the results of bank lending, one can see that banks under capital and liquidity requirements would have higher bank lending at 1.949, compared with 1.896 when banks are unregulated. However, social welfare of the regimes under capital and liquidity requirements is 3.831, even lower than that of unregulated banks, at 5.381. One main reason behind this is that the capital and liquidity requirements highly reduce bank equity value by boosting equity issuance and limiting dividend payments, which, based on Equation (17), lowers social welfare.

liquidity holdings are counter-cyclical, in other words, the ratios of liquid assets to deposits are lower in the expansionary periods ($Z = 1.02$).[39] In other words, banks are more illiquid in economic expansions. However, adding the liquidity requirement would help to raise banks' liquidity in economic expansions as banks' ratios of liquid assets to deposits are higher in booms (0.087) than recessions (0.084). This novel result thus suggests that the liquidity requirement is more effective in economic upturns.

Interbank rates and interbank trading volume are both higher in recessions, indicating the liquidity are more expensive in economic downturns. This finding is line with Acharya and Merrouche (2012), who find that interbank rates are higher in economic downturns. Loans are normally higher when banks hold larger values of deposits $D = 2.03$ and banks' liquid asset holdings are thus lowered as banks would prefer transforming the deposits into loans to obtain higher profitability from lending. In other words, banks are more illiquid when they hold higher value of deposits. However, adding liquidity requirements would help to remedy this trend, which makes liquid asset holdings higher (0.173) when deposits are at their highest levels. This finding indicates that liquidity requirements are effective in mitigating banks' liquidity issues. Interbank rates and the trading volumes are thus higher when banks hold higher value of deposits, where banks have lower liquidity. When mass of liquidity-deficit banks is of higher value, i.e., when $\lambda = 0.505$, which means the aggregate liquidity in the economy is lower, there is a reduction in loans. Interbank trading volume reduces while interbank rate rises. These two findings are intuitive as there are more banks suffering from liquidity shortages, thus there would be lower liquidity supply in the interbank market. This fact makes liquidity more expensive and hence raises the interbank rate.

6.2 Model versus Data

[39] As mentioned in Section 3, the aggregation deposit variation is (negatively) correlated with the systematic credit shocks. We thus opt for presenting the results by dividing the value of deposits to avoid the dependency of deposits on the credit shock.

We use this subsection to present the comparison of the results obtained from our simulations and the targets we observe from the empirical data. The comparison is presented in Table 4. Overall, the targets are generally matched.

<Insert Table 4 here>

This result thus indicates that our aims of targeting the dynamics from the observed data using the US market are achieved. In other words, our model generates an economy which matches some key dynamics of the US macro-economy.

6.3 Sensitivity Analysis

We use this subsection to present sensitivity analyses for some of the key variables of our model. For comparison, we use our baseline results when banks are under both capital and liquidity requirements as benchmark and compare the changes in the results against the benchmark. We present the results in Table 5.

<Insert Table 5 here>

We first raise the loan rate from $a = 0.075$ to $a = 0.080$. We find that this change results in a higher bank lending and a lower liquid asset holding, which means that with an increase in loan rate, bank lending become more profitable. Interbank rate is reduced as banks are in a better condition, thanks to the increased revenues from loans. Accordingly, social welfare raises to 4.72 from our baseline results (3.83). We then compare the results when the annual rate of matured loans rises from $\sigma = 0.20$ to $\sigma = 0.40$, which implies that loans are more liquid. The trend of changes is similar to an increase in the loan rate, as when loans become more liquid, they would be more preferred by banks with their higher liquidity, and the resulting social welfare would rise to 5.148.

We then increase the loan trading cost from $\phi_L = 6$ to $\phi_L = 8$, which means the adjustment of loans to deal with the idiosyncratic shocks is more costly. Hence, there is a slight increase in bank lending to 1.969 (from our baseline 1.949) as banks would reduce the trading of loans to meet the idiosyncratic liquidity shortages. Interbank trading rises to 0.110, together with an increased interbank rate to 6.16%, which witnesses a higher demand of liquidity from the interbank market. Social welfare rises to 4.053, primarily thanks to the sustained bank lending. Lastly, we raise the equity issuance cost $\phi_E = 4$ to $\phi_E = 6$, which creates a situation where issuing equity become more costly. As a result, equity issuance ratio lowers to 1.37% while the net dividend pay-out ratio increases to 9.23%. This change then results in a higher bank lending at 1.969 and a higher value of social welfare at 4.030.

7. Conclusions

In this paper, we build a macro-economic model in which banks are subject to various shocks and rely on an interbank market to manage their idiosyncratic shocks. Banks choose an optimal level of loans, liquid assets, and interbank borrowing, which leads to an equilibrium of interbank rates and interbank trading volume. We aim to investigate the macro-prudential effects of Basel-style capital and liquidity requirements on banks, interbank market, and social welfare. We endogenise several macro-prudential forces, such as interbank rates and interbank trading volume, which have been less documented in the existing literature.

We find that implementing liquidity requirements would lead to a lowered interbank rate, which means the liquidity requirement would help to reduce the price of liquidity within the interbank market. For the first time, we identify a U-shaped relationship between the interbank trading volume and the liquidity requirements, indicating that banks' reliance on the interbank market (captured by the interbank trading volume) could be mitigated only if an appropriate level of liquidity is required. We also suggest that the ratio recommended in Basel III (100% set for the liquidity requirements) seems to violate its aim of limiting banks' excessive reliance on the interbank market, and that liquidity requirement ratios (for both LCR and NSFR ratios) around 65% would minimise banks' excessive reliance on the interbank market. Lastly, we find that imposing capital requirements alone would be nearest to the optimal level of social welfare and the benefits of implementing liquidity requirements are at the cost of lowered social welfare. We also suggest that the current liquidity ratio required at 100% seems sub-optimally high in terms of its impact to the interbank market and of its contribution to social welfare.

Future studies could extend our model by introducing endogenous liquidity runs, while in our model the liquidity deposit variations are exogenous factors. Relaxing this assumption could better reflect the reality and help to evaluate the performance of the capital and liquidity requirements more comprehensively. Second, considering several heterogeneities within the bank system, such as systemic importance, would further improve the generality of our model. The analysis concerning the systemic importance would be in line with the implementation of the Basel III Accord, which regards Global *Systemically Important Banks* (G-SIBs) as a main concern (BCBS, 2011).

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Table 1
Baseline parameters

This table presents the notation and description of parameters in the model proposed in this paper and reports their target or source. The value of each parameter is presented in the rightmost column.

Notations	Description	Target & Source	Value
ρ_Z	Persistence of systematic shock	AR(1) bank Inve. Ret., 84-19	0.81
σ_Z	Standard deviation of systematic shock	AR(1) bank Inve. Ret., 84-19	0.00962
σ_ω	Standard deviation of idiosyncratic credit shock	Bank fail. rate of 0.739%, 84-19	0.045
ρ_D	Persistence of deposits	HP-detrended deposits, 84-19	0.88
σ_D	Standard deviation of deposits	HP-detrended deposits, 84-19	0.0145
$\overline{D}$	Unconditional average of deposits	Mean of (log) depts in tri$, 84-19	$2
θ	Corr. between deposit and systematic credit shock	Corr. of des and Inve. Ret., 84-19	-0.66
A	Loan rate parameter	Average loan rate, 84-19	0.075
α	Diminishing return to scales	De Nicolo *et al.* (2014)	0.90
τ	Significance of vari. in mass of liquidity-deficit banks	Mean. Intb./Deps. of 5.8%, 84-17	0.12
σ_λ	S.D. of vari. in mass of liquidity-deficit banks	Bank failure rate of 0.739%, 84-19	0.005
β	Time discount factor	Real risk-free rate of 2.5%, 84-19	0.976
$r_d = r_f$	Deposit rate, risk-free rate	Real risk-free rate of 2.5%, 84-19	2.5%
γ_0	Constant price of risk parameter	Jones and Tuzel (2013) De Nicolo *et al.* (2014)	3.22
γ_1	Time varying price of risk parameter	Jones and Tuzel (2013) De Nicolo *et al.* (2014)	-15.30
σ	Annual percentage of matured loans	De Nicolo *et al.* (2014)	20%
(φ^-, φ^+)	Tax rates for negative and positive profits	US Cor. Tax rate of 20%, 84-19	(0%, 20%)
η	Equity issuance cost	Return on equity of 8.63%, 84-19	0.09
c	Bankruptcy cost	Mendicino *et al.* (2018)	0.30
ς	Recovery cost	Overhead costs/assets of 3%, 96-17	0.03
υ	Ratio of bank loans to deposits	Ratio of Cre./Deps of 1.12, 84-19	112%
ϱ	Deposit insurance cost	Ratio of Cre./Deps of 1.12, 84-19	0.80
(ϕ_L, ϕ_C)	Adjustment costs of loans and liquid assets	Mean and S.D. of Intb. Rate of 4.13% and 2.63%, 86-18	(6, 2)
(Φ_0, Φ_1)	Dividend pay-out and share repurchase	Elenev *et al.* (2021)	(6.8%, 3.8%)
ϕ_E	Equity issuance cost	Eqt. Iss. Ratio of 4.8%, Elenev *et al.* (2021)	4
m	Loan management cost	Div. Ratio of 5.8%, Elenev *et al.* (2021)	7.8
(h_L, h_D)	Liquidity 'haircut' on loans, deposits	BCBS (2013), (2014)	(0.5, 0.90)
κ	Capital requirements	BCBS (2011)	6%
(ι_1, ι_2)	Liquidity requirements	BCBS (2011)	(100%, 100%)

The notation 84-19 means that the time period range from 1984 to 2019. AR(1) represents an autoregressive process of order one. *Inve.* is investment, *Ret.* stands for revenue, *Corr.* means correlation, and *Intb.* represents interbank. *Vari.* Means variation; *Deps.* means deposits; *Cre.* stands for credit; and *Divd.* is dividend. *Idio.* represents idiosyncratic, *S. D.* is standard deviation, *Eqt.* denotes equity, *Iss.* is issuance, and *Div.* means dividends.

Table 2
The impact of bank regulation

This table presents the results of the banks under various regulation regimes. The results are obtained using the value function in Equation (15) and the parameter values in Table 1. The column *No regulation* refers to the case when no requirement regimes are in place, *Capital* is the scenario when only the capital requirements are imposed, and *Capital and Liquidity* is the situation when both the requirements are introduced. The parameters shown below present the cases when different ratios of the requirements are imposed. The results of this table are the averages across the simulated results of the time-series (1000 periods) averages of the cross-sectional averages (100 times).

	No regulation	Capital		Capital and Liquidity					
		$\kappa = 6\%$	$\kappa = 12\%$	$\iota_1 = 100\%$ $\iota_2 = 100\%$	$\iota_1 = 110\%$ $\iota_2 = 100\%$	$\iota_1 = 80\%$ $\iota_2 = 100\%$	$\iota_1 = 100\%$ $\iota_2 = 110\%$	$\iota_1 = 100\%$ $\iota_2 = 80\%$	$\iota_1 = 50\%$ $\iota_2 = 50\%$
Loans	1.896	2.177	2.158	1.949	1.948	1.949	1.946	1.950	1.952
Liquid Assets	–0.427	–0.048	0.086	0.172	0.174	0.172	0.176	0.168	0.165
Equity Issuance Ratio	–29.50%	–38.90%	–26.66%	4.79%	4.79%	4.77%	5.09%	4.37%	1.80%
Pay-out Ratio	29.50%	49.50%	37.26%	5.81%	5.81%	5.83%	5.51%	6.23%	8.80%
Interbank trading volume	0.192	0.073	0.070	0.107	0.112	0.085	0.107	0.107	0.060
Interbank rate	20.84%	11.61%	11.25%	4.24%	0.44%	12.05%	4.24%	3.68%	12.10%
S.D. of Interbank rate	1.32%	0.80%	0.04%	2.44%	2.36%	0.76%	2.43%	2.45%	0.18%
Bankruptcy Prob.	0.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Bank Equity Value	3.494	4.034	3.982	1.971	1.970	1.970	1.970	2.107	2.291
Social Welfare	5.831	6.114	6.035	3.831	3.830	3.831	3.819	3.977	4.158
S.D. of Soc. Welfare	0.047	0.252	0.259	0.330	0.331	0.330	0.436	0.341	0.421

Table 3
The impact of exogenous shock variations

This table presents the results of the banks under various regulation regimes, sorted by the realisations of exogenous shocks. The results are obtained using the value function in Equation (15) and the parameter values in Table 1. The column *No regulation* refers to the case when no requirement regimes are in place, *Capital* is the scenario when only the capital requirements are imposed, and *Capital and Liquidity* is the situation when both the requirements are introduced. The columns shown as '*Unconditional'* refer to the cases where all samples are included, while other columns show the results of the subsamples where the realisations of the respective exogenous shocks are sorted and chosen against the given realisations of the total sample. The results of this table are the averages across the simulated results of the time-series averages (1000 periods) of the cross-sectional averages (100 times).

	No regulation			Capital			Capital and Liquidity		
	Systematic credit shocks Z								
	0.98	Unconditional	1.02	0.98	Unconditional	1.02	0.98	Unconditional	1.02
Loans/Deposits	0.944	0.946	0.948	1.073	1.088	1.093	0.951	0.974	0.979
Liquid Assets/Deposits	–0.209	–0.211	–0.213	–0.023	–0.024	–0.025	0.084	0.086	0.087
Interbank trading volume	19.36%	19.24%	19.13%	6.77%	7.33%	7.37%	10.65%	10.67%	10.69%
Interbank rate	21.03%	20.84%	20.62%	13.41%	11.61%	11.12%	7.10%	4.24%	3.35%
Social welfare	5.805	5.831	5.863	6.093	6.114	6.144	3.783	3.831	3.902
	Aggregate deposit value D								
	1.97	Unconditional	2.03	1.97	Unconditional	2.03	1.97	Unconditional	2.03
Loans	1.872	1.896	1.912	2.155	2.177	2.220	1.922	1.949	1.974
Liquid Assets	–0.426	–0.427	–0.428	–0.043	–0.048	–0.054	0.171	0.172	0.173
Interbank trading volume	19.14%	19.24%	19.44%	7.24%	7.33%	7.36%	10.58%	10.67%	10.83%
Interbank rate	20.97%	20.84%	20.56%	11.47%	11.61%	11.81%	4.17%	4.24%	4.39%
Social welfare	5.805	5.831	5.888	6.094	6.114	6.152	3.651	3.831	3.589
	Mass of Liquidity-deficit banks λ								
	0.495	Unconditional	0.505	0.495	Unconditional	0.505	0.495	Unconditional	0.505
Loans	1.899	1.896	1.894	2.178	2.177	2.176	1.950	1.949	1.948
Liquid Assets	–0.428	–0.427	–0.426	–0.048	–0.048	–0.048	0.173	0.172	0.171
Interbank trading volume	19.32%	19.24%	19.16%	7.44%	7.33%	7.20%	10.75%	10.67%	10.59%
Interbank rate	19.08%	20.84%	22.59%	11.18%	11.61%	11.75%	1.22%	4.24%	7.32%
Social welfare	5.832	5.831	5.830	6.117	6.114	6.110	3.832	3.831	3.830

Table 4
Model versus data

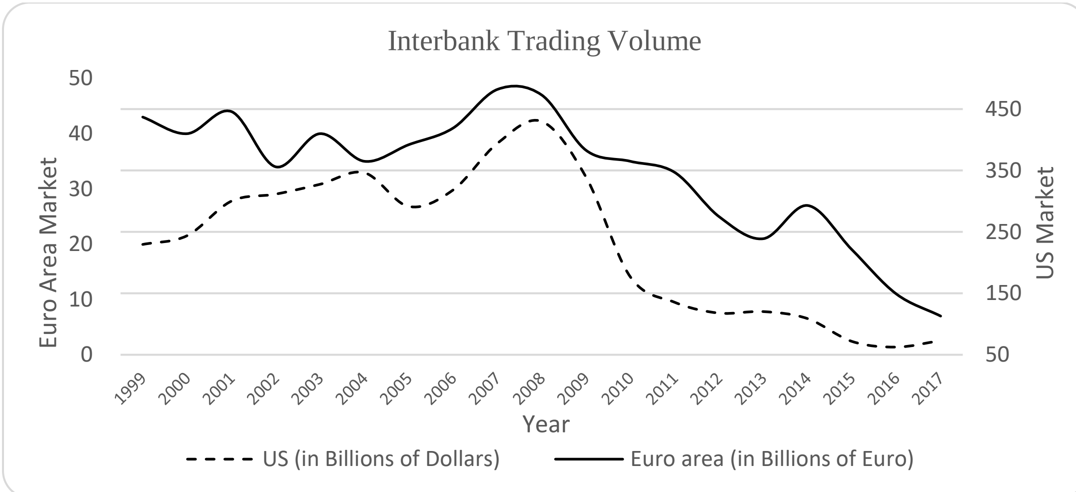
This table compares the results from the model and the collected data. Unless specifically mentioned, the data is to compare the baseline results when banks are under capital and liquidity requirements. We mainly calibrate the model to the US economy under the regime when both the capital and liquidity requirements are imposed. Since our model includes three requirement regimes, i.e., *No requirement*, *Capital requirement*, and *Capital and liquidity requirements*, the results of these regimes show a large degree of variation. To make the comparison of our results across regimes more straightforward, some of the targets, as indicated in brackets, are calibrated to different requirement regimes.

Description	Data	Model
Bank failure rate	0.739%	0.89% (No requirement)
Net dividend pay-out ratio	5.8%	5.81%
Equity issuance ratio	4.8%	4.79%
Interbank rate	4.13%	4.24%
S.D. of Interbank rate	2.63%	2.44%
Interbank volume to deposit ratio	5.9%	5.35%
Bank credit to deposits	112%	109% (Capital requirement)
Loans to deposits	85.9%	78.2% (No requirement)

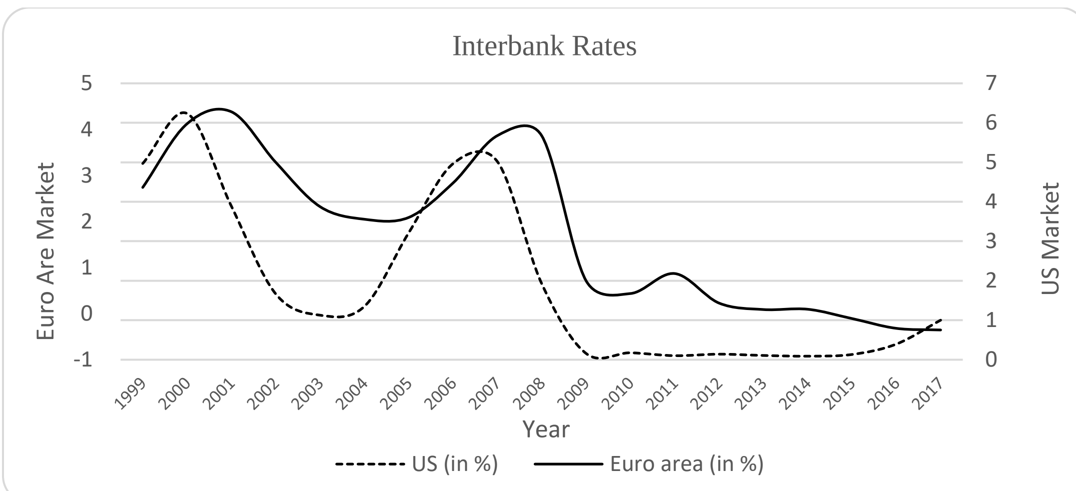
Table 5
Sensitivity Analysis

This table presents the results of the sensitivity analysis. The results are obtained using the value function in Equation (15), the parameter values in Table 1, and the values specified in the second row of the table. The result *Baseline* is the case when banks are under both the capital and liquidity requirements. The column *Higher loan rate* is the case when $a = 0.075$ rises to $a = 0.080$. *Higher matured loans* is the scenario when $\sigma = 0.20$ increase to $\sigma = 0.40$. *Higher loan trading cost* refers to the situation when $\phi_L = 6$ is raised to $\phi_L = 8$. *Higher loan trading cost* refer to the situation when $\phi_L = 6$ is raised to $\phi_L = 8$. *Higher equity issuance cost* refers to the situation when $\phi_E = 4$ rises to $\phi_E = 6$. The results of this table are the averages across the simulated results of the time-series averages (1000 periods) of the cross-sectional averages (100 times).

	Baseline	Higher loan rate	Higher matured loans	Higher loan trading cost	Higher equity issuance cost
		$a = 0.080$	$\sigma = 0.40$	$\phi_L = 8$	$\phi_E = 6$
Loans	1.949	1.996	2.047	1.969	1.969
Liquid Assets	0.172	0.162	0.129	0.172	0.174
Equity Issuance Ratio	4.79%	–9.48%	–18.79%	0.78%	1.37%
Pay-out Ratio	5.81%	20.08%	29.39%	9.82%	9.23%
Interbank trading volume	0.107	0.107	0.111	0.110	0.107
Interbank rate	4.24%	3.09%	–4.86%	6.16%	4.04%
Bankruptcy Prob.	0.00%	0.00%	0.00%	0.00%	0.00%
Social Welfare	3.831	4.719	5.148	4.053	4.030



(a) Interbank trading volume



(b) Interbank rates

Figure 1
Interbank trading volume and interbank rate of US and Euro area

This figure reports the collected for the interbank loans and overnight interbank rates for the US and European markets, for the years from 1999 to 2017. Figure 1(a) reports the interbank loans and Figure 1(b) shows the overnight interbank rates. The data are calibrated annually and are collected from database of Federal Reserve Bank of St. Louis (FRED) and European Central Bank (ECB).

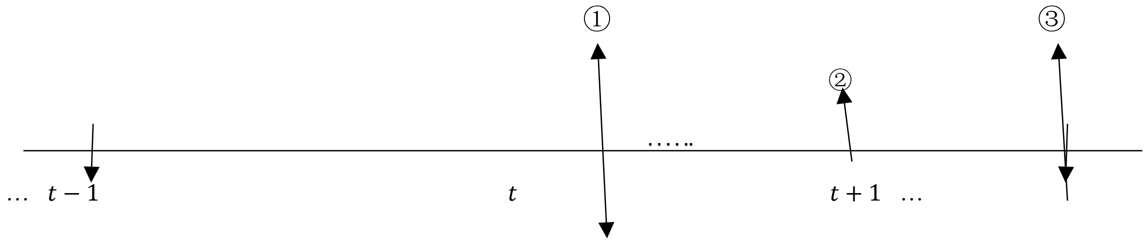


Figure 2
Bank's dynamics

Dynamics of banks in period t, consisting of credit shock Z_{t-1}, realisation of aggregate deposit d_t, investment choices (l_t, c_t), idiosyncratic credit shock $f_{\omega,t+v}$, idiosyncratic deposit value variations $f_{\psi,t+v}$, mass of liquidity-deficit banks λ_t, decisions for $\left(l_{t+v}^j, c_{t+v}^j, r_{t+v}^j\right)$ following the idiosyncratic shocks, bankruptcies and born of a new bank, and levy of corporate tax $\varsigma(y_t)$. The numbers in the figure indicate the order of the events.

Time Sequences:

①: Banks make new investment choices (l_t, c_t), based on the systematic credit shock Z_{t-1} and new aggregate deposits value d_t.

②: Idiosyncratic profit shock $f_{\omega,t+v}$ and idiosyncratic deposit value variation $f_{\psi,t+v}$ occur continuously within $v \in [0,1]$. The profit shock occur randomly to banks and the deposit variation makes them a probability of λ_t to become liquidity-deficit ones and a probability of $1-\lambda_t$ to become liquidity-surplus banks. For each interval $t+v$, banks make decisions $\left(l_{t+v}^j, c_{t+v}^j, r_{t+v}^j\right)$. Banks may default following the idiosyncratic shocks.

③: Corporate tax is levied and systematic credit shock Z_t and new aggregate deposits value d_{t+1} realise. Banks may default following the realisation of these shocks.

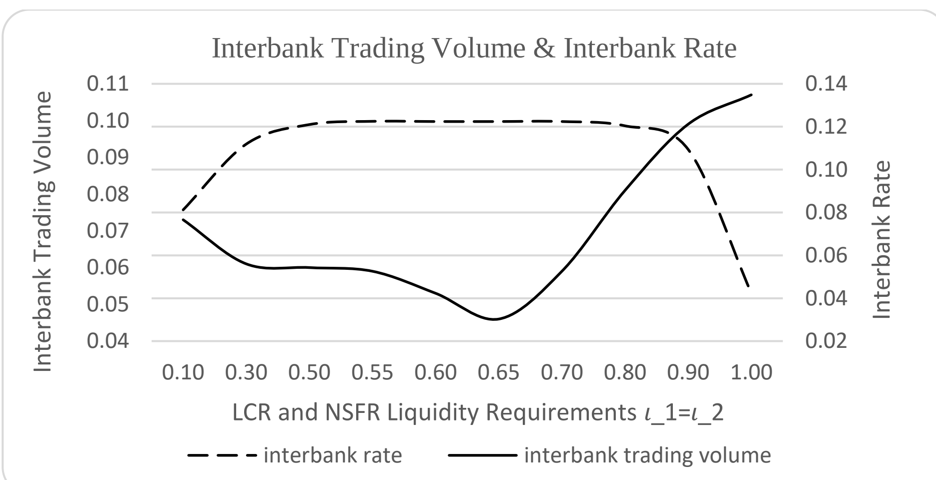


Figure 3
Interbank trading volume, interbank rate, and (LCR and NSFR) liquidity requirements

This figure reports the relationship between interbank trading volume, interbank rate, and the ratios of liquidity requirements. ι_1 stands for the ratio of LCR liquidity requirements, while ι_2 represents the ratio of NSFR liquidity requirements. In this analysis, we set $\iota_1 = \iota_2$, and their value is shown in the horizontal axis. The vertical axis presents the corresponding interbank trading volume (left) and interbank rate (right).

Online Appendix

A. Modelling the correlation coefficient $\boldsymbol{\theta}$

The simulation of the correlation coefficient $\theta < 0$, between error terms $\varepsilon_{D,t}$ and $\varepsilon_{Z,t}$, can be modelled using the method of Lkhagvasuren and Galindev (2008). To simplify the terminology, we denote Lkhagvasuren and Galindev (2008) as L&G 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 following equation

$$x_{1,t} = \sqrt{1-\rho_1^2}u_{1,1,t}, \tag{23}$$

$$x_{2,t} = v_{2,t} + \sqrt{1-\gamma^2}\sqrt{1-\rho_2^2}u_{2,2,t}, \tag{24}$$

where $v_{2,t}$ can be represented by pre-generated series $\hat{u}_{1,1,t}$ using equation below

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

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:

$$y_{1,t} = \rho_1 y_{1,t-1} + \varepsilon_{1,t}, \tag{25}$$

$$y_{2,t} = \rho_2 y_{2,t-1} + \gamma\varepsilon_{1,t} + \sqrt{1-\gamma^2}\varepsilon_{2,t}. \tag{26}$$

To prove equation above is equivalent to Equation (24), we introduce $Z_{1,t}$ and $Z_{2,t}$ to rewrite $y_{2,t}$ as

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

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 $\sigma_{yi}^2 = 1/\left(1-\rho_i^2\right)$. To make the variances in Equations (25) and (26) equal to one, as in Equations (23) and (24), we rescale the above processes, which yield the following:

$$X_{1,t} = \sqrt{1-\rho_1^2}\left(\rho_1 y_{1,t-1} + \varepsilon_{1,t}\right) = \sqrt{1-\rho_1^2}y_{1,t},$$

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

Comparing above two equations with (23), (24), we can prove that if $x_{2,t} = X_{2,t}$, $u_{1,1,t} = y_{1,t}$, $u_{2,2,t} = Z_{2,t}$ 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 (25), (26) is equivalent to the L&G decomposition method. Our proof thus completes.

B. Aggregation

To solve our model, we have made following assumptions to allow us to obtain the aggregation problem by investigating the problem of a representative bank i, with the application of the law of large numbers. These assumptions are: (i) that banks are facing with the same systematic credit shocks and aggregation deposit variations, and all banks' objective is linear in the idiosyncratic shocks, and the idiosyncratic shocks are memoryless; (ii) that if a bank fails it is replaced by a bank with same amount of deposits and capital as those surviving banks.

In addition, we have introduced several assumptions to obtain the aggregation problem of banks in terms of their decisions for the idiosyncratic shocks. These assumptions are: (iii) that the shocks are *i.i.d.* and only last for one period, with economic situation unchanged, and thus the discounting issues play a limited role in affecting banks' decisions; (iv) that the realisations of these shocks are subject to a Brownian motion and banks' objective is unchanged across each period; (v) banks' constraints at each time interval are addictive and thus the constraints still hold when we sum up their constraints within the period.

The equity valuation of surviving banks is

$$E(x_t, W_t) = \max\left\{0, \max_{\{Q_t, Q_{t+v}^j\}} \left\{I_t(x_t, W_t) + \int_t^{t+1} \left[\sum_{j=d,s} I_{t+v}^j\left(x_t, W_{t+v}^j\right)\right] dv + \mathbb{E}_t\left[M_{t,t+1} E(x_{t+1}, W_{t+1})\right]\right\}\right\},$$

subject to budget constraints and regulatory constraints, if any, as aforementioned. Given that those banks are subject to a same set of (endogenous and exogenous) state variables x_t, and based on assumptions (i) to (v), we can conclude that the surviving banks have identical objectives which result in same decision choices of Q_t for credit and aggregate deposit variation shocks and of Q_{t+v}^j for idiosyncratic shocks. Although the idiosyncratic shocks divide banks into liquidity-surplus and liquidity-deficit banks, which causes different wealth for each group of the banks, this can be resolved by investigating them separately and by relying on the assumptions that the wealth gained by both groups of banks can be regarded as the wealth of the whole banking system, as in W_t, as the idiosyncratic shocks are memoryless across periods.

How about defaulting banks? Since they are replaced by new ones with same amount of deposit and capital as surviving banks, the replaced banks thus possess equal resources to reach W_t or W_{t+v}^j and then choose the same optimal choices Q_t or Q_{t+v}^j as in the surviving banks. Therefore, all new banks will have same wealth and make the same optimal choices upon bailout. Thus, we can solve the problem for a representative bank, even considering the defaulting banks.

C. Model Solution

C.1 Decisions for the Idiosyncratic Shocks

C.1.1. Optimalisation Problem for Liquidity-deficit Banks

The optimal decision choices of the liquidity-deficit banks at time interval $t+v$ can be summarised as $\left\{I_{t+v}^d, L_{t+v}^d, C_{t+v}^d, R_{t+v}^d\right\}$, given the realisations of $x_t = \left\{Z_{t-1}, D_t, \lambda_t, L_t, C_t, f_{\omega,t+v}, f_{\psi,t+v}\right\}$. Accordingly, the optimal function can be rewritten as, where we denote the cumulative value of idiosyncratic shocks in $t+1$ as $F_{\omega+\psi,t+1}$,

$$E^d\left(x_t, W_{t+v}^d\right) = \max\left\{0, \max_{\left\{I_{t+v}^d, L_{t+v}^d, C_{t+v}^d, R_{t+v}^d\right\}} \left\{-(1+\eta) I_{t+v}^d + \mathbb{E}_t\left[M_{t,t+1}\left\{0, E^d\left(x_{t+1}, W_{t+1}^d\right) + F_{\omega+\psi,t+1}\right\}\right]\right\}\right\},$$

subject to

$$-I_{t+v}^d - L_{t+v}^d - C_{t+v}^d - q_t^R R_{t+v}^d + \Phi_L\left(L_{t+v}^d, L_t^d\right) + \Phi_C\left(C_{t+v}^d, C_t^d\right) + W_{t+v^-}^d \leq W_{t+v}^d, \quad (27)$$

$$W_{t+1}^d = [1 + (1-\varphi)\pi(L_t) Z_t]\left(L_t^d - \hat{L}_{t+1}^d\right) + \left[1 + (1-\varphi) r_f\right]\left(C_t^d - \hat{C}_{t+1}^d\right) - \hat{R}_{t+1}^d - \varphi\left[(1-\tau) r_d D_t - (1 - q_t^R)\hat{R}_{t+1}^d\right], \quad (28)$$

$$L_{t+v}^d - C_{t+v}^d - \varrho\left(C_{t+v}^d\right)^2 \cdot \chi_{C_t^d < 0} + R_{t+v}^d \leq f_{\omega+\psi,t+v}, \quad (29)$$

$$(1-\kappa) L_{t+v}^d + C_{t+v}^d + R_{t+v}^d \leq f_{\omega+\psi,t+v}, \quad (30)$$

$$\frac{h_S}{\iota_1 \mu_d} L_{t+v}^d + \frac{1}{\iota_1 \mu_d} C_{t+v}^d + \frac{1}{\mu_d} R_{t+v}^d \leq f_{\omega+\psi,t+v}. \quad (31)$$

In (27), we denote $W_{t+v^-}^d$ as net wealth prior to the realisation of idiosyncratic shocks at $t+v$ and $W_{t+v}^d = W_{t+v^-}^d - f_{-\omega+\psi,t+v} - R_{t+v^-}^d$ as the net worth after the realisation of the shocks and the repayment of interbank borrowing. In (28), we denote W_{t+1}^d as their (after-tax) wealth at the end of t, where $\hat{L}_{t+1}^d = \int_0^1 L_{t+v}^d dv$ and $\hat{C}_{t+1}^d = \int_0^1 C_{t+v}^d dv$ are cumulative changes in the asset holding positions. Equation (29) is the collateral constraint as in (12) to reflect the deposit insurance fee when banks' holdings of liquid assets are negative. Equations (30) and (31) are the (applicable) capital and liquidity requirement constraints, as defined in (19) and (21), respectively, where we have modified these equations as the changes in the assets are negative.

Using equation (27), we can eliminate R_{t+v}^d to rewrite (28), (29), (30) and (31) as

$$W_{t+1}^d = [1+(1-\varphi)\pi(L_t)Z_t]\left(L_t^d - \hat{L}_{t+1}^d\right) + \left[1+(1-\varphi)r_f\right]\left(C_t^d - \hat{C}_{t+1}^d\right) - (1-\varphi)(1-\tau)r_d D_t - [1-\varphi(1-q_t^R)]\int_0^1 \frac{-W_{t+v}^d + W_{t+v^-}^d + \Phi_L\left(L_{t+v}^d, L_t^d\right) + \Phi_C\left(C_{t+v}^d, C_t^d\right) - I_{t+v}^d - L_{t+v}^d - C_{t+v}^d}{q_t^R}\,dv,$$

$$L_{t+v}^d - C_{t+v}^d - \varrho\left(C_{t+v}^d\right)^2 \cdot \chi_{C_t^d<0} + \frac{-W_{t+v}^d + W_{t+v^-}^d + \Phi_L\left(L_{t+v}^d, L_t^d\right) + \Phi_C\left(C_{t+v}^d, C_t^d\right) - I_{t+v}^d - L_{t+v}^d - C_{t+v}^d}{q_t^R} \le f_{\omega+\psi,t+v}, \tag{32}$$

$$(1-\kappa)L_{t+v}^d + C_{t+v}^d + \frac{-W_{t+v}^d + W_{t+v^-}^d + \Phi_L\left(L_{t+v}^d, L_t^d\right) + \Phi_C\left(C_{t+v}^d, C_t^d\right) - I_{t+v}^d - L_{t+v}^d - C_{t+v}^d}{q_t^R} \le f_{\omega+\psi,t+v}, \tag{33}$$

$$\frac{h_S}{\iota_1\mu_d}L_{t+v}^d + \frac{1}{\iota_1\mu_d}C_{t+v}^d + \frac{-W_{t+v}^d + W_{t+v^-}^d + \Phi_L\left(L_{t+v}^d, L_t^d\right) + \Phi_C\left(C_{t+v}^d, C_t^d\right) - I_{t+v}^d - L_{t+v}^d - C_{t+v}^d}{\mu_d q_t^R} \le f_{\omega+\psi,t+v}. \tag{34}$$

C.1.1.1 First-order Conditions

A). Dividends/Cash Flows The FOC of E_t^d with respect to dividends/cash flows I_{t+v}^d is

$$\frac{1}{q_t^R}\psi_{t+v}^{d1} + \frac{1}{q_t^R}\psi_{t+v}^{d2} + \frac{1}{\mu_d q_t^R}\psi_{t+v}^{d3} - (1+\eta) + \frac{1-\varphi\left(1-q_t^R\right)}{q_t^R}\mathbb{E}_t\left[M_{t,t+1}V_{W,t+1}^d\right] = 0, \tag{35}$$

where ψ_{t+v}^{d1}, ψ_{t+v}^{d2} and ψ_{t+v}^{d3} are the Lagrange multipliers of (32), (33) and (34) respectively. We also denote $V_{W,t+1}^d = \partial\left[E_{t+1}^d + F_{\psi+\omega,t+1}\right]/\partial W_{t+1}^d$.

B). Loans The FOC of E_t with respect to loan holdings L_{t+v}^d is

$$-\psi_{t+v}^{d1} - (1-\kappa)\psi_{t+v}^{d2} - \frac{h_S}{\iota_1\mu_d}\psi_{t+v}^{d3} - \mathbb{E}_t\left[M_{t,t+1}V_{W,t+1}^d[1+(1-\varphi)\pi(L_t)Z_t]\right] = -\frac{1}{q_t^R}\left\{\left(\psi_{t+v}^{d1} + \psi_{t+v}^{d2} + \frac{1}{\mu_d}\psi_{t+v}^{d3}\right) + [1-\varphi(1-q_t^R)]\mathbb{E}_t\left[M_{t,t+1}V_{W,t+1}^d\right]\right\}\left[1-\Phi_L'\left(L_{t+v}^d\right)\right], \tag{36}$$

where we denote $\Phi_L'\left(L_{t+v}^d\right) = \partial\Phi_L'\left(L_{t+v}^d, L_t^d\right)/\partial L_{t+v}^d$.

C). Liquid Assets The FOC of E_t with respect to liquid assets C_{t+v}^d is

$$\psi_{t+v}^{d1} - \psi_{t+v}^{d2} - \frac{1}{\iota_1\mu_d}\psi_{t+v}^{d3} - \mathbb{E}_t\left\{M_{t,t+1}V_{W,t+1}^d\left[1+(1-\varphi)r_f\right]\right\} = -\frac{1}{q_t^R}\left\{\left(\psi_{t+v}^{d1} + \psi_{t+v}^{d2} + \frac{1}{\mu_d}\psi_{t+v}^{d3}\right) + [1-\varphi(1-q_t^R)]\mathbb{E}_t\left[M_{t,t+1}V_{W,t+1}^d\right]\right\}\left[1-\Phi_C'\left(C_{t+v}^d\right)\right], \tag{37}$$

where we denote $\Phi_C'\left(C_{t+v}^d\right) = \partial\Phi_C\left(C_{t+v}^d, C_t^d\right)/\partial C_{t+v}^d$.

C.1.1.2 Function Deductions

We use this section to derive Euler equations to be used for simulation, based on the first-order conditions obtained from B.1.1.1.

We first derive that

$$V_t^d = H_{\omega+\psi,t}^d E^d\left(x_t, W_t^d\right) + \int_{-E^d\left(x_t,W_t^d\right)}^{\infty} F_{\omega+\psi,t}\,d\mathcal{F}_{\omega+\psi,t},$$

where $H_{\omega+\psi,t}^d = 1 - \int_0^1 \eta_{\omega+\psi,t+v}^d dv$ represents the portion of the surviving banks at the end of t, where $\eta^{d}_{\omega+\psi,t+v} = \Pr\left[\hat{f}^{d}_{\omega+\psi,t+v} \geq L^{d}_{t} + C^{d}_{t} - D_{t}\right]$, and $\mathcal{F}_{\omega+\psi,t}$ is the c.d.f. of $F_{\omega+\psi,t}$ .By the application of Leibniz's rule, differentiating the above equation with respect to W^{d}_{t} gives:

$$V^{d}_{W,t} = \frac{\partial V^{d}_{t}}{\partial W^{d}_{t}} = H^{d}_{\omega+\psi,t} E^{d}_{W,t} - E^{d}_{W,t} \not{f}_{\omega+\psi,t} E^{d}_{t} + E^{d}_{W,t} \not{f}_{\omega+\psi,t} E^{d}_{t} = H^{d}_{\omega+\psi,t} E^{d}_{W,t},$$

where $\not{f}_{\omega+\psi,t}$ is the p.d.f. of $F_{\omega+\psi,t}$ evaluated at $-E^{d}\left(x_{t}, W^{d}_{t}\right)$.

Applying the envelope condition, we can get

$$\frac{\partial E^{d}\left(x_{t}, W^{d}_{t+v}\right)}{\partial W^{d}_{t+v}} = E^{d}_{W,t+v} = \frac{1}{q^{R}_{t}}\left[\psi^{d1}_{t+v} + \psi^{d2}_{t+v} + \frac{1}{\mu_{d}}\psi^{d3}_{t+v}\right] + \frac{1-\varphi\left(1-q^{R}_{t}\right)}{q^{R}_{t}} \mathbb{E}_{t}\left[M_{t,t+1} V^{d}_{W,t+1}\right].$$

Combining the above equation with (35), we can obtain

$$E^{d}_{W,t+v} = 1 + \eta.$$

Customising the above equation to t and $t+1$ and inserting the customised expression into (35), (36) and (37) to rewrite these Euler equations as

A). Dividends/Cash Flows

$$1 = \hat{\psi}^{d1}_{t+v} + \hat{\psi}^{d2}_{t+v} + \hat{\psi}^{d3}_{t+v} + \tilde{q}^{R}_{t} \mathbb{E}_{t}\left\{M_{t,t+1} H_{\omega+\psi,t+1}\right\}, \tag{38}$$

where $\hat{\psi}^{d1}_{t+v} = \psi^{d1}_{t+v}/q^{R}_{t}(1+\eta)$, $\hat{\psi}^{d2}_{t+v} = \psi^{d2}_{t+v}/q^{R}_{t}(1+\eta)$, $\hat{\psi}^{d3}_{t+v} = \psi^{d3}_{t+v}/\mu_{d} q^{R}_{t}(1+\eta)$ and $\tilde{q}^{R}_{t} = 1 - \varphi(1-q^{R}_{t})/q^{R}_{t}(1+\eta)$.

B). Loans

$$1 - \Phi'_{L}\left(L^{d}_{t+v}\right) = \tilde{\psi}^{d1}_{t+v} + \tilde{\psi}^{d2}_{t+v} + \tilde{\psi}^{d3}_{t+v} + \mathbb{E}_{t}\left\{M_{t,t+1} H_{\omega+\psi,t+1}\left[1 + (1-\varphi)\pi(L_{t+1}) Z_{t+1}\right]\right\}, \tag{39}$$

where $\tilde{\psi}^{d1}_{t+v} = \psi^{d1}_{t+v}/(1+\eta)$, $\tilde{\psi}^{d2}_{t+v} = (1-\kappa)\,\psi^{d2}_{t+v}/(1+\eta)$, $\tilde{\psi}^{d3}_{t+v} = h_{S}\,\psi^{d3}_{t+v}/\iota_{1}\mu_{d}(1+\eta)$.

C). Liquid Assets

$$1 - \Phi'_{C}\left(C^{d}_{t+v}\right) = -\ddot{\psi}^{d1}_{t+v} + \ddot{\psi}^{d2}_{t+v} + \ddot{\psi}^{d3}_{t+v} + \mathbb{E}_{t}\left\{M_{t,t+1} H_{\omega+\psi,t+1}\left[1 + (1-\varphi) r_{f}\right]\right\}, \tag{40}$$

where $\ddot{\psi}^{d1}_{t+v} = \psi^{d1}_{t+v}/(1+\eta)$, $\ddot{\psi}^{d2}_{t+v} = \psi^{d2}_{t+v}/(1+\eta)$ and $\ddot{\psi}^{d2}_{t+v} = \psi^{d2}_{t+v}/\iota_{1}\mu_{d}(1+\eta)$.

Note that we drop the notation of d from $H^{d}_{t}(\omega+\psi)$ as the banks have an equal (expected) probability of becoming liquidity-surplus or liquidity-deficit banks in the next period. To apply these FOCs to each period, we can aggregate (38), (39) and (40) as these Euler equations hold for each time interval and will also hold if we aggregate the intervals within the period, from t to $t+1$. We will use the equations after the aggregation for simulations, which we will introduce later.

C.1.2. Optimalisation Problem for Liquidity-surplus Banks

The optimal decision choices of liquidity-surplus banks at time interval $t+v$ can be summarised as $\{I^{s}_{t+v}, L^{s}_{t+v}, C^{s}_{t+v}, R^{s}_{t+v}\}$, given the realisations of $x_{t} = \left\{Z_{t-1}, D_{t}, \lambda_{t}, L_{t}, C_{t}, f_{\omega,t+v}, f_{\psi,t+v}\right\}$, and the optimal function can be rewritten as, where we denote the cumulative value of idiosyncratic shocks in $t+1$ as $F_{\omega+\psi,t+1}$,

$$E^{s}(x_{t}, W^{s}_{t+v}) = \max\left\{0, \max_{\{I^{s}_{t+v}, L^{s}_{t+v}, C^{s}_{t+v}, R^{s}_{t+v}\}}\left\{I^{s}_{t+v} + \mathbb{E}_{t}\left[M_{t,t+1}\left\{E^{s}(x_{t+1}, W^{s}_{t+1}) + F_{\omega+\psi,t+1}\right\}\right]\right\}\right\},$$

subject to

$$I^{s}_{t+v} + L^{s}_{t+v} + C^{s}_{t+v} + q^{R}_{t} R^{s}_{t+v} + \Phi_{L}(L^{s}_{t+v}, L^{s}_{t}) + \Phi_{C}(L^{s}_{t+v}, C^{s}_{t}) + W^{s}_{t+v^{-}} \leq W^{s}_{t+v}, \tag{41}$$

$$W^{s}_{t+1} = \left[1 + (1-\varphi)\pi(L_{t}) Z_{t}\right]\left(L^{s}_{t} + \hat{L}^{s}_{t+1}\right) + \left[1 + (1-\varphi) r_{f}\right]\left(C^{s}_{t} + \hat{C}^{s}_{t+1}\right) + \{1 +$$

$$(1-\varphi)(1-q_t^R)\}\left[1-H_t^d(\omega+\psi)\right]\hat{R}_{t+1}^s-\varphi(1+\tau)r_d D_t, \tag{42}$$

$$L_{t+v}^s+C_{t+v}^s+\varrho(C_{t+v}^s)^2\cdot\chi_{C_t^s<0}+R_{t+v}^s\geq f_{\omega+\psi,t+v}, \tag{43}$$

$$(1-\kappa)L_{t+v}^s+C_{t+v}^s+R_{t+v}^s\geq f_{\omega+\psi,t+v}, \tag{44}$$

$$\frac{h_S}{\iota_1\mu_d}L_{t+v}^s+\frac{1}{\iota_1\mu_d}C_{t+v}^s+\frac{1}{\mu_d}R_{t+v}^s\geq f_{\omega+\psi,t+v}. \tag{45}$$

In (41), we denote $W_{t+v^-}^s$ as the net wealth of these banks prior to the realisations of the idiosyncratic shocks at $t+v$ and $W_{t+v}^s=W_{t+v^-}^s+f_{\omega+\psi,t+v}+\left[1-\eta_{t+v^-}^d(\omega+\psi)\right]R_{t+v^-}^s$ as the wealth after the realisations of the shocks and maturity of the interbank lending. In (42), we denote W_{t+1}^s as their (after-tax) wealth at the end of t. (43) is the collateral constraint as in (12) to reflect the deposit insurance fee when banks' holdings of liquid assets are negative. (44) and (45) are the (applicable) capital and liquidity requirements, as defined in (19) and (21), respectively. Similarly, we can use (41) to eliminate R_{t+v}^s and rewrite equations (42), (43) and (44) and (45) as

$$W_{t+1}^s=[1+(1-\varphi)\pi(L_t)Z_t]\left(L_t^s+\hat{L}_{t+1}^s\right)+\left[1+(1-\varphi)r_f\right]\left(C_t^s+\hat{C}_{t+1}^s\right)+\{1+(1-\varphi)(1-q_t^R)\}H_t^d(\omega+\psi)\int_0^1\frac{W_{t+v}^s-W_{t+v^-}^s-\Phi_L(L_{t+v}^s,L_t^s)-\Phi_C(L_{t+v}^s,C_t^s)-I_{t+v}^s-L_{t+v}^s-C_{t+v}^s}{q_t^R}dv-(1-\varphi)(1+\tau)r_d D_t,$$

$$L_{t+v}^s+C_{t+v}^s+\varrho(C_{t+v}^s)^2\cdot\chi_{C_t^s<0}+\frac{W_{t+v}^s-W_{t+v^-}^s-\Phi_L(L_{t+v}^s,L_t^s)-\Phi_C(L_{t+v}^s,C_t^s)-I_{t+v}^s-L_{t+v}^s-C_{t+v}^s}{q_t^R}\geq f_{\omega+\psi,t+v}, \tag{46}$$

$$(1-\kappa)L_{t+v}^s+C_{t+v}^s+\frac{W_{t+v}^s-W_{t+v^-}^s-\Phi_L(L_{t+v}^s,L_t^s)-\Phi_C(L_{t+v}^s,C_t^s)-I_{t+v}^s-L_{t+v}^s-C_{t+v}^s}{q_t^R}\geq f_{\omega+\psi,t+v}, \tag{47}$$

$$\frac{h_S}{\iota_1\mu_d}L_{t+v}^s+\frac{1}{\iota_1\mu_d}C_{t+v}^s+\frac{W_{t+v}^s-W_{t+v^-}^s-\Phi_L(L_{t+v}^s,L_t^s)-\Phi_C(L_{t+v}^s,C_t^s)-I_{t+v}^s-L_{t+v}^s-C_{t+v}^s}{\mu_d q_t^R}\geq f_{\omega+\psi,t+v}. \tag{48}$$

C.1.2.1 First-order Conditions

A). Dividends/Cash Flows The FOC of E_t with respect to dividends/cash flows I_{t+v}^s is

$$-\frac{1}{q_t^R}\psi_{t+v}^{s1}-\frac{1}{q_t^R}\psi_{t+v}^{s2}-\frac{1}{\mu_d q_t^R}\psi_{t+v}^{s3}+1-\frac{1+(1-\varphi)(1-q_t^R)}{q_t^R}H_t^d(\omega+\psi)\mathbb{E}_t\left[M_{t,t+1}V_{W,t+1}^s\right]=0, \tag{49}$$

where ψ_{t+v}^{s1}, ψ_{t+v}^{s2} and ψ_{t+v}^{s3} are the Lagrange multipliers of (46), (47) and (48) respectively. We also denote $V_{W,t+1}^s=\partial[E_{t+1}^s+F_{t+1}(\psi+\omega)]/\partial W_{t+1}^s$.

B). Loans The FOC of E_t with respect to loan holdings L_{t+v}^s is

$$\psi_{t+v}^{s1}+(1-\kappa)\psi_{t+v}^{s2}+\frac{h_S}{\iota_1\mu_d}\psi_{t+v}^{s3}+\frac{1}{L_t}\mathbb{E}_t\left\{M_{t,t+1}V_{W,t+1}^s[1+(1-\varphi)\pi(L_t)Z_t]\right\}=\frac{1}{q_t^R}[1+\Phi_L'(L_{t+v}^s)]\left\{\psi_t^{s1}+\psi_t^{s2}+\frac{1}{\mu_d}\psi_t^{s3}+\frac{1+(1-\varphi)(1-q_t^R)}{q_t^R}H_t^d(\omega+\psi)\mathbb{E}_t\left[M_{t,t+1}V_{W,t+1}^s\right]\right\}, \tag{50}$$

where we denote $\Phi_L'(L_{t+v}^s)=\partial\Phi_L'(L_{t+v}^s,L_t^s)/\partial L_{t+v}^s$.

C). Liquid Assets The FOC of E_t with respect to liquid assets C_{t+v}^s is

$$\psi_{t+v}^{s1}+\psi_{t+v}^{s2}+\frac{1}{\iota_1\mu_d}\psi_{t+v}^{s3}+\mathbb{E}_t\left\{M_{t,t+1}V_{W,t+1}^s\left[1+(1-\varphi)r_f\right]\right\}=\frac{1}{q_t^R}[1+\Phi_C'(L_{t+v}^s)]\left\{\psi_t^{s1}+\psi_t^{s2}+\frac{1}{\mu_d}\psi_t^{s3}+\frac{1+(1-\varphi)(1-q_t^R)}{q_t^R}H_t^d(\omega+\psi)\mathbb{E}_t\left[M_{t,t+1}V_{W,t+1}^s\right]\right\}, \tag{51}$$

where we denote $\Phi_C'(C_{t+v}^s)=\partial\Phi_C(C_{t+v}^s,C_t^s)/\partial C_{t+v}^s$.

C.1.2.2 Function Deductions

We use this section to derive Euler equations to be used for simulation, based on the first-order conditions obtained from B.1.2.1.

We first derive that

$$V_t^s = H_{\omega+\psi,t}^s E^s(x_t, W_t^s) + \int_{-E^s(x_t,W_t^s)}^{\infty} F_{\omega+\psi,t} d\mathcal{F}_{\omega+\psi,t},$$

where $H_t^s(\omega+\psi) = 1 - \int_0^1 \eta_{\omega+\psi,t+v}^s dv$ represents the portion of the surviving banks at the end of t, where $\eta_{t+v}^s(\omega+\psi) = \Pr\left[\hat{f}_{\omega+\psi,t+v}^s \geq L_t^s + C_t^s - D_t\right]$. By the application of Leibniz's rule, differentiating the above equation with respect to W_t^s gives:

$$V_{W,t}^s = \frac{\partial V_t^s}{\partial W_t^s} = H_{\omega+\psi,t}^s E_{W,t}^s - E_{W,t}^s \not{f}_{\omega+\psi,t} E_t^s + E_{W,t}^s \not{f}_{\omega+\psi,t} E_t^s = H_{\omega+\psi,t}^s E_{W,t}^s,$$

where $\not{f}_{\omega+\psi,t}$ is the p.d.f. of $F_{\omega+\psi,t}$ evaluated at $-E^s(x_t, W_t^s)$.

Applying the envelope condition, we can get

$$\frac{\partial E^s(x_t, W_{t+v}^s)}{\partial W_{t+v}^s} = E_{W,t+v}^s = \frac{1}{q_t^R}\left[\psi_{t+v}^{s1} + \psi_{t+v}^{s2} + \frac{1}{\mu_d}\psi_{t+v}^{s3}\right] + \frac{1+(1-\varphi)(1-q_t^R)}{q_t^R} H_t^d(\omega+\psi)\mathbb{E}_t\left[M_{t,t+1}V_{W,t+1}^s\right].$$

Combining the above equation with (49) we can obtain

$$E_{W,t+v}^s = 1.$$

Customising it to t and $t+1$ and inserting the customised expression into (49), (50) and (51) to rewrite these Euler equations as

A). Dividends/Cash Flows

$$1 = \hat{\psi}_{t+v}^{s1} + \hat{\psi}_{t+v}^{s2} + \hat{\psi}_{t+v}^{s3} + \ddot{q}_t^R \mathbb{E}_t\{M_{t,t+1}H_{\omega+\psi,t+1}\}, \tag{52}$$

where $\hat{\psi}_{t+v}^{s1} = \psi_{t+v}^{s1}/q_t^R$, $\hat{\psi}_{t+v}^{s2} = \psi_{t+v}^{s2}/q_t^R$, $\hat{\psi}_{t+v}^{s2} = \psi_{t+v}^{s3}/\mu_d q_t^R$ and $\ddot{q}_t^R = \frac{1+(1-\varphi)(1-q_t^R)}{q_t^R} H_t^d(\omega+\psi)$.

B). Loans

$$1 + \Phi_L'(L_{t+v}^s) = \tilde{\psi}_{t+v}^{s1} + \tilde{\psi}_{t+v}^{s2} + \tilde{\psi}_{t+v}^{s3} + \mathbb{E}_t\{M_{t,t+1}H_{\omega+\psi,t+1}[1 + (1-\varphi)\pi(L_{t+1})Z_{t+1}]\}, \tag{53}$$

where $\tilde{\psi}_{t+v}^{s1} = \psi_{t+v}^{s2}$, $\tilde{\psi}_{t+v}^{s2} = (1-\kappa)\psi_{t+v}^{s2}$ and $\tilde{\psi}_{t+v}^{s3} = h_S\,\psi_{t+v}^{s3}/\iota_1\mu_d$.

C). Liquid Assets

$$1 + \Phi_C'(C_{t+v}^s) = \psi_{t+v}^{s1} + \psi_{t+v}^{s2} + \ddot{\psi}_{t+v}^{s3} + \mathbb{E}_t\{M_{t,t+1}H_{\omega+\psi,t+1}[1 + (1-\varphi)r_f]\}. \tag{54}$$

where $\ddot{\psi}_{t+v}^{s3} = \psi_{t+v}^{s3}/\iota_1\mu_d$.

Note that we drop the notation of s from $H_{\omega+\psi,t+1}^s$ as the banks have an equal (expected) probability of becoming liquidity-surplus or liquidity-deficit banks in the next period. To apply these FOCs to each period, we can aggregate (52), (53) and (54) as these Euler equations hold for each time interval and will also hold if we aggregate the intervals as a period, from t to $t+1$. We will use the equations after the aggregation for simulations, which we will introduce later.

C.2 Decisions for Systematic Credit Shocks and Aggregate Deposit Variations

The calculation of these decisions will employ valuation iteration as there are only two decision variables $\{L_{t+1}, C_{t+1}\}$. The decision problem is to maximise (15), the steps of which will be introduced in Online Appendix D.3.

D. Simulation Steps

D.1 Discretisation

For decisions introduced in Online Appendix C.1 and C.2, we need discretised state space consisting of:

Five state variables $[Z_t, D_t, \lambda_t, L_t, C_t]$ for decision (D1) for idiosyncratic shocks,

Four state variables $[Z_t, D_t, \tilde{L}_t, \tilde{C}_t]$ for decision (D2) for systematic credit shocks and aggregate deposit variations.

We discretise Z_t (D_t) into a N^Z (N^D)-state Markov chain following Rouwenhorst (1995), which will result in a $N^Z \times N^Z$ ($N^D \times N^D$) transition matrix. We also introduce N^λ points for λ_t, N^P points for P_t, and N^D for D_t. For the policy variables $[L_t, C_t]$, and $[\tilde{L}_t, \tilde{C}_t]$, we assume these variables can take on values in a continuous and convex subset of the reals, and each of the variables is within $[\bar{S}_l, \bar{S}_u]$. Note that for consistence, we assign a same set of values for $[\tilde{L}_t, \tilde{C}_t]$ as $[L_t, C_t]$, and we then express them as L, C, thereafter. Thus, we can rewrite the sets of the variables as in $\boldsymbol{H}_n = \prod_o [\bar{S}_{o,l}, \bar{S}_{o,u}]$, where S_o represents L, C, respectively. Choose an appropriate number of grids for each endogenous variable for the simulation, which will result in $\boldsymbol{H}_n = \{L_p\}_{p=1}^{N_L} \times \{C_q\}_{q=1}^{N_C}$, where N_L and N_C are the number of L and C, respectively. These grids are chosen to ensure they cover the ergodic distribution of the economy and to minimise simulation errors. Thus, the total number of $\boldsymbol{H_1}$ (for D1) is $N_{s1} = N_Z \cdot N_D \cdot N_\lambda \cdot S_n$, where S_n is the total number of $\boldsymbol{H}_n$. Total number of $\boldsymbol{H_2}$ (for D2) is $N_{s2} = N_Z \cdot N_D \cdot S_n$.

D.2 Decisions for the Idiosyncratic Shocks

The simulation solution for this problem is based on the global projection method, pioneered by Judd (1998). This method, as pointed out by Begenau and Landvoigt (2018), outperforms the Perturbation-based solution method in terms of a better quality of approximation for nonlinear dynamic models with constraints. There are two steps of the simulations, which are described as follows.

STEP 1: We first aggregate equations (38), (39), (40), (52), (53) and (54), which are obtained for $t + v$ and transform the problem to the period $[t, t+1]$. We can adopt the aggregation because: 1) all the periods $v \in [0,1]$ follow these Euler equations; 2) the expectation terms (on the right-hand side of the equations) are independent of the decision choices made on $t + v$; and 3) the constraints are addictive in terms of time periods since the constraints are satisfied at every $t + v$ and they should also satisfy the constraints aggregated for the whole period of $[t, t+1]$; this additivity also applies to the Lagrange multipliers of these equations.

STEP 2: Give an initial guess $\overline{\boldsymbol{U}}_C^m$, where m denotes the number of iterations and $m = 1$ represents the first iteration. The guess $\overline{\boldsymbol{U}}_C^m$ is set for each point of $H_u \subseteq \boldsymbol{H_1}$, where $u = 1,2 \ldots N_{s1}$. The variable to guess is liquidity-deficit banks' cash flows $\bar{I}_u^{d,m}$. For each point of H_u, obtain forecast variables, given each possible realisation of exogenous shocks l, where $i = 1,2 \ldots N_Z \times N_D$. This then results in a forecast matrix $\overline{\boldsymbol{U}}_F^m$, which each entry as $f_{u,l}^m = \overline{\boldsymbol{U}}_F^m(H_u, ZD_i)$, which contains stochastic discount factor $M_{u,i}$ and survival indicators of banks $H_{\omega+\psi,u,l}^m$, i.e.,

$$f_{u,l}^m = \{M_{u,i} H_{\omega+\psi,u,l}^m\}.$$

The calculation of $f_{u,l}^m$ requires some pre-calculations which will be determined in decision D2, to be introduced in C.3. This calculation reduces potential repeating computation of $f_{u,l}^m$, thereby reducing the time for computation.

STEP 3: Upon obtaining matrices $\overline{\boldsymbol{U}}_C^m$ and $\overline{\boldsymbol{U}}_F^m$, we can use them to solve a system of nonlinear equations, which will feature the equilibrium values of variables for each point of u. This step will result in a matrix $\boldsymbol{\bar{U}}_P^m$ with each entry as the equilibrium results:

$$p_u^m = \left\{\widetilde{\hat{L}}_u^d, \widetilde{\hat{C}}_u^d, \widetilde{\hat{L}}_u^s, \widetilde{\hat{L}}_u^d, \widetilde{q}_u^R, \widetilde{R_u}, \widetilde{\psi}_u^{d1}, \widetilde{\psi}_u^{d2}, \widetilde{\psi}_u^{s1}, \widetilde{\psi}_u^{s2}, \widetilde{\psi_u}\right\}.$$

The equations for obtaining $\boldsymbol{\bar{U}}_P^m$ are:

$$1 = \widetilde{\hat{\psi}}_u^{d1} + \widetilde{\hat{\psi}}_u^{d2} + \widetilde{\hat{\psi}}_u^{d3} + \widetilde{\tilde{q}}_u^R \mathbb{E}_u\left[M_{u,l} H_{\omega+\psi,u,l}^m\right] \tag{E1}$$

$$1 - \Phi_L'\left(\widetilde{\hat{L}}_u^d\right) = \widetilde{\tilde{\psi}}_u^{d1} + \widetilde{\tilde{\psi}}_u^{d2} + \widetilde{\tilde{\psi}}_u^{d3} - \widetilde{\psi_u} + \mathbb{E}_u\left\{M_{u,l} H_{\omega+\psi,u,l}^m [1 + (1-\varphi)\pi(L_l) Z_l]\right\} \tag{E2}$$

$$1 - \Phi_C'\left(\widetilde{\hat{C}}_u^d\right) = -\widetilde{\dddot{\psi}}_u^{d1} + \widetilde{\dddot{\psi}}_u^{d2} + \widetilde{\dddot{\psi}}_u^{d3} + \mathbb{E}_u\left\{M_{u,l} H_{\omega+\psi,u,l}^m \left[1 + (1-\varphi) r_f\right]\right\} \tag{E3}$$

$$1 = \widetilde{\hat{\psi}}_u^{s1} + \widetilde{\hat{\psi}}_u^{s2} + \widetilde{\hat{\psi}}_u^{s3} + \widetilde{\dddot{q}}_u^R \mathbb{E}_u\left[M_{u,l} H_{\omega+\psi,u,l}^m\right] \tag{E4}$$

$$1 + \Phi_L'\left(\widetilde{\hat{L}}_u^s\right) = \widetilde{\tilde{\psi}}_u^{s1} + \widetilde{\tilde{\psi}}_u^{s2} + \widetilde{\tilde{\psi}}_u^{s3} - \widetilde{\psi_u} + \mathbb{E}_u\left\{M_{u,l} H_{\omega+\psi,u,l}^m [1 + (1-\varphi)\pi(L_l) Z_l]\right\} \tag{E5}$$

$$1 + \Phi_C'\left(\widetilde{\hat{C}}_u^s\right) = \widetilde{\psi}_u^{s1} + \widetilde{\psi}_u^{s2} + \widetilde{\dddot{\psi}}_u^{s3} + \mathbb{E}_u\left\{M_{u,l} H_{\omega+\psi,u,l}^m \left[1 + (1-\varphi) r_f\right]\right\} \tag{E6}$$

$$\widetilde{\psi}_u^{d1}\left[\tau\lambda_u D_u - \widetilde{\hat{L}}_u^d + \widetilde{\hat{C}}_u^d + \varrho\left(\widetilde{\hat{C}}_u^d\right)^2 \cdot \chi_{C_u^d<0} - \widetilde{R_u}\right] = 0, \tag{E7}$$

$$\widetilde{\psi}_u^{d2}\left[\tau\lambda_u D_u - (1-\kappa)\widetilde{\hat{L}}_u^d - \widetilde{\hat{C}}_u^d - \widetilde{R_u}\right] = 0 \tag{E8}$$

$$\widetilde{\psi}_u^{d3}\left[\tau\lambda_u D_u - \frac{h_S}{\iota_1\mu_d}\widetilde{\hat{L}}_u^d - \frac{1}{\iota_1\mu_d}\widetilde{\hat{C}}_u^d - \frac{1}{\mu_d}\widetilde{R_u}\right] = 0 \tag{E9}$$

$$\widetilde{\psi}_u^{s1}\left[\widetilde{\hat{L}}_u^s + \widetilde{\hat{C}}_u^s + \varrho\left(\widetilde{\hat{C}}_u^s\right)^2 \cdot \chi_{C_u^s<0} + \widetilde{R_u} - \tau(1-\lambda_u)D_u\right] = 0, \tag{E10}$$

$$\widetilde{\psi}_u^{s2}\left[(1-\kappa)\widetilde{\hat{L}}_u^s + \widetilde{\hat{C}}_u^s + \widetilde{R_u} - \tau(1-\lambda_u)D_u\right] = 0 \tag{E11}$$

$$\widetilde{\psi}_u^{s3}\left[\frac{h_S}{\iota_1\mu_d}\widetilde{\hat{L}}_u^s + \frac{1}{\iota_1\mu_d}\widetilde{\hat{C}}_u^s + \frac{1}{\mu_d}\widetilde{R_u} - \tau(1-\lambda_u)D_u\right] = 0 \tag{E12}$$

$$\widetilde{\psi_u}\left(\widetilde{\hat{L}}_u^d - \widetilde{\hat{L}}_u^s\right) = 0 \tag{E13}$$

Note that the variables with a hat $\widetilde{(\cdot)}$ are the variables to be determined by the solver of the group of equations. The above equations are aggregated version of the equations we obtained in Section B.1, under the assumptions given in Step 1. Thereby, the variables subscripted with u are the variables after aggregation. Equation (E1) is the liquidity-deficit banks' FOC of dividends/cash flows as in (38). (E2) is the FOC of these banks' loan adjustments as in (39). (E3) is the FOC of their liquid asset adjustments in (40). (E4) is the liquidity-surplus banks' FOC of dividends/cash flows in (52). (E5) is the FOC of the liquidity-surplus banks' adjustments in loan in (53). (E6) is the FOC of their adjustments in liquid asset in (54). (E7), (E8) and (E9) are the collateral, capital and liquidity requirement constraints on liquidity-deficit banks, as in (29), (30) and (31), respectively. (E10), (E11) and (E12) are the respective requirement constraints on liquidity-surplus banks, as in (43), (44) and (45). (E13) is the non-positive net loan increment constraints, which rules out banks' net increase in loans as there lack in opportunities of investment in the middle of each period, while there exists the possibility of reduction in loans as banks can recall (i.e., liquidate) their loans in advance to meet the liquidity shortages.

The above system of equations implicitly uses the budget constraints of the liquidity-surplus banks, presented in (7), and we can rewrite $\widetilde{\dddot{q}}_u^R = (1-\varphi)\left(1 - \widetilde{q}_u^R\right)/\widetilde{q}_u^R$ in (E4) by expressing $\widetilde{q}_u^R$ as a function of $\widetilde{R_u}$ as:

$$\widetilde{q_u^R} = H^d_{\omega+\psi,u} - \frac{1}{\widetilde{R_u}}\left[\bar{I}^s_u + \widetilde{\hat{L}^s_u} + \widetilde{\hat{C}^s_u} - \tau\lambda_u D_u + \Phi_L\left(\widetilde{\hat{L}^s_u}\right) + \Phi_C\left(\widetilde{\hat{C}^s_u}\right)\right] \tag{M}$$

and inserting $\widetilde{q_u^R}$ back to $\ddot{\widetilde{q_u^R}}$ for simulation. In equation (M), $\Phi_L\left(\widetilde{\hat{L}^s_u}\right) = \frac{\phi_L}{2L^s_u}\left(\widetilde{\hat{L}^s_u}\right)^2$ and $\Phi_C\left(\widetilde{\hat{C}^s_u}\right) = \frac{\phi_C}{2C^s_u}\left(\widetilde{\hat{C}^s_u}\right)^2$ are the aggregated adjustment costs for loans (as defined in (4)) and liquid assets (as defined in (5)) for each point of u. Equation (M) thus ensures there are 11 equations to solve for 11 unknowns, as listed in p^m_u. Note that some Lagrange multipliers subscripted with $d1, d2, s1, s2$ are the functions of known variables, i.e., $\widetilde{\psi^d_u}, \widetilde{\psi^s_u}$, which means the addition of these multipliers to the system do not raise the number of unknown variables.

The calculation described above in Step 3 results in a $N_{s1} \times 11$ matrix $\bar{\boldsymbol{U}}^m_P$ with each row the solution vector p^m_u for each point of u. Following the calculation, we obtain the guessed variables for this iteration m:

$$\hat{I}^{s,m+1}_u = \widetilde{\hat{I}^s_u}, \tag{N}$$

where $\widetilde{\hat{I}^s_u} = \left[H^d_u(\omega+\psi) - \widetilde{q^R_u}\right]\widetilde{R_u} - \widetilde{\hat{L}^s_u} - \widetilde{\hat{C}^s_u} + \tau(1-\lambda_u)D_u - \Phi_L\left(\widetilde{\hat{L}^s_u}\right) - \Phi_C\left(\widetilde{\hat{C}^s_u}\right)$.

Then, check the variables $\widehat{\boldsymbol{U}}^{m+1}_C = \left\{\hat{I}^{d,m+1}_u\right\}$ with $\bar{\boldsymbol{U}}^m_C = \left\{\bar{I}^{d,m}_u\right\}$ for each point of u. If $\Delta_C = \left|\widehat{\boldsymbol{U}}^{m+1}_C - \bar{\boldsymbol{U}}^m_C\right| \leq Tol_C$, then stop the iteration and take $\widehat{\boldsymbol{U}}^{m+1}_C$ as the approximate solution; otherwise, continue the iteration to $m+1$ and update $\bar{\boldsymbol{U}}^{m+1}_C = \varrho \times \widehat{\boldsymbol{U}}^{m+1}_C + (1-\varrho) \times \bar{\boldsymbol{U}}^m_C$, where ϱ is a dampening variable set at $\varrho = 0.8$, as the initial guess for the next iteration $m+1$ and go back to **STEP 2.** We continue the procedure until the condition $\Delta_C \leq Tol_C$ is satisfied.

Accuracy of the solution. We perform two types of checks to assess the quality of our simulation. First, we verify that all the endogenous state variables are within the defined grid bounds. If the simulation hits the boundaries, we will expand the grid bounds. Second, we compute relative errors of (E1)-(E13) of each computed point u. Take (E1) as an example, the relative error is calculated as:

$$RE_{E1} = 1 - \hat{\psi}^{d1}_u - \hat{\psi}^{d2}_u - \hat{\psi}^{d3}_u - \tilde{q}^R_u \mathbb{E}_u\{M_{u,l}H^m_{\omega+\psi,u,l}\}. \tag{O}$$

These simulation errors will be small (or negligible) if the simulated path visits exactly at (or close to) one of the discretised grid points; however, the errors could be large if the simulated path more frequently visits points that are undefined, i.e., the points that are between the defined grid points. If the errors of some equations exceed the tolerance, we will add more points to the relevant endogenous variables and repeat the simulation.

Solutions of the system of equations. We solve the system of these nonlinear equations using a nonlinear equation solver (MATLAB's fsolve). Regarding the Kuhn-Tucker conditions in the equations, we conduct the following transformation, use (E1) as an example, to minimise the simulation bias originating from the slackness conditions with constraints.

$$(1+\eta)\widetilde{q^R_u} = \widetilde{\psi^{d1}_u} + \widetilde{\psi^{d2}_u} + \frac{1}{\mu_d}\widetilde{\psi^{d3}_u} + (1-\varphi)\left(1 - \widetilde{q^R_u}\right)\mathbb{E}_u\{M_{u,l}H^m_{\omega+\psi,u,l}\},$$

$$\widetilde{\psi^{d1}_u}\left[\tau\lambda_u D_u - \widetilde{\hat{L}^d_u} + \widetilde{\hat{C}^d_u} + \varrho\left(\widetilde{\hat{C}^d_u}\right)^2 \cdot \chi_{C^d_u<0} - \widetilde{R_u}\right] = 0$$

$$\widetilde{\psi^{d2}_u}\left[\tau\lambda_u D_u - (1-\kappa)\widetilde{\hat{L}^d_u} - \widetilde{\hat{C}^d_u} - \widetilde{R_u}\right] = 0,$$

$$\widetilde{\psi^{d3}_u}\left[\tau\lambda_u D_u - \frac{h_S}{\iota_1\mu_d}\widetilde{\hat{L}^d_u} - \frac{1}{\iota_1\mu_d}\widetilde{\hat{C}^d_u} - \frac{1}{\mu_d}\widetilde{R_u}\right] = 0.$$

Define three variables kt_1, kt_2 and kt_3 and three functions of these three variable, such that $\widetilde{\lambda^{K1,+}_J} = \max\{0, kt_1\}$ and $\widetilde{\lambda^{K1,-}_J} = \max\{0, -kt_1\}$; $\widetilde{\lambda^{K2,+}_J} = \max\{0, kt_2\}$ and $\widetilde{\lambda^{K2,-}_J} = \max\{0, -kt_2\}$; and $\widetilde{\lambda^{K3,+}_J} = \max\{0, kt_3\}$ and $\widetilde{\lambda^{K3,-}_J} = \max\{0, -kt_3\}$. Insert them to replace $\widetilde{\psi^{d1}_u}$, $\widetilde{\psi^{d2}_u}$ and $\widetilde{\psi^{d3}_u}$ in the above equations to obtain:

$$(1+\eta)q_u^R = \widetilde{\lambda_J^{K1,+}} + \widetilde{\lambda_J^{K2,+}} + \frac{1}{\mu_d}\widetilde{\lambda_J^{K3,+}} + (1-\varphi)\left(1-\widetilde{q_u^R}\right)\mathbb{E}_u\left[M_{u,l}H^m_{\omega+\psi,u,l}\right],$$

$$\tau\lambda_u D_u - \widetilde{\hat{L}_u^d} + \widetilde{\hat{C}_u^d} + \varrho\left(\widetilde{\hat{C}_u^d}\right)^2 \cdot \chi_{C_u^d<0} - \widetilde{R_u} - \widetilde{\lambda_J^{K1,-}} = 0, \tag{P}$$

$$\tau\lambda_u D_u - (1-\kappa)\widetilde{\hat{L}_u^d} - \widetilde{\hat{C}_u^d} - \widetilde{R_u} - \widetilde{\lambda_J^{K2,-}} = 0,$$

$$\tau\lambda_u D_u - \frac{h_S}{\iota_1\mu_d}\widetilde{\hat{L}_u^d} - \frac{1}{\iota_1\mu_d}\widetilde{\hat{C}_u^d} - \frac{1}{\mu_d}\widetilde{R_u} - \widetilde{\lambda_J^{K3,-}} = 0.$$

To interpret the above equations, we take kt_1 as an example. If $kt_1 > 0$, then $\widetilde{\lambda_J^{K1,+}} > 0$ and $\lambda_J^{K1,-} = 0$, which means the constraint (P) is binding and thus $\lambda_J^{K1,+}$ takes on the value of the Lagrange multiplier. However, if $kt_1 < 0$, then $\lambda_J^{K1,+} = 0$ and $\lambda_J^{K1,-} = -kt_1 > 0$, which means the constraint is not binding and $\lambda_J^{K1,-}$ can take on any value to make (P) hold.

D.3 Decisions for the Systematic Credit Shocks and Aggregate Deposit Variations

We employ value iteration method for this procedure. The tolerance for termination of value function iteration is set at 10^{-5}. This calculation results in a $N_{s2} \times 2$ matrix $\boldsymbol{Q}^m$ with each row the solution vector $[L_{u+1}, C_{u+1}]$ for each point of $H_u \subseteq \boldsymbol{H_2}$, where $u = 1,2 \ldots N_{s2}$.

D.4 Simulation Procedure

We start the simulation by presenting an initial set of endogenous variables $s_0 = [L_0, C_0]$ and a path of generated exogenous shocks $[Z_t, D_t, \lambda_t]$ for $T = T_{ini} + T_S$ periods. For each period t within the path, we 1) record the calculated results from $\overline{\boldsymbol{U}}_P^m$, and update the endogenous state variables using following equations, as in (8) and (9), respectively:

$$\tilde{L}_t = \sum_{j=s,d} H_{\omega+\psi,u}\left(L_u^j + \widetilde{\hat{L}_u^{j=s}}1_{\{j=s\}} - \widetilde{\hat{L}_u^{j=d}}1_{\{j=d\}}\right), \tag{Q1}$$

$$\tilde{C}_t = \sum_{j=s,d} H_{\omega+\psi,u}\left(C_u^j + \widetilde{\hat{C}_u^{j=s}}1_{\{j=s\}} - \widetilde{\hat{C}_u^{j=d}}1_{\{j=d\}}\right); \tag{Q2}$$

2) calculate SW_t, the value of social welfare as defined in (17); 3) use matrix $\boldsymbol{Q}^m$ and the calculated $[\tilde{L}_t, \tilde{C}_t]$, which are given by (Q1) and (Q2) to obtain $[L_{t+1}, C_{t+1}]$; 4) continue the simulation to $t+1$ and repeat the simulation procedure until reaching the period T. To remove the dependency of the initial state s_0, we discard the results of the first T_{ini} periods and keep, and record, those of the last T_S periods. We keep the same path of exogenous shocks for all tests, i.e., for different requirement regimes, to minimise the bias of sampling. For each test we simulate 5000 (pairs of) banks with 200 years. To avoid potential dependency of the results on the initial states we selected, we disregard the first 50 years of each series and use the last 150 years as our simulated results.

D.5 Grid Configuration

We adopt the grid configuration for both exogenous and endogenous state variables as follows:

Z: (5 points) $[0.9808, 0.9904, 1.0000, 1.0096, 1.0192]$. This exogenous shock is discretised into a 5-state Markov chain, using the Rouwenhorst (1995) method, with the transition matrix:

$$\begin{bmatrix} 0.6708 & 0.2817 & 0.0444 & 0.0031 & 0.0000 \\ 0.0704 & 0.6930 & 0.2136 & 0.0223 & 0.0007 \\ 0.0074 & 0.1424 & 0.7005 & 0.1424 & 0.0073 \\ 0.0007 & 0.0223 & 0.2136 & 0.6930 & 0.0704 \\ 0.0000 & 0.0031 & 0.0444 & 0.2817 & 0.6708 \end{bmatrix}.$$

D: (3 points) $[1.97, 2.00, 2.03]$. This exogenous shock is discretised into a 3-state Markov chain, using the Rouwenhorst (1995) method, with the transition matrix:

$$\begin{bmatrix} 0.8836 & 0.1128 & 0.0036 \\ 0.0564 & 0.8872 & 0.0564 \\ 0.0036 & 0.1128 & 0.8836 \end{bmatrix}.$$

λ*:* (3 points) $[0.495\ 0.500\ \ 0.505]$, with probability of [0.2741 0.4518 0.2741].

L*:* (30 points)

$[1.80\ \ 1.85\ \ 1.90\ \ 1.91\ \ 1.92\ \ 1.93\ \ 1.94\ \ 1.95\ \ 1.96\ \ 1.97\ \ 1.98\ \ 1.99\ \ 2.00\ \ 2.01\ \ 2.02\ \ 2.05\ldots$

$\ldots\ \ 2.10\ \ 2.12\ \ 2.14\ \ 2.16\ \ 2.17\ \ 2.18\ \ 2.19\ \ 2.20\ \ 2.21\ \ 2.22\ \ 2.23\ \ 2.24\ \ 2.25\ \ 2.30]$.

C*:* (30 points)

$[-0.550\ \ -0.450\ \ -0.400\ \ -0.370\ \ -0.360\ -0.355\ \ -0.350\ \ -0.345\ \ -0.330\ldots$

$\ldots\ -0.240\ -0.150\ \ -0.060\ \ -0.050\ -0.040\ \ -0.030\ \ -0.020\ -0.010\ \ 0.000\ \ldots$

$\ldots\ \ 0.030\ \ 0.060\ \ 0.090\ \ 0.120\ \ 0.150\ \ 0.160\ \ 0.165\ \ 0.170\ \ 0.180\ \ 0.190\ \ 0.200\ \ 0.300]$

This amounts to 40,500 points of the state grids for decision for variations in mass of liquidity-deficit banks and 13,500 points for decision of systematic credit shocks and aggregate deposit variations.

D.6 Errors of the calculations

In this section, we report the errors of the calculations of the equations, for both the decisions for the systematic credit shocks and aggregate deposit variations and the decisions for the idiosyncratic shocks, to assess the accuracy of our calculations.

D.6.1 Errors of the decisions of systematic credit shocks and aggregate deposit variations.

As addressed before, the tolerance of the termination of the value function iteration is set at 10^{-5}, the error of the calculation is thus controlled under that value.

D.6.2 Errors of the decisions of idiosyncratic shocks.

As we employ the policy function iteration for a system of equations, the tolerance of the iteration termination is set at 10^{-6}, the default tolerance set by fsolve function of Matlab, for the whole system of the equations. To show a better overview of the errors of each equation within the system, we will report the errors of each equation, the calculation of the errors is similar to equation (O) for (E1) and is applicable to all other equations within the system. The (maximum) errors of each equation, under different regulation regimes, are reported in Table OA1. From Table OA1, one can see that the maximum error of the equations is 6.60e-07, which is below 1e-06. This table thus proves that our results are of high accuracy.

E. A Simplified Version of the Model

We simplify our model to a static model to illustrate some impacts of the liquidity requirements on the interbank trading activities and to verify some results obtained in Section 6. In this simplified model, banks are short-lived and there are two periods: t and $t+1$. There are two banks, i.e., a liquidity-deficit bank and a liquidity-surplus bank. At time t, both banks' asset value ($L_t > 0, C_t >$

0) is exogenously determined, and the value of deposits is fixed at D.[40] There are two points of the systematic credit shocks, which realise at $t+1$: $Z_H > 0$ with probability of p, and $Z_L < \left(D + R_t^j - C_{t+1} - L_{t+1}\right)/L_{t+1}$ [41] with probability of $1-p$, where R_t^j is bank j's interbank market position and $j = d, s$ represents the liquidity-deficit and liquidity-surplus bank, respectively. Idiosyncratic liquidity variations occur at the beginning of t and realise at the value of $-\tau D$ and τD, respectively. For simplicity, idiosyncratic credit shocks are zero. To ensure that the interbank market is active, we assume that the value of idiosyncratic deposit variations $\tau D > C_t$.

We also assume that it is costly and takes longer time to adjust loans for the idiosyncratic liquidity variations and thus $l_t^s = l_t^d = 0$. Thus, banks make optimal decisions for idiosyncratic shocks, c_t^j and R_t^j, at the beginning of t. The discount factor is $\beta < 1$, and $r_t^{p,j} > r_f = 0$, where $r_t^{p,j}$ is the interbank rate. There are no taxes, no asset adjustment costs ($\phi_L = \phi_C = 0$), and no loan management costs ($m = 0$). The liquidity requirements are at $\iota_1 = \iota_2 = \iota$. Haircuts on deposits set by liquidity requirements are $h_D = 1 - H$. The liquidity requirements are assumed to be tighter than the capital requirements[42] and thus the capital regulations are not discussed in this model. We also assume that issuing equity to pay for the liquidity shortage is costly (especially for liquidity-deficit banks), which means $I_t^d = 0$.[43]

E.1 Liquidity-Deficit Bank

The liquidity-deficit bank chooses (c_t^d, R_t^d) to maximise

$$I_t^d + \beta\left[I_{t+1}^d\right] = -\bar{D} + R_t^d/\left(1 + r_t^{p,d}\right) + c_t^d + \beta\left\{p\left[Z_H\pi(\bar{L}) + \bar{L} + C_{t+1} - R_t^d - D\right] + (1-p)\max\left[0, (1+Z_L)\bar{L} + C_{t+1} - R_t^d - D\right]\right\}, \tag{55}$$

subject to

$$(1-\iota)\bar{L} + C_{t+1} \geq 2hD, \tag{56}$$

$$c_t^d + \iota R_t^d \leq \iota\bar{D}. \tag{57}$$

where $\bar{L} = L_{t+1} = 2L_t$, $C_{t+1} = 2C_t + c_t^s - c_t^d$, [44] and $\bar{D} = \tau D$. Equation (56) is the NSFR requirement constraint, and (57) is the LCR requirement constraint.

A). Interbank borrowing. The first-order condition of (55) with respect to R_t^d is

$$1/\left(1 + r_t^{p,d}\right) - \beta p - \iota\varpi^d = 0, \tag{58}$$

where ϖ^d is the Lagrange multiplier on (57).

B). Liquid assets. The first-order condition of (55) with respect to c_t^d is

$$1 = \beta p + \varpi^1 + \varpi^d, \tag{59}$$

where ϖ^1 is the Lagrange multiplier on (56).

E.2 Liquidity-Surplus Bank

[40] This implies that the aggregate amount of loans, liquid assets and deposits is at the value of $2L_t$, $2C_t$ and $2D$ as there are two banks in the economy. This consideration affects our calculation of (56).

[41] This assumption simplifies our calculations and ensures that banks will fail if they receive the systematic credit shocks at the value of Z_L. We will define L_{t+1} and C_{t+1} for the simplified model later.

[42] This assumption is also made for simplicity as the analysis for the liquidity requirements is of our utmost interest.

[43] This assumption ensures that there are seven equations, listed in Section 6.3, to solve for seven unknowns.

[44] As in our quantitative model, and for tractability, we assume that future dividend I_{t+1}^d is based on the aggregate value of loans L_{t+1}, irrespective of the realisations of idiosyncratic shocks.

The liquidity-surplus banks choose (c_t^s, R_t^s) to maximise

$$I_t^s + \beta[I_{t+1}^s] = \bar{D} - R_t^s/\left(1 + r_t^{p,s}\right) - c_t^s + \beta\{p[Z_H\pi(L_{t+1}) + L_{t+1} + C_{t+1} + R_t^s - D] + (1-p)\max[0, (1+Z_L)L_{t+1} + C_{t+1} + R_t^s - D]\}, \tag{60}$$

subject to (56), the NSFR requirement constraint, and

$$c_t^s + \iota R_t^s \geq \iota\bar{D}. \tag{61}$$

A). Interbank lending. The first-order condition of (60) with respect to R_t^s is

$$\beta p + \iota\varpi^s = 1/\left(1 + r_t^{p,s}\right), \tag{62}$$

where ϖ^s is the Lagrange multiplier on (61).

B). Liquid assets. The first-order condition of (60) with respect to c_t^s is

$$1 = \beta p + \varpi^1 + \varpi^s. \tag{63}$$

E.3 Equilibrium

The equilibrium of this simplified model is characterised by the equilibrium variables $\{c_t^d, c_t^s, R_t, r_t^p, \lambda^1, \lambda^d, \lambda^s\}$ with equations (56), (57), (58), (59), (61), (62), (63), and $I_t^d = 0$. We can eliminate ϖ^d and ϖ^s from (58) and (62), and rewrite the equations as

$$\frac{1}{1+r_t^{p,d}} - (1-\iota)\beta p - \iota(1-\varpi^1) = 0 \tag{64}$$

$$1 = \beta p + \varpi^1 + \varpi^d \tag{65}$$

$$\frac{1}{1+r_t^{p,s}} - (1-\iota)\beta p - \iota(1-\varpi^1) = 0 \tag{66}$$

$$1 = \beta p + \varpi^1 + \varpi^s \tag{67}$$

$$\varpi^1\left[(1-\iota)\bar{L} + C_{t+1} - 2\iota\bar{D}\right] = 0 \tag{68}$$

$$\varpi^d\left[\iota\bar{D} - c_t^d - \iota R_t^d\right] = 0 \tag{69}$$

$$\varpi^s[c_t^s + \iota R_t^s - \iota\bar{D}] = 0 \tag{70}$$

$$\frac{R_t^d}{1+r_t^{p,d}} + c_t^d = \bar{D} \tag{71}$$

In equilibrium, $r_t^{p,d} = r_t^{p,s}$ and $R_t^s = R_t^d$. Thus, equations (64) and (66) reduce to one equation, so there are seven equations in total to solve for seven unknowns.

E.4 Interbank Rate and Liquidity Requirements

Combining (64) and (66), we obtain

$$\frac{1}{1+r_t^p} - (1-\iota)\beta p - \iota(1-\varpi^1) = 0.$$

Case 1: we consider the case when $\varpi^1 = 0$, i.e., when (56) is not binding. This normally occurs when the liquidity requirements are not strict. Thus, the above equation reduces to $1/\left(1 + r_t^p\right) = (1-\iota)\beta p$. We can see that $dr_t^p/d\iota = \beta p\left(1 + r_t^p\right)^2 > 0$, which means r_t^p is increasing in ι.

Case 2: we consider the case when $\varpi^1 > 0$, i.e., when (56) is binding. This normally occurs when the liquidity requirements are strict so that the requirement constraint is binding. The above case reduces to $1/\left(1+r_t^p\right)=\beta p+\iota(1-\varpi^1-\beta p)$. In this context, there are two possibilities:

1) If $\varpi^d=0$, i.e., when (57) is not binding, $\lambda^1=1-\beta p$, we can see from (65) that $\varpi^1=1-\beta p$. Based on (67), we can obtain $\lambda^s=0$. Thus, under this circumstance, only (56) is binding, while (57) and (61) are not binding. Combining (57) and (61), we can obtain $c_t^s>c_t^d$. Inserting this condition to (56), which is binding, we can obtain $(1-\iota)L_t+C_t<hD$. This contradicts the assumption that banks are subject to the NSFR requirement at the beginning of t. Thus, (57) must be binding.

2) When (57) is binding, we can thus insert $c_t^d=\iota\left(\overline{D}-R_t^d\right)$ in (55), and replace c_t^d with R_t^d, which reduces the optimisation problem reduce to $\left\{R_t^d\right\}$. The first-order condition of (55) with respect to R_t^d is now: $1/\left(1+r_t^p\right)=\beta p+\iota(1-\beta p)$. We can thus see that $dr_t^p/d\iota=-\beta p\left(1+r_t^p\right)^2<0$. This means r_t^p is decreasing in ι.

Scenarios 1) and 2) suggest that if (56) is binding r_t^p is decreasing in ι.

Combining the above two cases, we can conclude that when the liquidity requirements are low (when the requirement constraint is not binding) the interbank rates are increasing in the liquidity requirements, while when the requirements become stricter, i.e., when the constraint is binding, the interbank rates is decreasing in the liquidity requirements. This finding thus indicates an inverted U-shaped relationship between interbank rates and the liquidity requirements.

E.5 Interbank Trading Volume and Liquidity Requirements

Following (71), we can obtain $R_t^d/\left(1+r_t^p\right)+c_t^d=\overline{D}$. Given the results from Section 6.4, there is only one case regarding the slackness of (57): it must be binding. Hence, we can insert $c_t^d=\iota\overline{D}-\iota R_t^d$ into the above equation to eliminate c_t^d, which obtains: $\left[1/\left(1+r_t^p\right)-\iota\right]R_t^d=(1-\iota)\overline{D}$. Total differentiating this equation, we can get:

$$\frac{dR_t^d}{d\iota}=\frac{-\left(\overline{D}-R_t^d\right)\left(1+r_t^p\right)+\frac{R_t^d}{1+r_t^p}\frac{dr_t^p}{d\iota}}{1-\iota\left(1+r_t^p\right)}.$$

The results from Section 6.4 indicate that $dr_t^p/d\iota<0$ when (57) is binding, which means that the numerator of the above equation is negative. Accordingly, we can find that $dR_t^d/d\iota<0$ when ι is low, i.e., when $\iota<1/\left(1+r_t^p\right)$, and $dR_t^d/d\iota>0$ when ι is high, i.e., when $\iota>1/\left(1+r_t^p\right)$. This finding indicates that there exists a U-shaped relationship between interbank trading volume R_t^d and the liquidity requirement ratio ι.

F. Tables

Table OA1
Maximum errors of each equation for the decision of idiosyncratic shocks

No. of Equation	No Requirement	Capital Requirement	Capital and Liquidity Requirement
E1	4.59e-12	4.94e-12	1.30e-10
E2	4.37e-12	3.45e-12	1.00e-10
E3	4.51e-12	7.63e-17	1.63e-11
E4	3.36e-09	4.75e-07	6.60e-07
E5	1.13e-12	3.27e-11	4.47e-11
E6	1.67e-12	1.06e-12	2.65e-11
E7	5.55e-17	1.57e-13	-
E8	-	2.11e-13	1.94e-13
E9	-	-	1.64e-13
E10	4.16e-17	2.02e-12	-
E11	-	4.59e-13	6.29e-13
E12	-	-	2.25e-13
E13	2.00e-13	4.33e-17	1.10e-13

In Table OA1, e stands for the exponent sign and e-12 equals to e^{-12}. The columns with '-' represent the equations which are not applicable to the respective requirement regime in question.

Table OA2
Impacts of liquidity requirements

This table presents the results of the banks under various levels of liquidity requirements. The results are obtained using the value function in Equation (15), using the parameter values in Table 1. The column *Baseline* refers to the case when liquidity requirement at $\iota_1 = \iota_2 = 100\%$. The column *Other Liquidity Levels* presents the results under various levels of liquidity requirements, ranging from $\iota_1 = \iota_2 = 0\%$ (The scenario when only capital requirements are added) to $\iota_1 = \iota_2 = 90\%$. The parameters shown below present the cases when different ratios of the liquidity requirements are imposed. The results of this table are the averages across the simulated results of the time-series averages of the cross-sectional averages.

	Capital and Liquidity	Other Liquidity Levels				
	$\iota_1 = 100\%$ $\iota_2 = 100\%$	$\iota_1 = 0\%$ $\iota_2 = 0\%$	$\iota_1 = 10\%$ $\iota_2 = 10\%$	$\iota_1 = 30\%$ $\iota_2 = 30\%$	$\iota_1 = 50\%$ $\iota_2 = 50\%$	$\iota_1 = 55\%$ $\iota_2 = 55\%$
Loans	1.949	2.177	1.955	1.952	1.952	1.951
Liquid Assets	0.172	–0.048	0.162	0.162	0.165	0.168
Interbank volume	**0.107**	**0.073**	**0.073**	**0.061**	**0.060**	**0.059**
Interbank rate	**4.24%**	**11.61%**	**8.12%**	**11.19%**	**12.10%**	**12.25%**
Bank Equity Value	1.971	4.034	2.501	2.360	2.291	2.271
Social Welfare	3.831	6.114	4.374	4.230	4.158	4.141
	– –	$\iota_1 = 60\%$ $\iota_2 = 60\%$	$\iota_1 = 65\%$ $\iota_2 = 65\%$	$\iota_1 = 70\%$ $\iota_2 = 70\%$	$\iota_1 = 80\%$ $\iota_2 = 80\%$	$\iota_1 = 90\%$ $\iota_2 = 90\%$
Loans	–	1.951	1.951	1.951	1.950	1.949
Liquid Assets	–	0.169	0.169	0.169	0.170	0.171
Interbank volume	–	**0.053**	***0.046***	**0.059**	**0.086**	**0.099**
Interbank rate	–	**12.24%**	***12.24%***	**12.24%**	**12.04%**	**10.94%**
Bank Equity Value	–	2.271	2.269	2.265	2.255	2.231
Social Welfare	–	4.136	4.133	4.128	4.112	4.093