Spontaneous Congestion Process in Inter-bank Payment System

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Abstract

With the highly development of information technology, the more efficient inter-bank payment system is required by modern financial system. This paper analyzes the spontaneous process of congestion in inter-bank payment system through creating multi-agents model between banks and customers. The simulation result indicates that the systemic liquidity congestion of inter-bank payment system is affected seriously by the demand of inter-bank payment. We find that the scale of bank system plays an important role on relieving the systemic payment pressure. On the other hand, the scale of bank system has a positive relationship with the probability of payment crisis occurrence, because the larger scale of the bank, the more pressure it takes in payment system.

Keywords: Swarm Intelligence, Systemic Congestion, Payment Crisis, Non-homogeneous Poisson Process.

1. INTRODUCTION

The rapid development of modern economy depends heavily on the reliable and high-efficiency financial market. The sustained advancement of information technology undoubtedly becomes a catalyst for the accelerated expansion of financial industry. It forms a complex network structure among financial institutions and the other market participants. In this structure, one core infrastructure is the interbank payment system which allows movement of funds between banks. Fund transfers may be related to transactions originating from money, foreign exchange or securities markets.

The financial regulatory agencies from almost all countries focus on internal liquidity of entire financial system. The U.S. subprime crisis which leads to the great recession in 2008 reminds the whole world of the significance of maintaining adequate liquidity. However, it is not enough for the transactions only assisted by efficient computers. To the banks, there are different total payment requests from their customers in the same period. If some bank or part of banks cannot satisfy customers' payment requests for shortage of liquidity, the payment system is hard to avoid accumulating unpaid orders which causes the decline of the liquidity of financial system eventually. Thereby financial difficulties or financial institutions' bankruptcy is very likely to happen among the other market participants through financial contagion, due to their capital chain rupture affected by those banks lacking liquidity, which will bring huge losses to the real economy. Trading payments' settlement instantly plays an important role in insuring the stability of financial market; however, the phenomenon of payment orders delaying occurs in both developed countries and developing countries. Therefore, it is great practical significance of preventing the emergence of systemic crisis and keeping financial system stable and healthy through studying how to avoid systemic congestion (payment orders delayed aggregating) occurring in the payment system.

2. BACKGROUND

At present, the financial market is a complicated system consisted of various functional organizations and entities. Most of participants in market settle the trade through interbank transfer, thus interbank payment system undoubtedly becomes the most important part of whole financial system. Furthermore, interbank payment system is the trading center of currency market, such as foreign exchange market and stock market. Today, the total payment requests processed by FFS (Fedwire Funds Service) in United States are more than 500,000 in one day, and the amount value is over 2 trillion dollars [1]. The TARGET system in EU has the similar function as FFS in U.S. [2].

In China, with the establishment of interbank payment system, our payment system has transformed from a measurement tool for recording the planned economic activities into a tool for helping banks to adapt for the development of market economy. In 2010, China Union Pay interbank information exchange system processed successfully transactions 8.453 trillion and the total transaction value is 11.23 trillion yuan, with a growth of 21.77% and 46.40% individually, and the ratio of successful transactions is 98.5% in 345 out of 365 days in one year [3]. According to the data, the economy of China works well with relatively high transaction success rate in payment system. However, the higher transaction success rate is, the harder latent problems are found, so congestion phenomenon in payment system is easily ignored by financial regulatory bureaus in those countries which is rarely in a payment crisis.

In fact, currently several experts have doubted about the safety of payment system. Participants of payment system have an economic incentive to minimize the funds committed to payment processing because liquidity used for settling payments imposes an opportunity cost on banks. Shortfalls of funds can delay a bank's payment processing, and payment systems can even enter gridlock states in which no bank can process a payment. Delayed payments are unavailable to intended recipients: in this way congestion in the payment system can propagate into the economy by restricting money flow among banks and eventually among their customers. Morten and Soramäki [4] pointed out in Annual Report of the ECB TARGET run (2006), there probably will be a large number of unpaid payment requests accumulated due to the shortage of liquidity of some banks in inter-bank payment system, and eventually make the liquidity of entire payment system decline, risk aggregates continuously, even part of banks have to delay the payment orders or go bankruptcy. For the complexity of payment system itself, most of researches on liquidity risk's formation resort to the simulation method [5]. These simulations have used detailed descriptions of the business rules followed by the diverse participants, including banks and system operators, to anticipate the response of specific systems to potential stresses. The study of Beyeler et al(2006) is representative of simulation methods[6]. Their conclusion showed that there would be numbers of unpaid payment instructions aggregated because of lacking external liquidity market for adjusting the liquidity. This phenomenon was called "Systemic Congestion". For assumptions on the fixed network structure and homogenous banks and customers, Beyeler's model is incompatible with reality. Soramäki [7] firstly used the network method for describing the complex structure of the bank payment system, which edges are links between banks formed by payment relationships. Factually, even the main structural feature of the real interbank payment system is scale-free topology [8], however, the structure of the interbank payment relationships vary dynamically with payment flows' changing over time. In this case, Beyeler's model is not very reasonable. Accordingly, Beyeler's research merely proved the existence of the "crowding" from the result, and barely explained the mechanism of "spontaneity" of systemic congestion phenomenon.

In addition, ABM(Agent-based Model) method is playing an important role in studying laws of complex system from bottom to up, since Bak [9] et al found that there would exist self-organization phenomenon in a nonlinear dynamical system formed by a large number of interacting agents. This paper builds an interbank payment system model based on swarm intelligence model, and then studies the emergence of systemic congestion and the main factors influencing the formation process of settlement system crowding phenomenon in a nonlinear dynamical system which is composed by banks, banks' clients (customers) and settlement center of the central bank in simulation. At last, some policy recommendations are proposed for keeping interbank settlement system stable operation in China, even other countries in the world.

3. MODEL
3.1 Environment Settings

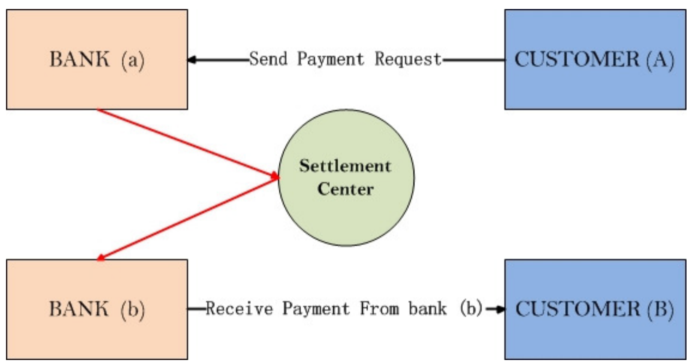

FIGURE 1: Payment Request Flow Chart.

The whole simulation system is constituted by the bank group (banks), the settlement center of central bank, customer group (customers), including financial and non-financial enterprises, individuals, and other entities.

Trading behaviors in the market usually are caused by a variety of real economic activities among agents in customer group. The liquidation of these transactions, except for little amount of cash transactions, are usually completing through the bank's payment function. As shown in Figure 1, some transaction happens between customer (A) and (B) for some real trade, customer (A) has to pay agent (B) for traded goods or other things. If the transaction is a non-cash transaction, custmer (A) need to send a payment instruction to bank (a), in which it has a deposit account. Bank (a) transfers the money to the bank (b) by the payment system of settlement center in central bank after receiving the instruction, if the surplus account balance of Bank(a) is of sufficient for paying. At last, bank (b) notifies the agent (B) to complete payment receiving.

To analyze the function of interbank payment system, firstly we must analyze the characteristics of commercial banks' accounts in the central bank. For example, In China, the commercial banks must register three accounts in local branches of the People's Bank of China: Reserve Account, Surplus Reserve Account, and the Loan Account. Reserve Account exists for the statutory reserve requirements so that the account balance are the sequestration of funds which can not be used, however, it usually makes corresponding adjustment based on the amount of deposits in a period. Loan account is the lending limits that commercial banks can borrow from the central bank, the credit scale will be distributed regionally and institutionally after being enacted by the head office of the central bank and commercial banks. The financial settlement of transactions payments are executed through the funds transfer among the commercial banks' surplus reserve accounts in the central bank's payment system. Although the surplus deposits obtain the interest income from central bank, the interest rate is lower than market interest rate, thus the banks will only retain a small proportion of their deposits as surplus to deal with the random payment requests in order to reduce the opportunity cost.

As shown in Figure 2, at time t, bank i receive a payment instruction $I_i(t)$ sent by one of its customers, if its surplus account balance $B_i(t)$ satisfies the constraint $B_i(t) \geq I_i(t)$, then transaction amount will directly transfer through payment system; if surplus account balance is not enough to pay, bank i can only pay $B_i(t)$, the unpaid part will enter the unsettled queue $Q_i(t)$ of bank i which will be settled after other banks' transfer payments to bank i.

In absence of external liquidity financing mechanism, it is very possible to lead $Q_i(t)$ to accumulate. Therefore the payment pressure of the entire banking system would rise continuously. With the formation of systemic liquidity congestion, bank default and bankruptcy are going to happen for lacking of liquidity. This paper analyzes the process of cumulating total balance in unpaid queue $\sum Q_i(t)$ through swarm intelligent model. The larger $\sum Q_i(t)$ is, the higher level of the systemic congestion is.

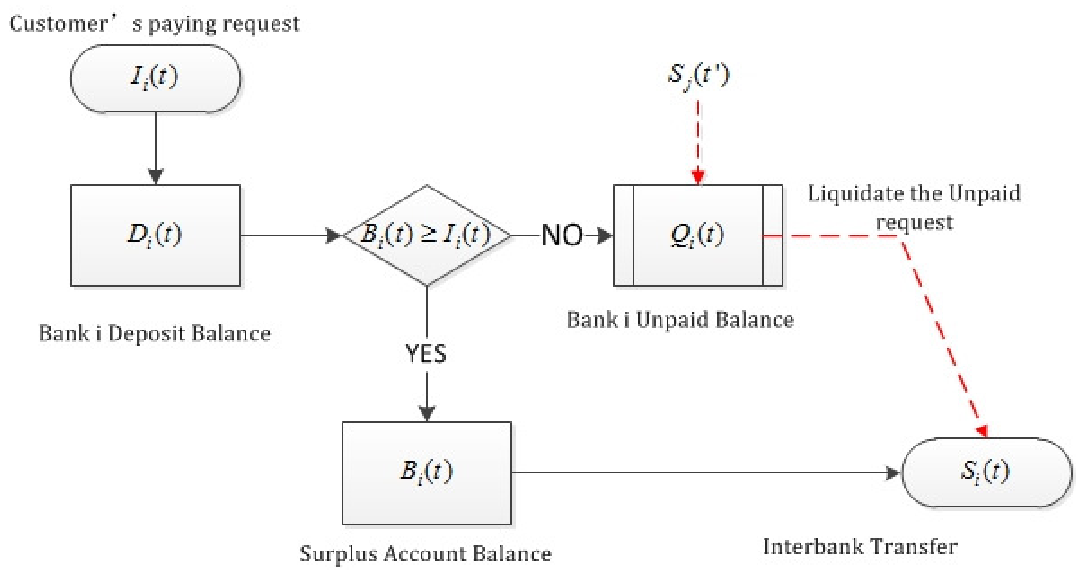

FIGURE 2: Response Process of Bank i after Receiving Payment Instruction $I_i(t)$.

3.2 Bank Group Model

V represents the set of all banks. As equation (1) shows, bank payment process involves three financial status variables, $D_i(t)$, $B_i(t)$, $Q_i(t)$, $i \in V$. As the difference of banks' financial status in reality, we define banks' scales are of heterogeneity, so their initial deposits are different each other. According to the research on the scale of USA corporations by Axtell Robert[10], this model assumes that the initial deposits size of each bank in the bank group obeys Pareto power-law distribution. That is:

$$P\left(D_i(0)>d\right)=\begin{cases}\left(d_m/d\right)^{\alpha} & d\ge d_m\\ 1 & d<d_m\end{cases} \tag{1}$$

d_m is the low-limit of bank initial deposits, α is a power-law distribution parameter. Then we assume that k is a fixed ratio of each bank's initial surplus account balance to initial total deposits. Then we have:

$$B_i(0)=k\cdot D_i(0) \tag{2}$$

At the beginning of simulation, all banks have no unpaid payment requests, that is $Q_{i\in V}(0)=0$.

We use Python to build a bank system project, and the major properties and methods of bank class are as follows (Table 1):

Properties	Methods
Deposit	Send payment request
Balance	Receive payment
Queue	Add unpaid payment part into queue
	Liquidate unpaid payment part in queue

TABLE 1: The Main Properties and Methods of Bank Class in Program.

$S_i(t)$ is the amount of payment that bank i actually transfer through payment system at time t, at the same time, we set payment amount received by bank i from other banks as $R_i(t)$. In continuous time model, bank i's deposits $D_i(t)$, the total surplus account balance $B_i(t)$ and the total unpaid payments $Q_i(t)$ at time t should satisfy the dynamic constraints (3) (4) (5):

$$D_i(t)=D_i(0)+\int_0^t\left(R_i(s)-I_i(s)\right)ds \tag{3}$$

$$B_i(t)=B_i(0)+\int_0^t\left(R_i(s)-S_i(s)\right)ds \tag{4}$$

$$Q_i(t)=\int_0^t\left(I_i(s)-S_i(s)\right)ds \tag{5}$$

In simulation process, as sending time of each customer's payment order is random and discrete, so the integral of equations (3) (4) (5) can be converted into summation calculation.

3.3 Customer Group Model

In our model, the main behavior of agent in customer group is sending randomly payment instructions to the agent in bank group. Due to the different amount included in each payment instruction in reality, there is no statistical distribution for each payment amount in payment system operation report of Chinese central bank, furthermore, Beyeler et al's equal payment order does not identical to reality, in this article, we assume that $I(t)$ obeys the uniform distribution in the interval $(0, I_{\max}]$.

On the other hand, the deposits size of bank should have positive correlation with the number of payment instructions received in unit time. Therefore this model set each customer's payment order sending as non-homogeneous Poisson process, which means the frequency of customer's payment order per unit time is proportional to bank(order source node)'s current scale of clients' deposits. The strength parameter $\lambda(t)$ of Poisson process satisfies constraint (6).

$$\lambda(t) \propto D_i(t) \tag{6}$$

According to characteristics of Poisson process, in a short period $\Delta t \to 0$, the probability of one payment order sent from one customer to bank i should be $\lambda(t) \cdot \Delta t$.

3.4 Banks and Customers Interaction Mechanism

The external parameters in our simulation system are total number of banks N , and the number of agents in customer group M . After determining quantity of bank group and customer group, the simulation is carried out according to the following steps:

1) In the light of the external parameters settings, bank and customer instances would be created. And then bank instance is initialized in order to make the bank sizes obey power-law distribution.

2) Traverse all instances of customer group at current system time, trigger the event of sending payment order, of course, the trigger mechanism should obey non-homogeneous Poisson process, and then we can determine whether each agent send a payment order currently and the payment amount of this order.

3) The bank instance designated to participate in the payment triggers the payment sending events. If the surplus reserve account balance is not sufficient, it covers partial payment request, and then triggers the event that unpaid part is added into the queue of due payments. In this process, it executes liquidation due payment event immediately once the bank receives the interbank transfer from other banks. Refer to some banks, sending and receiving events will recursive call several times. Of course, it is possible that one bank only deals transfer payments to another bank or receives transfer payments from some banks at the current time. These random situations are influenced by the instructions' randomly arriving in step (2).

4) Calculate current total unpaid payment requests of banks in simulating system, and then return to step (2). The simulation will continue until time is beyond the presetting total system time.

4. SIMULATION RESULTS

We use Python programming language to model the entire simulation system, and analyze the results in two aspects. On the one hand we observe the formation of systemic congestion, and find factors affecting the level of congestion. On the other hand, we can find the relative possibility of payment crisis for different banks, according to different banks final financial status when simulation ends.

4.1 Congestion of the Payment System

Firstly, we fix the total number of banks $N = 20$, and then change the number of customers, separately set $M = 100, 500, 1000$ to obtain the results in Figure 3.

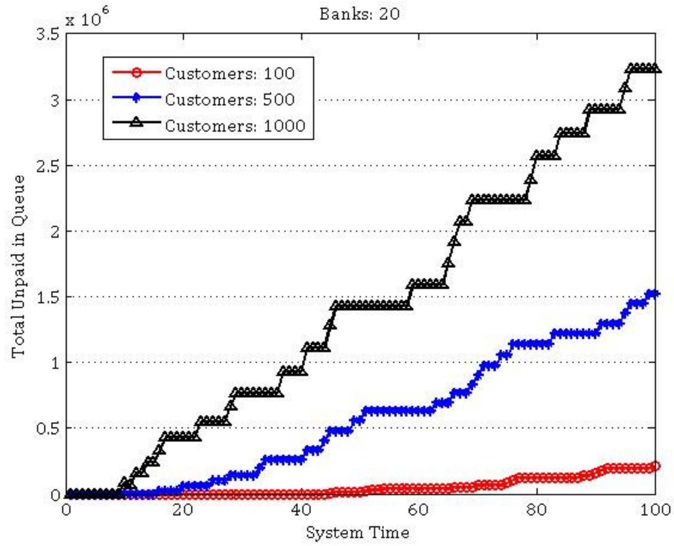

FIGURE 3: Customers Scale's Influence on The Level of Congestion.

In Figure 3, the curve with 1000 agents (customers) is on the top, and the curve with 100 agents (customers) is at the bottom. It shows that the systemic congestion will be higher with the total number of customers' systemic increasing. Finally, it will lead more rapidly aggregation of the unpaid payments.

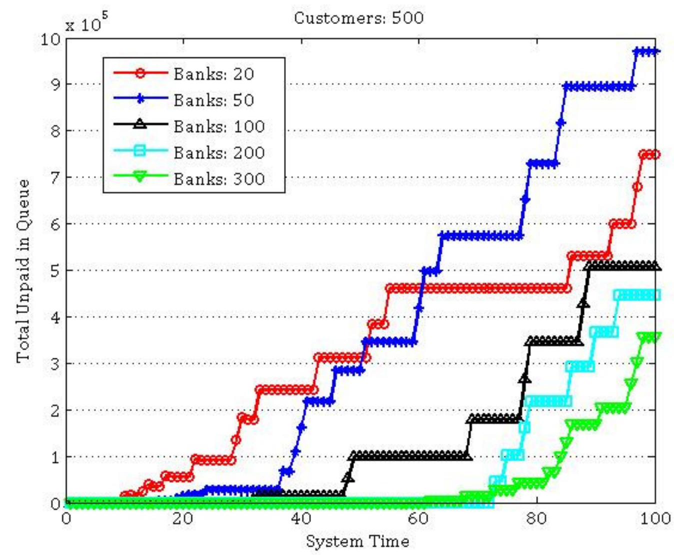

FIGURE 4: Banks Scale's Influence on The Level of Congestion.

The huger customers' scale inside simulation system is, the more payment orders sent in every time period, in other words, paying pressure for banks is proportional to the customers' scale.

In addition, the total number of customers is fixed as $M = 500$, and then we change the number of banks, $N = 20, 50, 100, 200, 300$, the result is shown in Figure 4.

As Figure 4 shows, the delayed paying requests will accumulate relatively slowly when the scale of banks in system expands. The reason is that more banks undertake the payment pressure, in this case, the probability of congestion in payment system will decrease with payment pressure's easing.

4.2 Payment Crisis Analysis

We get the values on financial status of the banks using numerical analysis at the end of the system simulation.

Bank ID	D_i	B_i	Q_i	Status
1	216566.94	919.69	315736.85	1
2	128503.96	37567.87	0.00	0
3	173718.16	0.00	255249.97	1
4	130199.32	17490.92	0.00	0
5	270273.71	0.00	601718.30	1
…	…	…	…	…

TABLE 2: Part of Values of Individual Financial State Variables in Bank Groups at the End of Simulation.

Table 2 shows financial status of banks at the end of simulation. The bank i can be defined "payment crisis occurrence", if the bank i's deposits balance D_i is less than unpaid Q_i. The bank needs to increase liquidity urgently, or it will have risk of default or go bankruptcy. We mark the banks which face liquidity problem with label 1, the other banks without payment crisis are labeled 0.

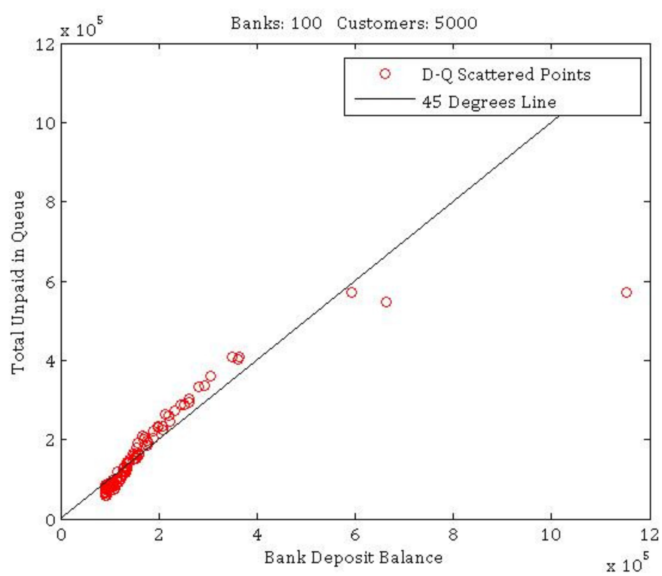

FIGURE 5: The Final Status about Bank Deposit and Unpaid Balance (100 Banks, 5000 Customers).

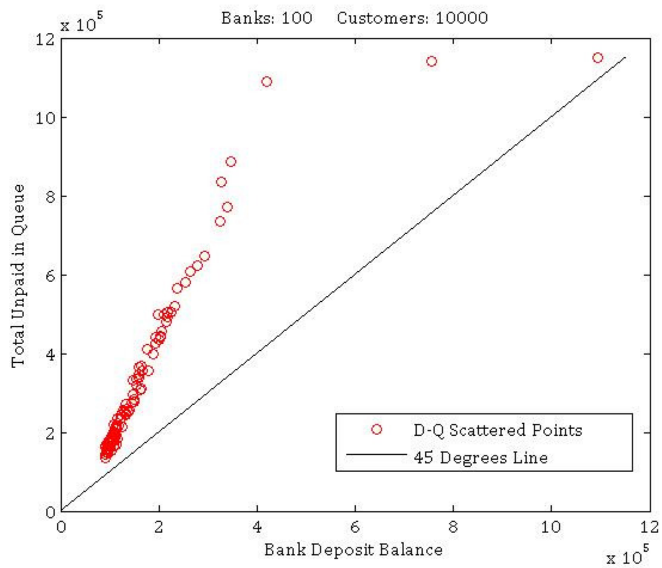

FIGURE 6: The Final Status about Bank Deposit and Unpaid Balance (100 Banks, 10000 Customers).

We run the simulation system on condition that the total number of banks is $N = 10^2$, the customers' scale is $M = 5000, 10000$. Part of data (D_i, Q_i) is shown in Table 1, and Figure 5 and Figure 6 are the scatter-plot graphs including all data.

Figure 5 indicates that the more deposits bank takes, the more unpaid balance is accumulated probably. However, the trend slows down gradually with the bank deposit balance increasing. The straight line in Figure 5 and Figure 6 is the point set P ($P = \{(D_i, Q_i) | D_i = Q_i\}$). Those points above the line satisfy the constraint $D_i < Q_i$, and it means those banks face payment crisis. And those points under the line satisfy the constraint $D_i > Q_i$, and it indicates those banks' financial status is safe. Obviously, in modern payment system, the medium-sized bank takes relatively more pressure, Both Figure 5 and Figure 6 show the curve, which consist of D-Q scattered points, is concave. Two reasons lead this result: on the one hand, the small banks is relatively safe for its smaller customer deposit scale, so they undertake light payment pressure. On the other hand, the large banks can maintain their financial status well, because their asset scale is relative large, which leads them to buffer more payment pressure.

5. CONCLUSION

The inter-bank payment system is the core of modern financial system, and it is an important tool for detecting the market liquidity. Appearance of "congestion" inside the inter-bank payment system is bound to lead to decrease the liquidity of entire market, hinder economic development, and even give rise to serious payment crisis to part of banks.

In this paper, simulation results mainly indicate that: 1) the formation speed of congestion phenomenon is severely influenced by the market payment demand. The total amount of unpaid requests will increase rapidly, when systemic payment pressure rises constantly. At present, Chinese economy is developing prosperously and the payment system in central bank is in the period of constructing and improving. With economic developing, liquidity for trading boost quickly, thus, the contradiction formed between payment pressure growing and paying settlement system's not well developed. 2) The total number of banks plays an important role on alleviating congestion phenomenon, therefore, the authorities can release the pressure in paying demand through establishing more banks to provide financial services. 3) Otherwise, we find that the medium-sized banks have the relatively greater payment pressure through analyzing the forming of bank payment crisis. Therefore the regulatory sectors need to more carefully monitor the liquidity index of medium-sized banks and suggest them to replenish liquidity timely so as to prevent excessive accumulation of payment delayed.

6. FUTURE WORK

This article focuses on the spontaneity of formation process of payment congestion, when there isn't a mechanism for bank system financing external liquidity through inter-bank borrowing. The follow-up research will add the external liquidity market and the central bank into simulation system, then study how to reduce the level of systemic congestion, and estimate the total cost of eliminating systemic congestion.

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