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Research Article

Systemic Risk in the Interbank Market with Overlapping Portfolios

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The increasing frequency and scope of the financial crisis have attracted more attention in the research of the systemic risk of banking system. A new model for the interbank market with overlapping portfolios is proposed to simulate a banking system in this work. The proposed model uses a bipartite network of banks and their assets to analyze the impact of bank investment on the stability of the banking system. In addition, this model introduces investment risk and allows banks to make up for liquidity by selling devaluated assets, which reflects the operating rules of the banking system more realistically. The results show that allowing banks to sell devaluated assets to make up for liquidity can improve the stability of the banking system and the interbank market can also improve the stability of the banking system. For the investment of banks, the investment risk is an uncertain factor that affects the stability of the banking system. The proposed model further analyzes the impact of average investment interest rate, savings interest rate, deposit reserve ratio, and investment asset diversity on the stability of the banking system. The model provides a tool for policy-makers and supervision agencies to prevent the systemic risk of banking system.

1. Introduction

The increasing frequency and scope of the financial crisis have attracted more attention in the research of the systemic risk of banking system [1, 2]. Most of the current research on the systemic risk of banking system analyzed the risk of financial systems from the perspective of interbank lending [3, 4]. The interbank market provides convenience for banks making up for liquidity and also provides an infectious channel for the spread of the crisis [5]. The network formed by interbank lending relations plays an important role in the systemic risk of banking system [6, 7]. Kaufman and Scott [8] believed that systemic risk referred to the risk or possibility of the collapse of the entire system by the interbank network. Mistrulli's empirical research [9] showed that the interbank market was able to handle liquidity shocks but also acted as a risk communication channel for bank failures through interbank lending. Allen and Gale [10] studied the risk contagion of banking systems under different static network structure. It was found that the possibility of financial contagion in the interbank market largely depended on the market structure and the complete market structure was more robust than the incomplete market structure. Freixas et al. [11] found that the higher the connection among banks, the faster recovery of single banks in crisis. The shortcoming was not to eliminate inefficient banks, which was similar to the results of Allen and Gale [10]. Leitner [12] studied the optimal structure of banking network, which showed that the optimal banking network structure should be trade-off between risk sharing and potential "Domino collapse." Vivier-Lirimont [13] studied the optimal network structure from the perspective of improving the depositors' utility. He found that the sparse network structure accorded with the Pareto optimal assignment. Iori et al. [14] and Lenzu and Tedeschi [15] studied the stability of bank network systems in the case of heterogeneous or homogeneous bank nodes. They found that banking networks were more stable when banks were homogenous. When banks were heterogeneous, the stability of the banking network system had a nonmonotonic relationship with the connectivity. Nier et al. [16] found that the impact of the connectivity among banks on systemic risk was not monotonous. At the initial time, a slight increase in connectivity increased the infection. When the connectivity was increased to a certain value, the connectivity increased

the ability of the banking system to absorb the shock and thus increased the stability of the banking system. Caccioli et al. [17] studied the impact of the network topology on systemic risk when nodes in a banking network were subjected to random shocks and selective shocks. They found that when a node in the banking network was subjected to a random shock, the scale-free network structure had less systemic risk than the random network structure. When a node with high connectivity was chosen, the systemic risk of a scale-free network structure was larger than that of a random network structure. Lenzu and Tedeschi [15] studies had shown that there was a critical connection value between banks with scale-free network structure, which was more likely to be contagious exceeding the critical connection value. Smerlak et al. [18] analyzed the characteristics of single bank's risk contagion in systemic risk contagion from the section dimension and found that large and low capital banks could increase systemic risk. Georg [19] studied different interbank network structures and the results showed that money-centre networks were more stable than random networks. Kok [20] proposed a sequential network formation mechanism to investigate how key parameters may affect interbank network structures. Han and Cao [21] found that liquidity hoarding behaviors mitigated systemic risk contagion at early stage and the composition of risk-averse behaviors exacerbated the systemic risk contagion. Steinbacher et al. [22] proposed a network-based structural model of credit risk to demonstrate how idiosyncratic and systemic shocks propagate across the banking system and evaluate the costs. Yao's work [23] found that contagion effect was most significant if the originating shocked bank was leveraged highly or had high network connectivity.

The above researches mainly analyzed systemic risk from the perspective of interbank market, while there was little consideration for the devaluation of portfolios caused by systemic risk. Lagunoff's study [24] found that overlap portfolios between banks were an important reason of financial risk. Based on overlap portfolios, Uhlig [25] had studied two types of financial crises. One type was that a bank was redistributing its portfolio because of the external shocks. In this case, the loss of assets had gradually expanded, making more banks' assets in crisis and leading to the financial crisis. Another type was due to the fact that some banks had shifted their assets to safer portfolios, leading to a decline in some asset prices, causing some banks to fall into crisis. Vries [26] did a similar research of Uhlig's work. Due to the correlation of bank assets, the fat tail nature of bank asset distribution caused the risk of bankruptcy for banks. Cifuentes et al. [27] and Greenwood et al. [28] found that, in a network with overlap portfolios, the risk of infection mainly came from the decline in asset prices. Huang et al. [29] built a bank asset bilateral network model and used the 2007 US commercial bank balance sheet data to carry out an empirical study of the risk contagion. Caccioli et al. [30, 31] built a multiasset model of investment and discussed the probability and degree of financial contagion under the condition of leverage, market congestion, asset diversification, and market impact. The above researches mainly analyzed systemic risk from the perspective of overlap portfolio; the evolution law of the interbank network with overlap portfolios could not be fully analyzed.

In summary, there are still some problems in above works: (i) the above models consider either the role of interbank lending or overlap portfolios in the systemic risk, instead of considering both overlap portfolios and interbank lending; (ii) in the above interbank network models, the rate of return on investment assets is set to a fixed value, but, in fact, investment is risky, and the return rate of investment should be dynamic. Zhou and Li [32] proposed a complex network system from the obligation links among banks and links created by portfolio overlaps, which considered interbank lending and overlap portfolios. But in Zhou's work, the ratio of the interbank loan was certain, the ratio of capital asset was certain, and the strategy of investment and borrowing was still unclear. Based on the above analysis, inspired by the work of Iori et al. [14], this paper constructs a systemic risk contagion model based on the interbank network with overlapping portfolios. In Iori's work, only interbank lending is considered, the rate of return on investment is fixed, and the model does not allow banks to replenish liquidity by selling assets. In the proposed model, we consider the impact of both overlap portfolios and interbank lending on systemic risk and then analyze the evolution rule of overlap portfolios and interbank network when systemic risk occurs. In the proposed model, there are multiple channels to improve liquidity, including interbank loans and asset sales when banks are in low liquidity, and asset depreciation is also considered when assets are sold. In the proposed model, the return rate of assets is dynamic, and the return rate of different assets is different. This hypothesis is more in line with the actual economic laws.

2. The Model

In a banking system, a bank failure often results from lack of liquidity. The liquidity of a bank is closely related to savings, investment, and interbank lending. This paper proposed a systemic risk contagion model based on the interbank network with overlapping portfolios as shown in Figure 1, which can well reflect the reality of banking systems. Unlike the traditional bank systemic risk model based on interbank lending [14], the proposed model considers both interbank lending and overlapping portfolios and establishes the relationship rules of overlapping portfolios. Compared with the traditional model based on interbank lending, the model proposed in this paper is more in line with the actual operation rules of the banking system.

2.1. A Dynamic Banking Network System. When banks are short of liquidity, they will borrow from each other in the interbank market, which is shown in Figure 1. In a random interbank network, nodes are randomly connected and the connection matrix is expressed as J, in which J_{ij} is either one or zero. $J_{ij} = 1$ indicates a possible credit linkage between bank i and bank j, while $J_{ij} = 0$ indicates no relationship between bank i and bank j. Bank i and bank j are connected by probability p_{ij}.

N_t is the number of banks in the network at time t; N_t is a bounded integer. The system operates in discrete time $t = 1, 2, 3, \ldots, T$. The liquidity of bank i at time t can be described as [14]

$$L_i(t) = \widehat{L}_i(t) - D_i(t) - I_i(t) + \sum_{j=1}^{N_t} c_{ij}(t) B_{ij}(t), \quad (1)$$

where $\widehat{L}_i(t)$ is a liquidity asset before banks invest, dividend, and borrow; $D_i(t)$ is the dividend of bank i at time t; $I_i(t)$ is the investment of bank i at time t; c_{ij} describes the connection relationship between bank i and bank j; if there is a loan relationship between bank i and bank j, $c_{ij}(t) = 1$; otherwise $c_{ij}(t) = 0$ (note that $c(t)$ is not equal to J and $c_{ij}(t)$ represents a real loan relationship between bank i and bank j, while J_{ij} indicates a possible credit linkage between bank i and bank j); $B_{ij}(t) > 0$ indicates the amount of bank i borrowed from bank j, and $B_{ij}(t) < 0$ indicates that bank i loans to bank j.

At time t, the liquidity of every bank will change, including the interest paid to the depositors, the income from the investment, the expiry investment income, and the fluctuation of the deposit. At time t, the liquidity before banks invest, dividend, and borrow can be described:

$$\widehat{L}_i(t) = L_i(t-1) + A_i(t) - A_i(t-1) - r_a A_i(t-1) + U_i(t), \quad (2)$$

where $A_i(t)$ denotes deposits held by the general public in bank i at time t, r_a is the bank deposit rate, and $U_i(t)$ is a realized investment and profit in each time step. In the absence of investment, all investment assets held by the bank i before the investment recovery are as follows:

$$Y_i(t) = \sum_{j=1}^{M} Q_{ij}(t-1) g_j(t), \quad (3)$$

where $Q_{ij}(t-1)$ is the number of shares of asset j held by bank i at time $t-1$. $Q_{ij}(t)$ is a dynamic change value, because bank i is likely to make new investments at each time step and the liquidation of assets can also be realized in each time step. $g_j(t)$ is the price of asset j at time t, which can be described as follows:

$$g_j(t) = g_j(t-1)\left(1 + \delta_j(t)\right), \quad (4)$$

where $\delta_j(t)$ is the rate of return on investment j at time t, which obeys the normal distribution based on the mean of τ; that is, $\delta_j(t) \in N(\tau, \theta)$. τ can be considered as the average rate of return for all investments, θ is the asset price volatility. In Iori's model, investment risk is not taken into account; rate of return on investment is fixed. In reality, the real rate return on investment of different assets is different, and the different return on investment of banks directly reflects the different investment strategies. Different from Iori's model, the rate of return on investment of different assets is different, and the rate of return on investment of all assets obeys normal distribution in this work. At time step t, bank i will recover a part of its investment assets randomly in this work; that is, $U_i(t) = p \times Y_i(t)$, where p is the proportion of investment recovery. After investment recovery, all investment assets held by the bank i before investment is $\widehat{Y}_i(t) = \sum_{j=1}^{M} \overline{Q}_{ij}(t) g_j(t)$, where $\overline{Q}_{ij}(t)$ is the number of shares of asset j held by bank i after investment recovery.

Thus, the owner's equity of bank i at time t before dividend and investment is

$$\widehat{V}_i(t) = \widehat{L}_i(t) + \widehat{Y}_i(t) - A_i(t) - \left(1 + r_b\right) B_i(t-1), \quad (5)$$

where $B_i(t-1)$ is the total loan of bank i at time $t-1$; r_b is the interbank lending rate. In (1), the dividend $D_i(t)$ of bank i at the time t is calculated as follows:

$$D_i(t) = \max\{0, \min\left[U_i(t) - r_a A_i(t-1), \widehat{L}_i(t) - \beta A_i(t), \widehat{L}_i(t) + \widehat{Y}_i(t) - (1+\chi) A_i(t)\right]\}, \quad (6)$$

where χ is the capital savings ratio and β is the deposit reserve ratio. The condition of the bank's dividend is $\widehat{V}_i(t)/A_i(t) \geq \chi$. In practice, depositories $A_i(t)$ for bank i are decided by the following equation:

$$A_i(t) = \left(1 + \sigma_A \eta_t\right) \overline{A}, \quad (7)$$

where σ_A is the standard deviation of all bank's random deposits, $\overline{A}$ is the mean of all bank's deposits, and $\eta_t \in N(0,1)$. The investment $I_i(t)$ of bank i at time t can be decided by

$$I_i(t) = \min\left\{\max\left[0, \widehat{L}_i(t) - \beta A_i(t) - D_i(t)\right], w_i(t)\right\}, \quad (8)$$

where $w_i(t)$ is the investment opportunity of bank i at time t, which is defined as follows:

$$w_i(t) = \overline{w}\left(1 + \sigma_w \mu\right), \quad (9)$$

where $\overline{w}$ is the mean value of all banks' investment opportunities, σ_w is the standard deviation of all banks' investment opportunities, and μ obeys normal distribution $N(0,1)$. It is assumed that the quantity of assets j invested by the bank i is $\Delta Q_{ij}(t)$ at time t, which satisfies $I_i(t) = \sum_{j=1}^{M} \Delta Q_{ij}(t) g_j(t)$. Thus, the value of $Y_i(t)$ after investment is updated as $Y_i(t) = \sum_{j=1}^{M} Q_{ij}(t) g_j(t)$, where $Q_{ij}(t) = \overline{Q}_{ij}(t) + \Delta Q_{ij}(t)$.

In the above banking system, a bank appears to bankrupt in the following situations: lack of liquidity, being unable to settle the expired depositor's deposit, or debt maturity. For a bank with its equity more than 0, if there is a surplus of liquidity after dividends and investment, then the bank is a potential creditor bank, which can provide funds in the interbank market. In order to maintain the normal operation, a debt bank needs to borrow money from the interbank market. For debt banks, repayments are made if the borrowing from the interbank market is sufficient to repay the borrowing of the previous period. At the same time, the liquidity of the debt banks has changed to 0. If the borrowing is not available or the borrowing will not be paid enough to repay the last loan and deposits, debt banks will sell the

investment assets until they can repay the previous loan and deposits. If the sale of assets is not enough to reimburse the previous dismantling, then the debt bank fails and carries out the liquidation of the assets; the assets must be used to pay back the deposits firstly and the resting will be paid back to the creditor bank in proportion. The operation process of banking network in this paper is different from Iori's model [14]. Iori's model does not allow banks to replenish liquidity by selling assets, which is inconsistent with the actual operation of the banking system, making Iori's model overestimate the systemic risk of banking system.

2.2. Investment Constraints in Interbank Lending. In the process of interbank lending, interbank lending funds are strictly limited to make up for the shortage of short-term funds rather than for investment. For a bank with liquidity surplus, (8) clearly limits the amount of its investment and cannot exceed its existing liquidity funds. For banks with insufficient liquidity, only through the interbank market to borrow their lack of liquidity $\sum_{j=1}^{N_{t-1}}(1+r_b)c_{ij}(t-1)B_{ij}(t-1) - \widehat{L}_i(t)$, r_b is the interbank market interest rate. The dynamic interbank lending process is described in Figure 2. The interbank lending process with investment constraints can be described as follows.

Step 1. Calculate the liquidity $\widehat{L}_i(t)$ of bank i at time t according to (2). If the liquidity $\widehat{L}_i(t)$ of bank i is positive, but the debt $B_i(t-1)$ of bank i at time $t-1$ is negative, then bank i is temporary potential creditor bank. If the liquidity $\widehat{L}_i(t)$ and liability $B_i(t-1)$ are positive at the same time and there is $\widehat{L}_i(t) > (1+r_b)B_i(t-1)$, then all the debts are repaid and the liquidity is updated to $\widehat{L}_i(t) = \widehat{L}_i(t) - (1+r_b)B_i(t-1)$. At the same time, bank i becomes a temporary potential creditor bank. If liquidity is not able to repay the loan, that is, $\widehat{L}_i(t) < (1+r_b)B_i(t-1)$, then bank i is a potential debt bank.

Step 2. For each temporary potential creditor bank, the dividends and investment are operated according to (6) and (8), and the liquidity is updated to $\widehat{L}_i(t) - D_i(t) - I_i(t)$.

Step 3. For a temporary potential creditor bank i, if $\widehat{L}_i(t) - \beta A_i(t) > 0$, then bank i is a potential creditor bank, and it can lend its liquidity to other banks. The largest loan amount is $\widehat{L}_i(t) - \beta A_i(t)$.

Step 4. For time t, the debt bank i keeps borrowing from the potential creditor banks in a random order, with a total amount of B_{ij} (B_{ij} is the maximum amount that the potential creditor bank j can offer the loan), until bank i borrowed money from other potential creditor banks enough to repay the previous interbank loan $(1+r_b)B_i(t-1)$. At this time, the debt Bank i's loan amount is $(1+r_b)B_i(t-1) - \widehat{L}_i(t)$; the debt bank's liquidity is set as $\widehat{L}_i(t) = 0$. After the repayment of the debt bank i, the liquidity of the creditor bank j is updated to $\widehat{L}_j(t) = \widehat{L}_j(t) + (1+r_b)B_{ij}(t-1)$. If bank i has already made loans to all potential creditor banks but still cannot borrow enough loans to repay $(1+r_b)B_i(t-1)$, then the bank sells assets Q_{ij} randomly until it meets the repayment requirements. If the sale of the asset S_Q^i is still unable to repay the loan, the bank is bankrupt and liquidated (the assets must be used to pay back the deposits firstly, and all the remaining assets are returned to all creditor banks in proportion).

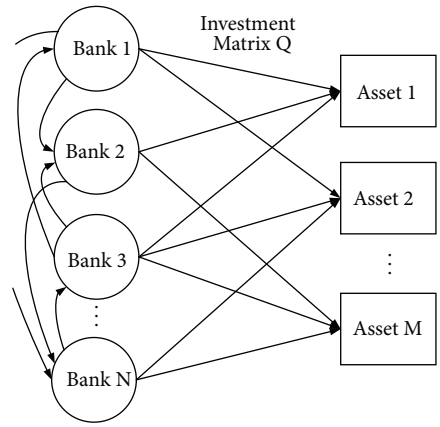

Figure 1: The structure of interbank market with overlapping portfolios.

2.3. Dynamic Evolution of Assets Prices with Overlapping Portfolios. From Section 2.2, it can be seen that when a bank has insufficient liquidity to repay its debt, it needs to sell assets for repayment. If the sale of the assets is still not able to repay the debt, the bank will go bankrupt and liquidate. In the above process, the selling of bank assets will lead to a fall in asset prices. A network of financial institutions holding the different assets is a bipartite graph shown as in Figure 1. Assuming that there are N financial institutions and M assets in the network, the market density is defined as $MD = M/N$. Each bank makes an investment according to (8), the asset portfolio of the bank i is $\{H_{i1}, H_{i2}, \ldots, H_{iM}\}$ ($H_{ij} = Q_{ij}(t)g_j(t)$), and the total investment assets are $H_i = H_{i1} + H_{i2} + \cdots + H_{iM}$. It is obvious that many financial institutions will invest in the same asset at the same time. There is an indirect connection between different financial institutions through the overlapping portfolios. The change in asset prices also affects multiple holding agencies. The changes in assets of a bank will affect other banks through overlapping portfolios. Assuming that the number of assets holds by the bank i is d_i, the average asset diversity of all banks in the interbank network system is

$$\overline{d} = \frac{1}{NM}\sum_{i=1}^{N} d_i. \tag{10}$$

The average asset diversity represents the indirect intensity of interbank. Banks should sell assets to make up for liquidity when they are short of liquidity and cannot make loans. In addition, if bank fails, the bankrupt banks will sell their asset portfolios due to asset liquidation. The assets sold will depreciate. Banks holding the same assets will be affected by the depreciation of assets, resulting in loss of all owners' rights and interests, which may lead to insolvency, thus

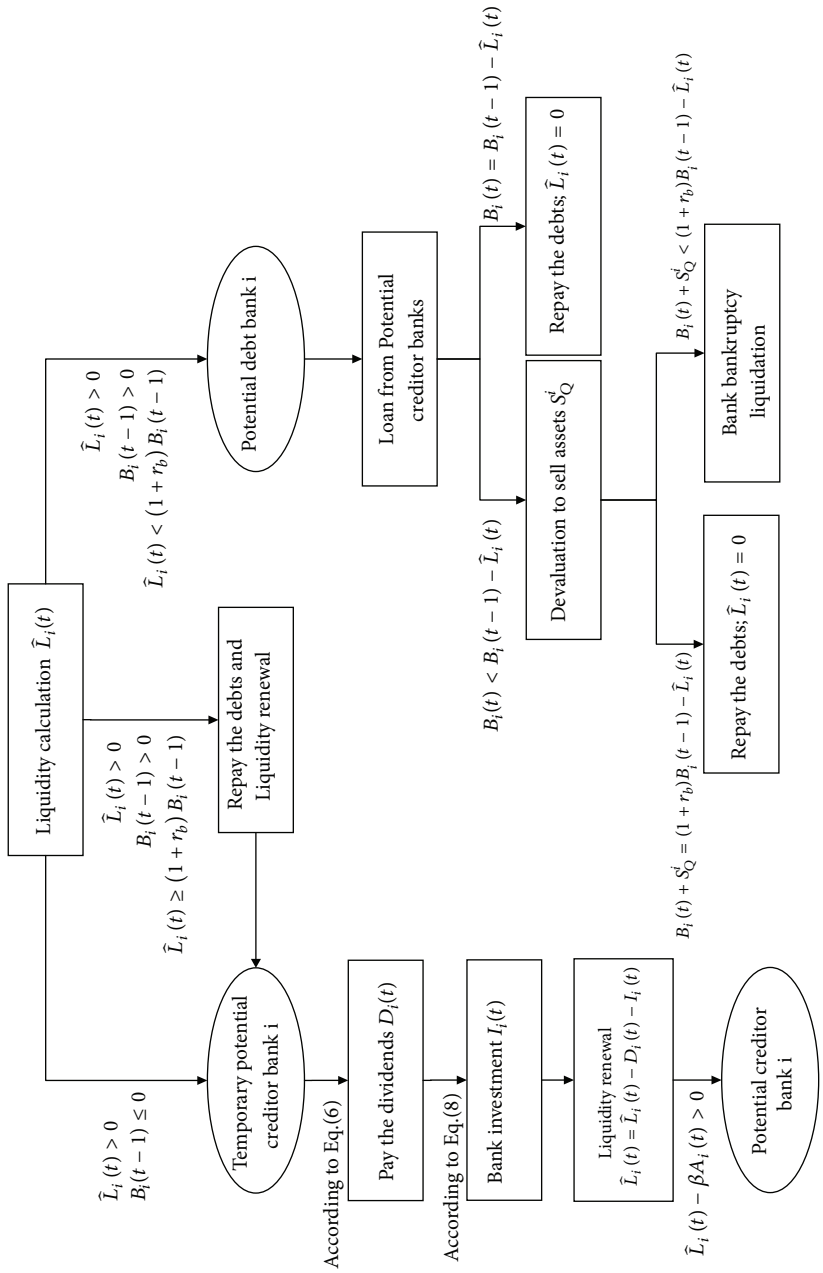

FIGURE 2: The dynamic process of bank i.

resulting in bank bankruptcy, which will further damage the assets of creditor banks. Through this evolutionary process, the initial shock of the interbank network is constantly propagated in the system. At time t, $Q_{ij}(t)$ is the quantity of shares of asset j held by bank i and $g_j(t)$ is the price of asset j. When banks sell their assets due to lack of liquidity or a bank is liquidated because of bankruptcy, assets will be sold in devaluation [33, 34]. Here, the market impact function is introduced to reflect the change of asset prices [30]:

$$f\left(x_j^t\right) = e^{-\alpha x_j^t}, \tag{11}$$

where x_j^t is the fraction of asset j liquidated up to time t. α represents the sensitivity of asset prices, that is, the degree of price volatility produced by the selling of assets. Thus, the price of asset j at time t is

$$g_j(t) = g_j(t)\, f\left(x_j^t\right). \tag{12}$$

In this paper, we refer to Caccioli's study [30] to take $\alpha = 1.0536$; that is, when 10% of the asset is sold, the price of the asset is also reduced by 10%, which corresponds to linear market impact for log-prices [35]. All prices are set to $g_j(0) = 1$ at time 0.

3. Simulation and Analysis

The whole banking network system evolves with time t. For a bank, its liquidity assets, owner's equity, and rate of return on investment (ROI) vary with time t. In the evolution of the bank network system, banks in the bank network system will fail due to the different operating conditions and operation strategies of the banks. One or several banks failures will lead to cascading failures of other banks in the system, which is due to the systemic risk of the banking system. The systemic risk of banking network system at time t is determined by the internal state and internal parameters of network system rather than the external factors of bank network system, such as savings interest rate and ROI. External factors affect the bank network systemic risk by influencing the internal variables of the bank's network system. The network evolves with external factors such as savings interest rate r_a, lending interest rate r_b, capital reserve ratio β, and average investment return rate δ. The failure of the banking system can reflect current systemic risk. To effectively characterize the systemic risk of banks, we calculate the normalized value $Risk(t)$ of the average number of bankrupt banks in $[t+1, t+T]$. $Risk(t)$ is the calculated value of systemic risk, which can be expressed as follows:

$$Risk(t) = \frac{1}{TN_e} \sum_{i=1}^{N_e} \sum_{j=t+1}^{t+T} \frac{M_j^i}{N_j^i}, \tag{13}$$

where N_e is the number of repeated simulations, N_j^i the number of surviving banks in the network at time j, and M_j^i is number of banks that fail during the ith simulation. T is the time scale, which is set as $T = 200$ in this work.

In order to further verify the effectiveness of the proposed model in characterizing the credit risk contagion, this paper simulates the model from different angles: (i) evolution process of systemic risk under different ROI; (ii) the impact of asset price volatility on the stability of the banking system; (iii) the impact of asset diversity on the stability of the banking system; (iv) the effect of banks' reserve ratio on the liquidity and stability of the banking system; and (v) the dynamic process of banks suffering asset depreciation in the financial crisis.

Establishing this model needs a certain theoretical background and needs to understand the practical operation rules and supervision rules of the banking system. In fact, the setting of parameters in this paper corresponds well with the parameters in the actual banking network system. Different parameter values will lead to different evolution results of the banking network system, which is also consistent with the operation process of the actual banking system. Our model is able to analyze the risk of the banking system under different parameters, which is conducive to our analysis of the systemic risk of the banking system and can also provide relevant reference for decision-makers.

In this work, 200 banks are used for simulations (more banks can be selected for simulation, but the 200 are already sufficiently responsive to the characteristics of banking network). The maximum simulation time step is 2000 (within 2000 time steps, the dynamic characteristics of the banking network can be fully embodied). There are 150 types of assets that banks can invest. At each time, each bank will recover 35% of its investment assets randomly. In this work, the initial owner's equities are subject to a standard normal distribution with a mean of 200. The average rate of return on investment is greater than the interest rate of deposit, that is, $\delta > r_a$, which ensures that the banking system has a profit margin. The profit margin will affect the stability of the banking system [36]. The greater the profit margin is, the more profits in the banking system are and the more stable the operation of the bank is. The capital saving ratio χ is set as 30% in this work; that is say, the dividends must satisfy the condition that the bank's liquidity is more than 30% of the savings. The condition guarantees that only a profitable bank can pay dividends. We only consider constraint behavior for banks; that is, the banks' loan cannot be used for investment and can only be used to repay the loan.

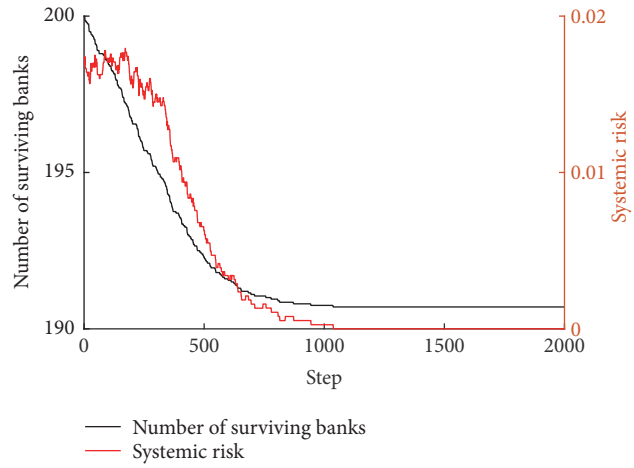

Figure 3: Changes in the number of surviving banks in the bank network as well as the corresponding systemic risks. The parameters are set as $\overline{d} = 0.1067$, $\theta = 0.02$, $\delta_{ave} = 0.009$, $p = 0.05$, $C = 0.03$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $\beta = 0.25$, $N = 200$, $M = 150$, $r_a = 0.004$, and $r_b = 0.008$.

Figure 3 shows the changes in the number of surviving banks in a banking network as well as the corresponding systemic risks. Figure 3 indicates that there may be banks collapsing from the first step, until the banking system is stable around 1000 steps. Systemic risk is the largest in the beginning of the network evolution, which is caused by the different initial state of the banks in the banking system. The initial net assets of banks are in the normal distribution with mean value of 200. The initial liquidity, the initial investment value, and the investment strategy of each bank are different. In the real financial market, investment is risky, so the return rate of investment in this work is in the normal distribution. For banks with low net assets and less liquidity, if the investment strategy is not good enough, then the investment income is not enough to pay the savings interest and loan; it is easy to go bankrupt. The bankrupt bank will be wound up, which devaluates the assets. On one hand, the bankrupt bank may not be able to fully repay the interbank borrowing. On the other hand, these bankrupt banks will devalue the

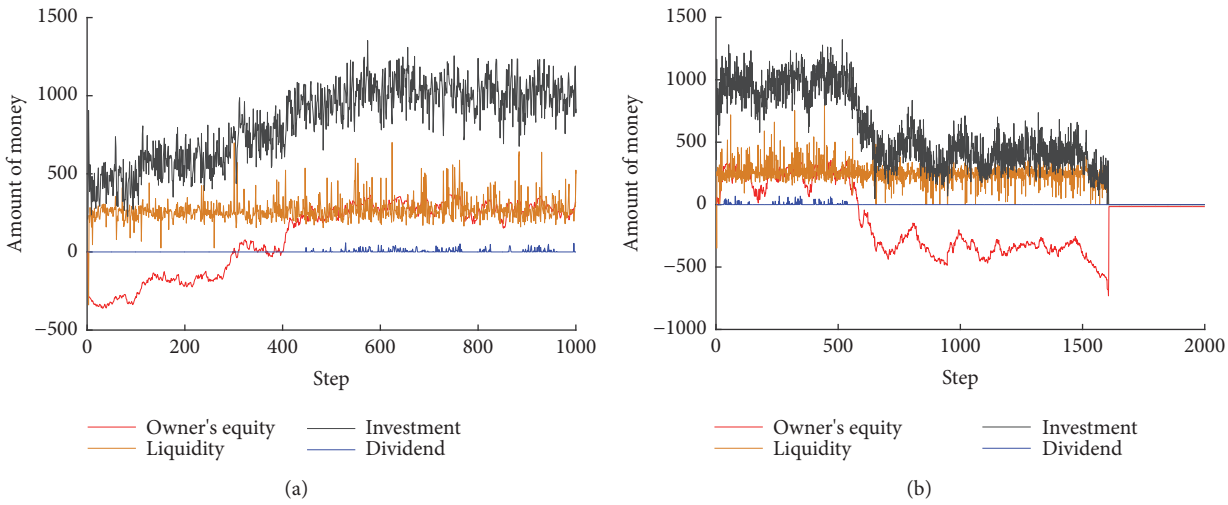

FIGURE 4: (a) The evolutionary process of a bank with negative initial value of ownership, but it eventually can run a stable operation. (b) The evolutionary process of a bank with positive initial value of ownership, and it finally goes bankrupt. The parameters are set as $\overline{d} = 0.0533$, $\delta_{ave} = 0.009$, $\theta = 0.06$, $p = 0.05$, $C = 0.03$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $\beta = 0.25$, $BankNo = 200$, $AssetNo = 150$, $r_a = 0.004$, and $r_b = 0.008$.

assets of other banks because of the overlapping portfolios. These two reasons will lead to the "domino effect" of bank bankruptcy and form the contagion of bank credit risk. Of course, for a bank with good initial state (high net assets and liquidity), if the investment strategy is not good, it will also lead to a decline in profit or even loss and finally bankruptcy. After 1000 steps, the banking system will be stable and no bank will fail. This is because the banking system has digested the risk in the system. Without external shocks, the banking system has enough capacity to resist the fluctuation of asset prices.

Figure 4 shows the dynamic evolution of two banks with different initial states. The net initial net value of one bank is negative, as shown in Figure 4(a). The net assets of another bank are positive, as shown in Figure 4(b). From Figure 4(a), it can be seen that the bank has gradually increased its net assets through continuous investment income and then further increases the total amount of investment and expands revenue, which has transformed the bank from a unhealthy state to a well-run bank. However, the initial state of the bank shown in Figure 4(b) is good, but at about 500 steps, the investment strategy is not good enough, resulting in the loss of assets, resulting in the gradual decline of net assets and the lack of liquidity, which eventually leads to bankruptcy. As can be seen from Figure 4, the state of a bank is not only related to the initial state, but also related to the investment strategy of the bank in the evolution process.

In real financial networks, the average rate of ROI represents the overall situation of the current financial market. Therefore, in order to reflect the impact of ROI on the stability of banking system, the average ROI is used to analyze the evolution of banking network. Figure 5 shows the changes in the banking system under different average ROI. Figure 5 shows that the higher the average ROI is set, the more stable the banking system can be achieved. When the average ROI

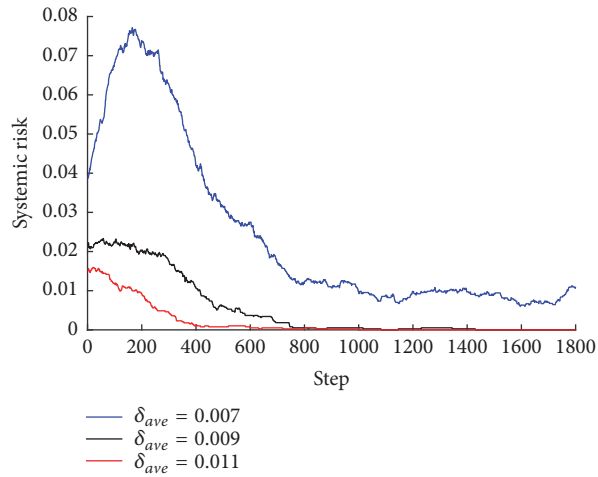

FIGURE 5: Systemic risk under different values of δ_{ave}. The parameters are set as $\overline{d} = 0.0533$, $\theta = 0.04$, $p = 0.05$, $C = 0.03$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $\overline{A} = 1000$, $\overline{w} = 500$ $\chi = 0.3$, $\beta = 0.25$, $N = 200$, $M = 150$, $r_a = 0.004$, and $r_b = 0.008$.

is 0.011 and 0.009, the banking system is able to quickly reach a stable state. When the average ROI is 0.07, the probability of banks failure in the banking system is greater than zero. From Figure 5, it can be seen that when the average ROI is 0.011 and 0.009, the risk of the system can be changed to 0 within 800 steps, while the average ROI is 0.007; the systemic risk always exists in the banking network. This is because the average ROI is too small to generate enough margin between deposit rate and investment income, which leads to the decline of banks' profitability, resulting in the weak ability to resist risk. Therefore, the low average ROI makes the banking network always have systemic risk.

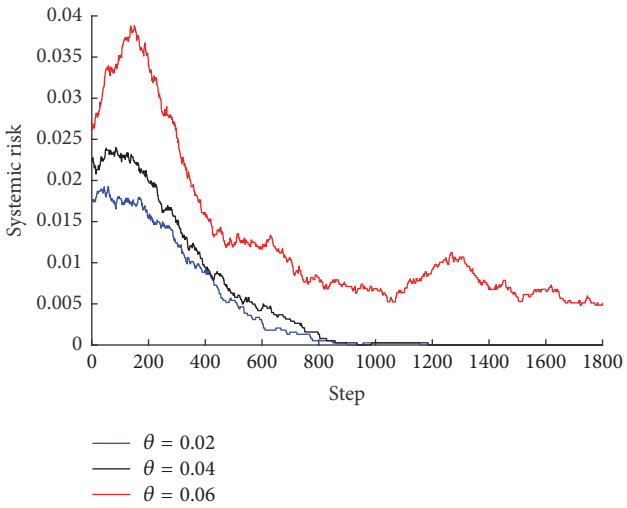

Figure 6: Systemic risk under different values of θ. The parameters are set as $\overline{d} = 0.0533$, $\delta_{ave} = 0.009$, $p = 0.05$, $C = 0.03$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $\beta = 0.25$, $BankNo = 200$, $AssetNo = 150$, $r_a = 0.004$, and $r_b = 0.008$.

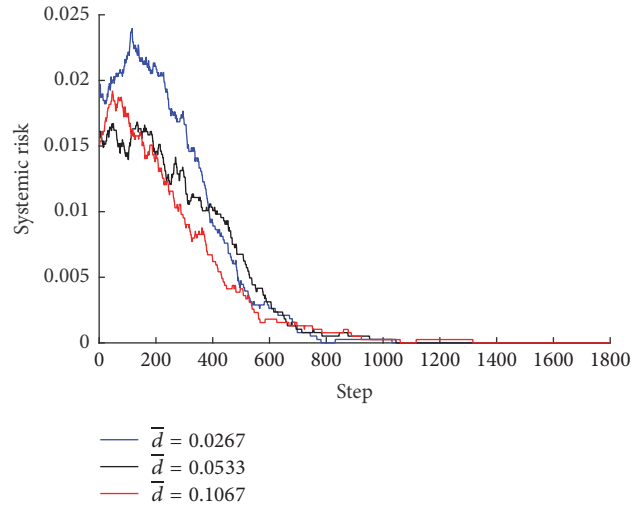

Figure 7: Systemic risk under different values of $\overline{d}$. The parameters are set as $\theta = 0.02$, $\delta_{ave} = 0.009$, $\theta = 0.02$, $C = 0.03$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $\beta = 0.25$, $BankNo = 200$, $AssetNo = 150$, and $r_b = 0.008$.

The choice of the investment strategy of banks has an important influence on the stability of the banking system. In addition to the average ROI, the objective description of the financial market should also take into account the volatility of the ROI θ. The greater θ is, the greater difference of ROI between different investment products at the same time step is and the greater the difference of ROI for the same investment product at different time steps is, which puts forward higher requirements for banks' asset selection. Figure 6 shows the results of the evolution of the banking system under different θ values. The more volatility of ROI is seen in Figure 6, the more banks that fail in the banking network. When the values of θ are 0.02 and 0.04, the network can evolve into a stable state. But when the value of θ is 0.06, that is, when the ROI is very volatile, the network will always have the probability of banks failure. From Figure 6, we can see that when the ROI of the network fluctuates greatly, the risk of the system increases sharply, reaching the maximum value at about 200 steps, and then the systemic risk is gradually released, but the systemic risk is consistent. Before the 200th step, banks that have low net assets and poor liquidity will have a certain probability of excessive investment losses, which leads to the bankruptcy. This phenomenon is caused by the following reasons: when the fluctuation of return on investment is very small, the probability of excessive loss of investment products is small. Banks can make up for the loss through borrowing and other investments. When the volatility of ROI is too large, the probability of excessive loss of investment products will increase. If the current state of a bank is not good enough, it is easy to see that the overall investment income is not enough to pay interest on savings and loans. In the financial crisis of 2008, many financial institutions were heavily invested in high-risk investment products, leading to bankruptcy.

The average asset density can reflect the distribution of bank investment. The greater the average asset density, the more decentralized the bank investment. The smaller the average asset density, the more centralized the bank investment. Figure 7 shows that the evolution of the banking network under the different average asset density. The values 0.02, 0.05, and 0.1 for $\overline{d}$ represented the average invest numbers 4, 8, and 16, respectively. Figure 7 shows that the banking network can all tend to be stable under different density of assets. But more banks will fail in the network with greater average asset density. This result indicated that the more decentralized a bank's investment is, the more stable the bank is. When the average ROI and the volatility of the ROI are fixed, all investment products suffer losses with same probability in the model. If there are too few investment types, every investment product is heavily loaded. Once an investment product has a big loss, the loss of the bank will become large, which will lead to the weakening of net assets and liquidity of the bank. In addition, once s asset is heavily loaded by a bank, if the bank fails, the price of the asset will depreciate substantially. On the contrary, if the investment is relatively scattered, even if an investment product suffers large losses, the impact on the overall investment income will not be too big. This model can be a good reflection of the fact of the real financial market, which is contrary to the existing model with overlapping portfolios [30]. The existing models based on overlapping portfolios only consider the degree of coupling between assets. If the investment is more dispersed, the asset coupling is greater, and the indirect association among the banks becomes stronger, which will increase the spread of the credit risk among the banks. In addition, the overlapping-portfolios-based model does not take into account the interbank market, while interbank market can provide support for the stability of the banking system (refer

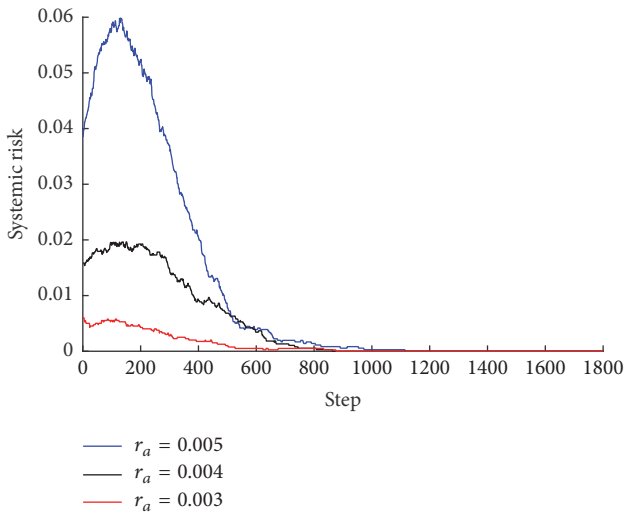

Figure 8: Systemic risk under different values of r_a. The parameters are set as $\overline{d} = 0.0533$, $\delta_{ave} = 0.009$, $p = 0.05$, $\theta = 0.02$, $C = 0.03$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $\beta = 0.25$, $BankNo = 200$, $AssetNo = 150$, and $r_b = 0.008$.

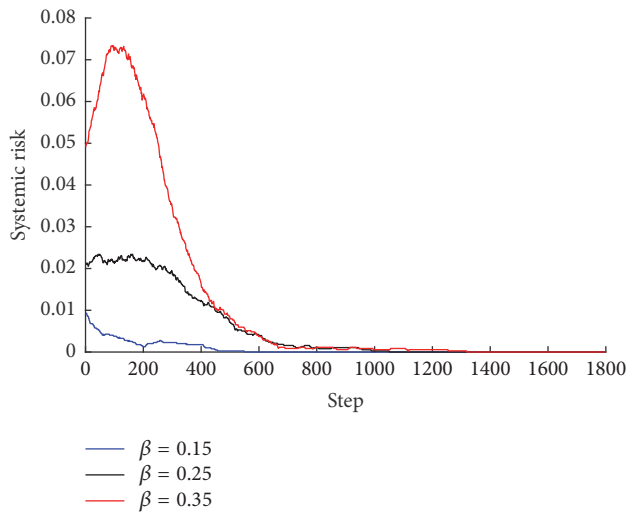

Figure 9: Systemic risk under different values of β. The parameters are set as $\overline{d} = 0.0533$, $\delta_{ave} = 0.009$, $\theta = 0.04$, $p = 0.05$, $C = 0.03$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $BankNo = 200$, $AssetNo = 150$, $r_a = 0.004$, and $r_a = 0.008$.

to the simulation in Figure 11), which can offset the risk of the coupling increase.

The margin of the investment and deposit is the main source of the banks' profit; the banks' profit level is affected by the deposit rate. Figure 8 shows the evolutionary results of an interbank network with different deposit rates. Figure 8 shows that the deposit rate has a greater impact on the stability of the banking system, and the higher the deposit rate, the more banks that eventually fail. In Figure 8, when the deposit rate is 0.005, the risk of the banking system increases sharply. The results show that the stability of the bank is sensitive to the deposit rate, and the change of the deposit rate will have a greater impact on the banking system. This is because, in the banking system, banks' liquidity is mainly provided by the savings, and the savings account for a large proportion of the funds in the bank. A slight increase of deposit rate will lead to the expansion of the deposit rate expenditure, thus causing a sharp shrinkage of banks' profits, which eventually leads to the failure of some banks with low net assets and liquidity.

The deposit reserve ratio can restrict the use of banks' funds and have an important impact on the stability of the banking system. Figure 9 shows the changes in the banking system under three different bank reserve ratios. From Figure 9, it can be seen that the lower the deposit reserve rate is, the less banks have to go bankrupt. When the deposit reserve is raised, the amount of money that can be used for investment is decreased; that is, the income of the investment is decreased, but the savings interest has not been reduced. Therefore, the increase of the deposit reserve ratio reduces the margin difference between investment and deposit, which will lead to a weaker bank's ability to deal with risks and increase the probability of a credit default.

During the financial crisis, many investment products will inevitably suffer huge losses, which will cause great damage to the banking system, for example, the global financial crisis in 2008. Here, we analyze the changes in the banking system when the price of the assets has fallen. One of the important manifestations of the financial crisis is the substantial fall in the price of assets. Figure 10 shows the evolution of the banking network when the assets fell at the 750th step. Figure 10(a) shows that when the average asset price fell by 15% and 30%, the number of bankrupted banks was not increased and the banking system remained stable. But when the average asset price falls by 45%, there will be a lot of credit default. This conclusion gives us an inspiration: there is a threshold. When the average asset price falls beyond this threshold, banks will have systemic risk. When the average asset price falls less than this threshold, the banking system can absorb the impact of asset shrinkage. Through our model simulation, the threshold is about 38% when the parameter setting is shown in Figure 10.

Interbank lending can make up for the lack of temporary liquidity and play an important role in the stability of banking system. At present, the research on the bank-assets bipartite network does not take into account the role of interbank lending. Figure 11 shows the evolution of banking system in the case of interbank lending compared with that without interbank lending. As can be seen from Figure 11, if there is no interbank loan, the banking network will accumulate lots of risks in the initial stage, and the number of bankrupt banks is large. In the absence of interbank lending, banks with insufficient liquidity can only sell assets to make up for liquidity, which can lead to a decline in the profitability of the banks, resulting in further reduction and even negative interest rates between investment and deposits, which further leads to the tension of the banks' liquidity, resulting in breach of contract. Figure 11 indicates that interbank lending can improve the stability of banking network.

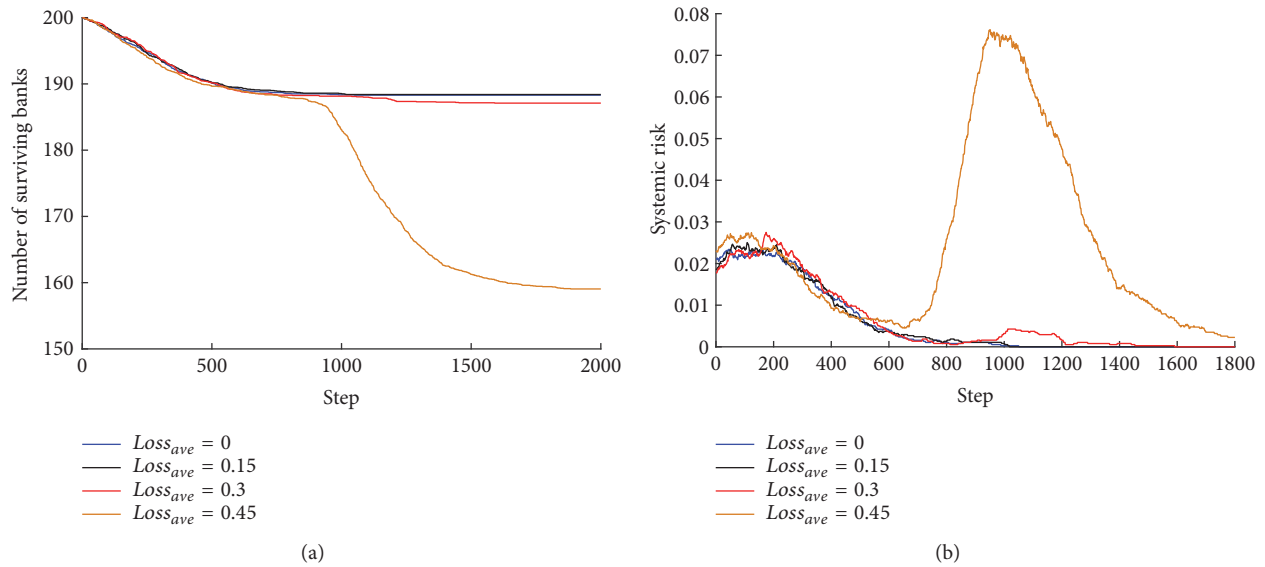

FIGURE 10: (a) The evolution process when the investment suffer a loss at step 750. (b) Systemic risk when the investment suffers a loss at step 750. The parameters are set as $\overline{d} = 0.0533$, $\delta_{ave} = 0.009$, $\theta = 0.04$, $p = 0.05$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $C = 0.03$ $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $\beta = 0.25$, $BankNo = 200$, $AssetNo = 150$, $r_a = 0.004$, and $r_a = 0.008$.

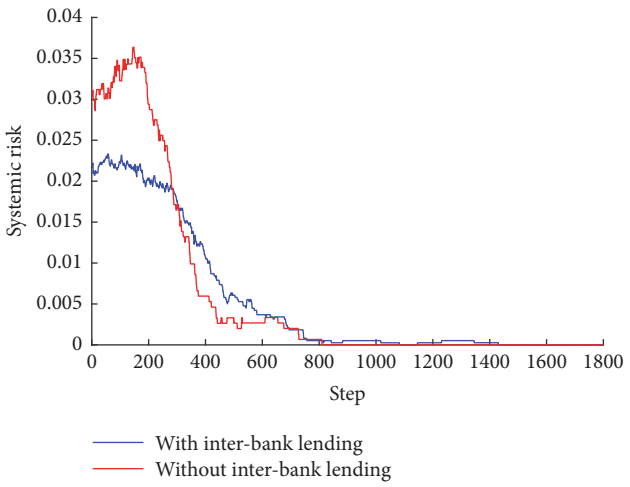

FIGURE 11: The evolution process of the system with interbank lending and without interbank lending. The parameters are set as $\overline{d} = 0.0533$, $\delta_{ave} = 0.009$, $\theta = 0.04$, $p = 0.05$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $\beta = 0.25$, $BankNo = 200$, $AssetNo = 150$, $r_a = 0.004$, and $r_a = 0.008$.

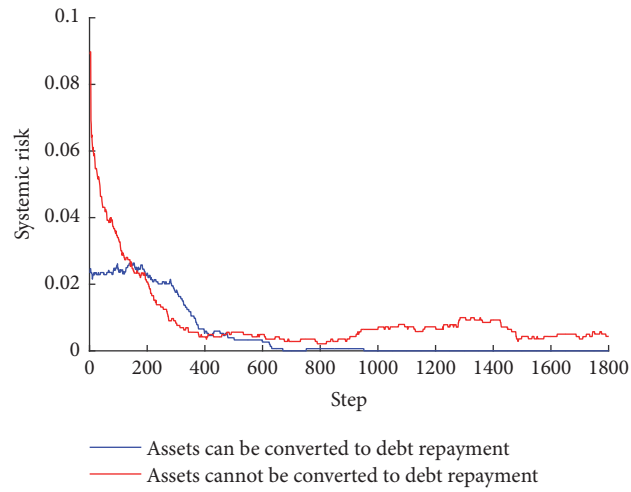

FIGURE 12: The evolution process of the system when the assets cannot be converted to debt repayment. The parameters are set as $\overline{d} = 0.0533$, $\delta_{ave} = 0.009$, $\theta = 0.04$, $p = 0.05$, $\sigma_A = 0.15$, $\sigma_w = 0.25$, $C = 0.03$ $\overline{A} = 1000$, $\overline{w} = 500$, $\chi = 0.3$, $\beta = 0.25$, $BankNo = 200$, $AssetNo = 150$, $r_a = 0.004$, and $r_a = 0.008$.

In the existing models of bank investment, when a bank lacks liquidity, it only considers the interbank loan but does not consider the liquidation of assets as well as asset devaluation when assets are realizable. Therefore, there are too many banks failures in the existing models, which is not in line with the reality. In fact, when banks encounter insufficient liquidity, they can sell some investment assets to supplement liquidity. Figure 12 shows the evolution process of banking network when banks cannot sell assets to supplement liquidity. From Figure 12, it can be seen that when banks cannot add liquidity by selling assets, the banking system will have a large systemic risk, and the systemic risk will always exist. When bank liquidity is insufficient and banks' borrowing is insufficient to meet the repayment of savings and loans, banks will fail if they are not able to make liquidity by selling assets. The result shows that the selling of assets plays an important role in the stability of the banking system. It can supplement the shortage of liquidity in time and solve the problem of the shortage of sudden liquidity in the banking system.

4. Conclusions and Discussion

Financial contagion is one of the most important forms for financial system to spread financial crisis. The financial system is a complex network system composed of a series of financial institutions and the interconnections between them. The connection relationship not only has the direct relation of the interbank market but also the indirect relation between the investment of the same assets among the financial institutions. Existing studies either focus on interbank market or pay attention to the overlapping portfolios of bank investment, which cannot accurately model the banking system. In addition, some hypothesis of current research is not practical. For example, the investment interest rate is fixed; liquidity cannot be complemented by devaluation to sell assets. Because of the one-sided and unrealistic assumptions of the research, the previous model cannot effectively respond to the real situation of a banking system, which leads to the banking system being too fragile reflected by the existing model. In order to better reflect the evolution of banking system, a new model for interbank market with overlapping portfolios is proposed in this work. In the proposed model, interbank lending and overlapping portfolios are both considered. The investment risk is also considered in this work, which plays an important role in the stability of the banking system. The proposed model allows banks to make up liquidity by devaluation to sell assets, with more realistic responses to the operating rules of the banking system. Through numerical simulation, this paper gets a series of conclusions which have important theoretical value and management significance. The main points are as follows:

(i) The bigger the average ROI, the more stable the banking system. If the average ROI is too small, the margin between deposit rate and investment income becomes small or negative, which leads to the decline of bank profitability, resulting in the weak ability to resist risk, making the banking network always have systemic risk.

(ii) If the volatility of ROI is increased, the probability of excessive loss of investment products will increase. If the current state of a bank is not good enough, there's not enough money to invest; the overall investment income may be not enough to pay interest on savings and loans, which leads to more systemic risk.

(iii) The model reveals that the more decentralized the bank's investment is (i.e., bigger average asset density), the more stable the bank is. The average asset density can reflect the distribution of bank investment.

(iv) The stability of the bank is sensitive to the deposit rate; the change of the deposit rate has a greater impact on the banking system. The higher the deposit rate, the greater the systemic risk.

(v) The increase of the deposit reserve ratio reduces the margin between investment income and deposit rate, which will lead to a weaker bank's ability to deal with risks and increase the systemic risk.

(vi) There exists a threshold for asset prices shrink. When the average asset price falls beyond this threshold, banks will have systemic risk. When the average asset price falls less than this threshold, the banking system can absorb the impact of asset shrinkage.

(vii) Interbank lending can make up for the lack of temporary liquidity and play an important role in the stability of banking system. The model presents that interbank lending can improve the stability of banking network.

(viii) Devaluation to sell assets plays an important role in the stability of the bank, which can supplement the shortage of liquidity in time and solve the problem of the shortage of sudden liquidity in the banking system.

These conclusions have important theoretical value and practical significance for systemic risk management practice. This work is of great theoretical and practical significance to the formulation of an effective, reasonable, and scientific systemic risk management strategy. The banking system is very complex; there are many points that can continue to be discussed. For example, the banking network structure is not a random network; relevant studies show that banking networks have significant scale-free network characteristics [37]. The investment of banks is not completely random, and there may be herd effect [38]. However, the model in this paper can well reflect the risk of the banking system. Above points can be empirically studied on the basis of the proposed model in the future.

At present, there are two main ways to model the banking system. The first way is the physical mechanism model for the operation process of the banking network system [14, 31]. Physical mechanism model can clearly describe the operation process of the banking network and can effectively model the banking behavior. The second way is a macroscopic dynamic equation model [39]. The second method is based on dynamic equation, which can get a series of conclusions through strict theoretical proof. However, the detailed description of the actual operation of the banking system is not clear enough, and it is difficult to model the banking behavior in the banking network. The physical mechanism model is adopted in this paper. The proposed method in this paper has not been proven and analyzed theoretically. At present, it is difficult to theoretically deduce the mechanism modeling of banking system. The model proposed in this paper is a dynamic process physical model with practical basis. It is very complex, highly nonlinear, and discontinuous, so it is difficult to get a conclusion through theoretical proof. Therefore, a series of meaningful conclusions are obtained through various simulations in this paper. However, theoretical derivation based on such models is an important research direction in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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