Jukka Topi

Bank runs, liquidity and credit risk

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Bank of Finland Research
Discussion Papers
12 • 2008

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I am grateful to Esa Jokivuolle, Tuomas Takalo and Jouko Vilmunen and seminar participants at the Bank of Finland for their helpful comments and suggestions. I am solely responsible for any remaining errors and omissions.

http://www.bof.fi

ISBN 978-952-462-440-4
ISSN 0785-3572
(print)

ISBN 978-952-462-441-1
ISSN 1456-6184
(online)

Helsinki 2008

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Bank of Finland Research
Discussion Papers 12/2008

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Abstract

In this paper, I develop a model that addresses the links between banks' liquidity outlook and their incentives to take credit risk. Assuming that both bank-specific liquidity shocks and credit losses are necessary to provoke bank runs, the model predicts that a bank's incentives to mitigate its credit risk by screening decrease if the probability of a bank-specific liquidity shock declines. This suggests that the benign liquidity outlook prevailing prior to the subprime crisis may have contributed to the lack of screening by banks that has been an important causal factor in the crisis.

Keywords: liquidity, credit risk screening, bank runs

JEL classification numbers: G12, G21, G28

Talletuspaot, likviditeetti ja luottoriski

Suomen Pankin keskustelualoitteita 12/2008

Jukka Topi
Rahapolitiikka- ja tutkimusosasto

Tiivistelmä

Tässä tutkimuksessa analysoidaan teoreettisen mallin avulla pankkien likviditeettinäkymien ja luottoriskinottokannustimien välistä vuorovaikutusta. Kun sekä likviditeettihäiriöt että luottotappiot oletetaan välttämättömiksi talletuspaon syntymiselle, havaitaan, että pankkikohtaisten likviditeettihäiriöiden todennäköisyyden pieneneminen heikentää pankin kannustimia supistaa luottoriskiään seulomalla luottoasiakkaitaan. Tulos viittaa siihen, että ennen ns. subprime-kriisiä vallinneet hyvät likviditeettinäkymät ovat voineet vähentää pankkien luottoasiakkaiden seulontaa ja siten myötävaikuttaa kriisin syntymiseen.

Avainsanat: likviditeetti, luottoriskin seulonta, talletuspaot

JEL-luokittelu: G12, G21, G28

Contents

1 Introduction

The US subprime crisis and its escalation to a global financial market turmoil in 2007–2008 have re-emphasized the question how banks' liquidity outlook affects their risk-taking behaviour. In particular, it could be asked whether the likelihood of banks' future liquidity problems has played a role in banks' credit screening decisions. The possible link between banks' liquidity outlook and screening decisions is important since lack of screening by banks and other market participants has been quoted as a significant underlying reason for the crisis.

In the years before the crisis, it was generally observed that financial market had become more flexible and resilient to shocks, which seemed to reduce the probability of liquidity problems threatening individual banks or other market participants. This development was seen to be at least partly due to financial innovations and new agents in the financial markets, as in Greenspan (2005), acknowledging '...the very important contributions hedge funds and new financial products have made to financial stability by increasing market liquidity and spreading financial risk, and thereby enhancing economic flexibility and resilience.'

Along with other possible factors, it is possible that the comfortable liquidity outlook in the financial markets prior to the crisis has encouraged banks to take more credit risks and not to mitigate them by screening their borrowers. Because liquidity problems were only an unlikely threat during this period, banks had little incentives to ensure high credit quality by screening so as to better cope with liquidity crises.

In literature of bank runs and liquidity crises, bank runs have been explained either to be caused by depositor panics (eg Diamond and Dybvig, 1983, or more recently von Thadden, 1998) or by the weak fundamentals like a downturn in the business cycle (eg Gorton, 1988, or Allen and Gale, 1998). In addition, Allen and Gale (2004b) have recently demonstrated how aggregate uncertainty can provoke large fluctuations in asset prices and subsequent bank runs on a number of banks in the economy.[1] While business cycle (and implicitly banks' credit losses) has a role in causing bank runs in this field of literature, it does not consider the possibility that banks' diligence in screening could affect the emergence of bank runs. On the other hand, the question about the possible effects of liquidity outlook on incentives to screen remains unanswered.

In this paper, I address the relationship between liquidity outlook and credit screening by developing a model where banks face potential liquidity problems and credit losses. In the model, I focus on cases where bank runs may be caused either by combinations of liquidity shocks and credit losses or severe liquidity shocks alone.[2] So, the model combines the possibility that aggregate

[1] A comprehensive review of the interlinking of financial fragility, bank runs and asset markets is offered by Allen and Gale (2007).

[2] To make credit risk interesting, I make the assumption that banks' credit losses are sufficiently large to make it optimal for banks short of liquidity to default but not too large to force banks with excess liquidity to default. In section 4, I discuss the case where credit losses are large enough to provoke bank runs alone.

liquidity uncertainty can cause bank runs (as in Allen and Gale, 2004a,b) with the possibility that weak economic fundamentals may contribute to a bank run (as in Allen and Gale, 1998). However, I let the banks endogenously choose whether they mitigate credit risk by screening or allow for a risk of weaker outcome (ie credit losses). I establish my model on the foundation of the framework in Allen and Gale (2004b). Similarly to Allen and Gale, part of the competitive banks in the economy have to sell at least some of their illiquid assets in an interbank asset market to acquire liquidity to meet their obligations to depositors.

The model confirms the idea that an increase in the probability of bank-specific liquidity problems tends to magnify banks' incentives to improve the quality of their borrowers by screening. This is because the liquidity problems trigger costly bank runs on banks with low credit quality. When liquidity problems become more likely, the expected value of high credit quality and screening increases. In the model, an increase in the probability of bank-specific liquidity problems has another, negative effect on banks' incentives because asset prices react to more common liquidity problems so that bank runs that could be averted by screening become less costly. Normally, when liquidity problems are relatively unlikely, the first effect dominates, but in periods of frequent liquidity problems in the economy, the second effect becomes more important and might reverse the effect of the probability of bank-specific liquidity problems on screening.

The model suggests that if the probability of aggregate liquidity problems increases, banks incentives to screen decrease. Aggregate liquidity problems cause bank runs on some banks irrespective of their screening choices. Credit risk screening becomes less tempting as it is not able to prevent liquidity crises if an aggregate shock occurs. Thus, it might be possible that if systemic liquidity crises become probable enough, banks stop screening, which may amplify the probability of a crisis.

It is important to note that the effects of aggregate liquidity problems on credit risk screening are normally opposite to those of bank-specific liquidity problems. While bank-specific liquidity problems urge banks to screen, systemic liquidity shocks restrain them from screening. An increase in bank-specific liquidity problems makes the costly runs more probable only on banks with poor credits which can be prevented by screening. If runs on banks with low credit quality are likely enough, the benefits from screening exceed the screening costs. In contrast, an increase in aggregate liquidity problems makes the costly bank runs more probable in all banks so that screening prevents bank runs less frequently than before, and the benefits of screening actually diminish.

The results of the model apply to analysing the screening behaviour of banks in different liquidity environments. Especially, the results would give a new interpretation on the effects on banks credit risk screening of changes in regulatory and policy arrangements as well as financial innovations. For example, the recent trend of securitization has transformed banks' assets more liquid, which reduces their needs to rely on illiquid assets to meet liquidity obligations. Thus, the result suggests that securitization could diminish banks' incentives to screen their borrowers by decreasing the probability of liquidity shocks. Note that this argument contrasts with much of recent discussion[3] where the adverse effects of securitization on screening incentives are explained by credit risk transfer out of the banks.

Since no incentive problems between banks and their customer are introduced in the model, it does not enable direct efficiency or welfare analysis or direct recommendations for public policy. For the perspective of the depositor welfare, it would be optimal to have neither bank-specific nor aggregate liquidity shocks.

However, if bank defaults are interpreted as a negative externality not internalized by the depositors in the model, the results of the model can be used for efficiency analysis. In the model, the expected number of bank defaults is inversely related to screening. Thereby, given certain conditions, bank defaults are decreasing in the probability of bank-specific liquidity shocks and increasing in the probability of aggregate shocks and subsequent systemic crises. This interpretation could make an increase in the probability of bank-specific liquidity shocks socially optimal but would make aggregate liquidity shocks even more harmful. To some extent, this interpretation relies on the simple structure of the screening decision in the model and deserves future research in a more realistic setting.

The rest of the paper is structured as follows. Section 2 describes the basic features of the model. Section 3 analyses banks' possible strategies with respect to screening and how liquidity shocks affect banks' strategy choices. Section 4 discusses the implications of the analysis. Finally, section 5 concludes.

2 Model

The model is based on Allen and Gale (2004b) where banks offer deposit contracts to ex ante identical, risk averse depositors who face heterogenous liquidity shocks. While the approach of the model has its roots in Diamond and Dybvig (1983), I drop (following Allen and Gale) their assumption of sequential service of depositors. Instead, depositors receive their fair share of deposits if bank is not able to fully repay their deposit payments (including interest rate). Thereby, I rule out the possibility of a coordination failure and panics by depositors as a reason for bank runs and assume that depositors withdraw deposits only when it is necessary for their utility maximization.

The economy lasts for two periods in the model with three dates, 0, 1, and 2. Banks offer consumers deposit contracts, acting in a fully competitive environment. Thus, banks maximize the expected utility of depositors so as to attract customers. There is a single good at each date that can be used for consumption or investment.

[3] See eg Duffie (2007).

2.1 Assets and projects

At date 0, banks (or consumers) may invest in two types of assets in the economy, short and long assets. In order to focus on the interaction between liquidity shocks and credit risk screening, I let both assets involve credit risk and exclude possible investments in pure storage technology. Investments in assets are used to conduct underlying projects. Fraction q of both short and long assets and their underlying projects are good and fraction $1-q$ of the assets and the respective projects are bad. Good projects always succeed whereas bad projects succeed only with probability $\lambda < 1$ and fail with probability $1-\lambda$.

Short assets are used to finance short projects that last for one period, from date 0 to date 1, or from date 1 to date 2. If a short asset is good, one unit of the good invested in it at date t always yields one unit at date $t+1$. If a short asset is bad, one unit of the good invested in it at date t yields one unit at date $t+1$ with probability λ and nothing with probability $1-\lambda$.

Long assets are used to finance long projects that last for two periods and can only be started at date 0, projects yielding at date 2. If a long asset is good, one unit of the good invested in it at date 0 always yields $R > 1$ units at date 2. If a long asset is bad, one unit of the good invested in it at date 0 yields R units at date 2 with probability λ and nothing with probability $1-\lambda$.

Clearly, good assets are strictly superior to bad assets with credit risk. However, at date 0, the quality of assets and their underlying projects is not publicly known, and if a bank (or another investor) invests one unit of goods in assets (short or long) without further attempts to discover their quality, fraction q of assets are good and fraction $1-q$ bad. As in Holmstrom and Tirole (1997), banks or other investors are not able to diversify their investments made at date 0. Therefore, the bad projects of an individual bank either all succeed (with probability λ) or all fail by date 1 (with probability $1-\lambda$). If the bad projects succeed, a bank's short assets yield one unit at date 1 and long assets yield R units at date 2, and if the bad projects fail, a bank's short assets yield q units at date 1 and long assets yield qR units at date 2 per unit of investments at date 0. At the level of the economy, investments are diversified, and fraction λ of bad projects and $q + (1-\lambda)\, q$ of all projects succeed.

Banks are able to find out the quality of assets at date 0 by screening them. If a bank screens the assets, it is able to invest only in good assets with certain yield, depending on the maturity of the asset. To enable screening, the bank has to invest C units of good in a screening technology at date 0 so that it can invest $1-C$ in short or long assets.

At date 1, all uncertainty disappears, so that the yields of both short and long existing assets as well as the quality of any new short assets become public knowledge. At date 1, new investments can be only made in short assets. Since the quality of the assets is common knowledge, all short projects financed are good.

2.2 Consumer preferences

There is a continuum (measure normalized to unity) of consumers that are identical at date 0 (ex ante identical). Each consumer has an endowment consisting of one unit of the good. Each individual consumer faces uncertainty about her consumption preferences at date 0. Each individual may be either an early consumer who values consumption only at date 1, or a late consumer who values consumption only at date 2. Consumers learn their consumption preference types at date 1. Each consumer is risk averse and her utility from consumption c at the date directed by her type is $U(c)$ where U has the following properties: $U'(c) > 0$, $U''(c) < 0$. I apply a logarithmic utility function $U(c) = \ln(c)$ to find explicit results.

At the level of an individual bank, the consumption preferences of its customers are stochastic. For simplicity, the fraction of early consumers among a bank's customers γ has a two-point support with

$$\gamma = \begin{cases} 0 \text{ with probability } (1-\pi), \\ \theta \text{ with probability } \pi, \end{cases}$$

where $0 < \pi < 1$. With probability π, a bank faces a bank-specific liquidity shock and fraction θ of its customers are early consumers.

At the level of the aggregate economy, there are two possible states of the world, and the fraction of early consumers in the banks with a shock is defined as follows

$$\theta = \begin{cases} \alpha \text{ with probability } (1-\eta), \\ 1 \text{ with probability } \eta, \end{cases}$$

where $0 < \alpha < 1$ and $0 < \eta < 1$. In State 0, occurring with probability $1-\eta$, there is no aggregate liquidity shock and a fraction α of the customers in those banks with a bank-specific liquidity shock are early customers. In State 1, occurring with probability η, an aggregate liquidity shock makes all the customers of those banks with a bank-specific shock withdraw their deposits at date 1. For simplicity, the aggregate liquidity shock is assumed to provoke an exogenous bank run in those banks with a bank-specific shock. Note that the same effect could be possible even with values of $\theta < 1$ in State 1 in which case the aggregate shock caused an endogenous bank run in those banks with a bank-specific shock through the collapse in the asset price. By assuming $\theta = 1$ complicated parameter restrictions can be avoided. The distributions of consumer preferences are common knowledge at date 0.

The aggregate liquidity shock differs from that of Allen and Gale (2004b) where an aggregate shock is additive and the fraction of early consumption grows by ε if an aggregate shock occurs. With my assumption, the fraction of early consumers in those banks without a bank-specific shock remains to be zero.

Credit quality shocks and consumers preferences facing an individual bank are assumed to be independent.

2.3 Asset markets

Asset markets are incomplete in the sense that there are no asset markets at date 0 where banks could ensure necessary liquidity for date 1 by trading Arrow securities or equivalently.[4] At date 1, there is an interbank market where long assets can be traded. This market enables banks to adjust to the stochastic consumption preferences of their customers. Market participation is incomplete as only banks can trade in the asset markets.

I denote the price of date 2 consumption in terms of date 1 consumption by p so that – for example – one unit of long asset yielding R units of consumption at date 2 is worth pR units of consumption at date 1. Note that $p > 1$ can never hold in equilibrium since no one would buy long assets at date 1 with this price level as their net return at date 2 would be negative while the comparable net return of short assets from date 1 to date 2 would be zero.

If price p is below unity, long assets follow the so-called 'cash-in-the-market' pricing (as introduced in Allen and Gale, 1994). In such a case, liquidity is scarce in the market and thereby liquidity available from buyers in the asset market divided by the number of assets determines the asset price. If $p = 1$, liquidity is abundant and the assets are priced according to the value of their future returns.

Price p differs across States 0 and 1 because the aggregate liquidity shock increases the demand for liquidity in State 1. When needed, price levels in States 0 and 1, are denoted as p_0 and p_1.

2.4 Banking

2.4.1 Date 0

At date 0, each bank offers its customers a deposit contract[5] which allows them to withdraw their deposits either at date 1 or at date 2. A fixed claim of d per unit of deposit is promised to depositors who withdraw at date 1. At date 2, the yield of banks' remaining assets is promised to those depositors who did not withdraw at date 1. Each bank receives 1 unit of goods against deposit contracts it makes. The bank invests $1 - y$ in long assets. If the bank decides not to screen the projects underlying its assets, it invests y in short assets. If it decides to screen the projects underlying its assets, it invests C in a screening technology and $y - C$ in short assets.

Banks earn zero profits in free competition. They must provide deposit contracts that maximize consumers' welfare subject to zero profits so as to

[4] See eg Allen and Carletti (2007) for a discussion of the possible effects of incomplete markets.

[5] A demand deposit contract is an incomplete contract that allows for a sufficiently inelastic demand for liquidity at date 1 and thereby also bank runs. The use of demand deposits can for instance be motivated '...as a counterpart to the empirical fact that financial contracts are typically written in a 'hard' way that requires strict performance of precisely defined acts, independently of many apparently relevant contingencies.' as argued in Allen and Gale (2007), p. 150.

attract any deposits. Consumers cannot diversify their deposits across several banks.

2.4.2 Date 1

At date 1, the consumption preferences of each bank's customers and the yield of the bank's assets are publicly observed. However, the consumption preference of an individual depositor is not verifiable so that the deposit contract cannot be made contingent on the preference. A bank's short asset portfolio yields either 1 or q units of good, depending on the success of the underlying projects. The bank is able to sell or buy long assets in interbank markets at price p, depending on its liquidity needs.

Each depositor decides whether she withdraws her deposits immediately or waits until date 2. If a depositor learns to be an early consumer, she always withdraws her deposits at date 1. Instead, if she is a late consumer, she withdraws if and only if the fixed claim d is greater than the anticipated deposit repayment at date 2 if only early consumers withdraw at date 1. Thus, to avoid the withdrawal of late consumers, the present value of the bank's assets at date 1 must be at least the present value of consumption at date 1 when all consumers receive d. For instance, if the bank screens, and there are no early consumers among the bank's customers, the incentive compatibility constraint for the late consumers (and the budget constraint for the bank) in State 0 is $p_0 d \leq y - C + p_0 R(1-y)$.[6] If a late consumer withdraws at date 1, she invests her withdrawal in short assets to enable consumption at date 2.

A bank run in this model refers to situation where all depositors withdraw their deposits at date 1, irrespective of whether they are early or late consumers. Bank run occurs either if all depositors are early consumers or if late consumers decide to withdraw at date 1.[7]

If there is no bank run at date 1, the bank balances its liquidity needs in the interbank asset market and holds the remaining assets until date 2. Instead, if there is a bank run, the bank defaults, liquidates all its long assets and pays out to its depositors the present value of the assets.

2.4.3 Date 2

At date 2, with no bank run at date 1, the long assets of a bank yield and the bank pays out the total present value of their assets to late consumers. For instance, if the bank screens its borrowers and there are α early consumers among the bank's customers (in State 0), and incentive compatibility constraint of late consumers is satisfied, there is no bank run at date 1 and the residual present value of the bank's assets is $\frac{y-C+p_0R(1-y)-\alpha d}{p_0}$.

[6]Note that late consumers incentive compatibility constraints also constitute their bank's budget constraint.

[7]There are several possible reasons for bank runs. As argued by Chen and Hasan (2008), bank runs looking like a panic are possible even if depositors act rationally and their expectations on the bank's fundamentals do not change.

The numerator defines the residual value of the bank's assets at date 1 after paying d per unit of deposit to early consumers. Dividing by the asset price yields the present value at date 2. When this residual value is distributed to all late consumers, their consumption per depositor is $\frac{y-C+p_0R(1-y)-\alpha d}{p_0(1-\alpha)}$.

2.5 Causes for bank runs

To specify banks' behaviour in the model, factors causing bank runs need to be identified. In general, bank runs occur either if all depositors in a bank are early consumers or if late consumers find out at date 1 that the present value of their bank's assets is not sufficient to provide them at least d if they withdraw only at date 2. In that case, the late consumers also withdraw at date 1 and invest their funds in short assets so as to consume at date 2.

Banks are assumed to become exposed to bank runs either due to credit losses or aggregate liquidity shocks. I focus on cases where neither banks' credit losses nor aggregate liquidity shocks are so severe that they alone would trigger a bank run. A bank-specific liquidity shock is required in addition to provoke a run on a bank that is exposed to runs.[8] The chain of events is summarized in Figure 1.

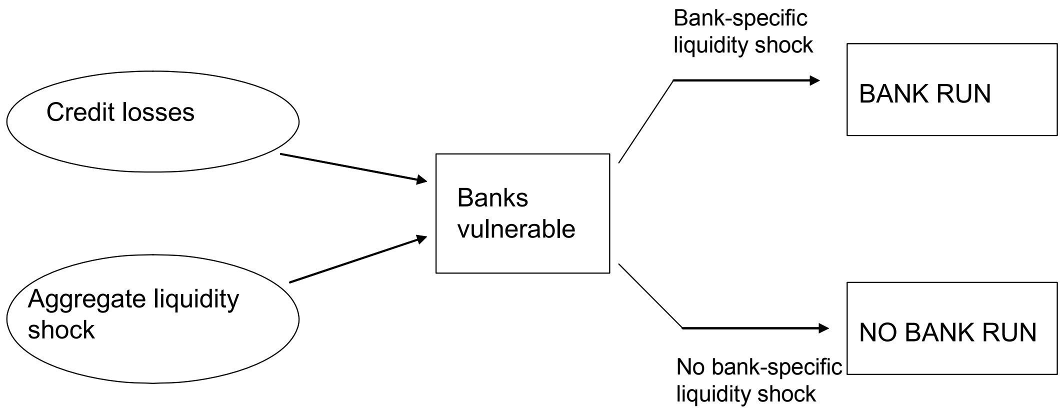

Figure 1: Contribution of shocks to bank runs.

This structure of shocks required to cause bank runs can be justified from different angles. First, if there were no other shocks than bank-specific liquidity shocks in the model, it would be optimal for banks to offer d low enough to avoid all bank runs. Therefore, other shocks are needed to make banks vulnerable to bank-specific liquidity shocks.

Second, if an aggregate liquidity shock alone would cause a run on every bank, a total meltdown of the banking sector would result. This would not be an equilibrium solution since at least some banks would find it optimal to hold

[8]In the model, the combination of an aggregate and a bank-specific liquidity shock makes all of the bank's depositors early consumers. In contrast, a combination of credit losses and a bank-specific liquidity shock makes it optimal for the given bank's depositor that are late consumers to withdraw their deposits already at date 1.

more short, liquid assets in reserve for State 1 so as to avoid the bank run and benefit from the extremely low price of long assets at date 1. Actually, in this model, the banks without a bank-specific shock have excess liquidity even in State 1, avoid a bank run and benefit from the low asset prices.

Third, credit losses might be large enough to provoke a run on a bank alone without any other shocks. Although this case could be possible, I focus on the more interesting case where solvency problems do make banks vulnerable to bank-specific liquidity shocks but do not alone provoke bank runs. If credit losses alone triggered a bank run, liquidity shocks would have no impact on the effects of credit losses on bank runs. Thus, the effects of the probability of liquidity shocks on the benefits of screening would be of less importance through banks that do not default. The case of large credit losses triggering runs on banks without liquidity problems is discussed in more detail in section 4.

Finally, in another case that is not in the focus of this paper, banks might find it optimal to prevent any bank runs due to the combination of credit losses and bank-specific liquidity shocks in State 0 by offering a low enough d so that the incentive compatibility constraint for the late consumers would hold in spite of simultaneous credit losses and bank-specific liquidity shocks. In such a case, credit losses would have no impact on bank runs and the effects of the probability of liquidity shocks on the benefits of screening would again be of minor importance.

In appendix 1, I formulate the necessary parameter assumptions to focus on the case where each bank finds it optimal to choose y and d so that a bank run occurs if and only if the bank faces a combination of credit losses and a bank-specific liquidity shock in State 0 or a bank-specific liquidity shock in State 1.

3 Banks' strategy choices

The main question in this paper is how changes in expected consumption preferences (liquidity needs) influence banks' screening choices. To address this question, I analyse two alternative pure strategies banks may choose: 1) a screening strategy in which banks make a costly investment in the screening technology and avoid thereby the risk of credit quality shock, and 2) a non-screening strategy in which banks do not invest in screening and face the risk of credit losses. To attract deposits, banks choose the most optimal of two strategies. When the liquidity outlook changes (ie the expected consumption preferences), screening becomes more or less attractive to the bank.

In the following, I focus on equilibria where banks choose between the two pure strategies. In fact, there is a non-empty region where banks have incentives to deviate both from the pure screening and the pure non-screening equilibrium, and only a mixed strategy equilibrium is possible. The mixed strategy case will be ignored here, however, as the major results from the model can be however found in the more well-defined pure strategy cases.

To simplify the notation, let us denote the expected utility of a bank's customers by $W_x(cr, bs, as)$ where subscript x refers to the strategy chosen by the bank (s = screening, n = non-screening). Argument cr refers to whether the bank's projects succeed or fail (s or f, respectively), argument bs refers to a bank-specific liquidity shock (1 if the bank faces a liquidity shock, 0 otherwise), and argument as to an aggregate shock (1 in State 1 with an aggregate shock, 0 in State 0).

3.1 Screening strategy

A bank choosing the screening strategy may end up in four different situation as both the bank-specific and aggregate shock have a two-point support. First, if an individual bank does not face a bank-specific liquidity shock in State 0, the utility of the bank's depositors is $W_s(s,0,0) = \ln\left(\frac{y-C}{p_0} + R(1-y)\right)$. All the depositors are late consumers and they are paid out all the banks assets at date 2. At date 1, the bank has excess liquidity and uses it to buy assets at price p_0. If $p_0 < 1$, the bank only buys long assets at date 1. Second, if the bank faces a bank-specific shock in State 0, the expected utility of the its depositors is $W_s(s,1,0) = \alpha \ln(d) + (1-\alpha)\ln\left(\frac{\frac{y-C-\alpha d}{p_0}+R(1-y)}{(1-\alpha)}\right)$. Fraction α of the bank's depositors are early consumers and they receive d at date 1 while the rest gets the residue of assets at date 2. At date 1, the bank's liquidity demand is αd and it covers this demand by the available liquidity $y - C$ and by selling $\frac{\alpha d-(y-C)}{p_0}$ of its long assets at price p_0. Third, if an aggregate liquidity shock (State 1) emerges but the bank does not face a bank-specific shock, the utility of its customers is $W_s(s,0,1) = \ln\left(\frac{y-C}{p_1} + R(1-y)\right)$. Similarly to the first case, the bank uses its excess liquidity to buy assets at date 1, but now at price p_1. At date 2, the return of bank's assets is paid out to all depositors. Finally, if the bank faces a bank-specific shock in State 1, the bank's budget constraint and the depositor's incentive constraint do not hold and a bank run occurs. All deposits are withdrawn at date 1 and the present value of bank's assets is paid out to depositors whose utility is $W_s(s,1,1) = \ln(y - C + p_1 R(1-y))$.

Altogether, if banks decide to screen the borrowers, the expected utility of the depositors that an individual bank maximizes is

$$\begin{aligned} &\max_{y,d}(1-\eta)\left((1-\pi)W_s(s,0,0)+\pi W_s(s,1,0)\right) \\ &+\eta\left((1-\pi)W_s(s,0,1)+\pi W_s(s,1,1)\right) \end{aligned} \tag{3.1}$$

Given the asset price levels, p_0 and p_1, each bank maximizes (3.1) with respect to y and d, giving the following choices

$$\begin{aligned} y_s &= \frac{(1-p_1R)(C-p_0R)+(1-C)(p_0-p_1)R(1-\eta)}{(1-p_1R)(1-p_0R)} \\ d_s &= \frac{(1-\eta)R}{1-p_1R}(p_0-p_1)(1-C) \end{aligned} \tag{3.2}$$

The expected value of the screening strategy V_s given the price levels in States 0 and 1 can be obtained by substituting the values of y and d from (3.2) in the expected utility function in the maximization problem (3.1)

$$\begin{aligned} V_s &= (1-\eta)\left(\ln\left(\tfrac{(1-\eta)R(p_0-p_1)(1-C)}{1-p_1R}\right) - (1-\pi+\pi(1-\alpha))\ln(p_0)\right) \\ &\quad +\eta\left(\ln\left(\tfrac{\eta R(p_0-p_1)(1-C)}{p_0R-1}\right) - (1-\pi)\ln(p_1)\right) \end{aligned} \quad (3.3)$$

Now, if each bank chooses to screen, market clearing condition at date 1 is[9] in State 0

$$\pi\alpha d_s \leq y_s - C \quad (3.4)$$

and in State 1

$$\pi\left(y_s - C + p_{1s}R(1-y_s)\right) \leq y_s - C \quad (3.5)$$

By assumption (see section 2.5 and appendix 1), I focus on cases where asset prices are below unity in equilibrium. In each state, as the asset price level is below unity, no bank is willing to buy short assets at date 1 as long assets provide return higher than one from date 1 to date 2. Thereby, (3.4) and (3.5) hold as equalities and combining them with (3.2) yields the screening equilibrium outcome (marked with asterisk)

$$\begin{aligned} p_{0s}^* &= \frac{1}{R}\left(1+\tfrac{(1-\alpha)\eta}{((1-\pi)(\alpha+\eta(1-\alpha))+(1-\eta)(1-\alpha))\alpha}\right) \\ p_{1s}^* &= \frac{1}{R}\left(1-\tfrac{(1-\eta)(1-\alpha)}{(1-\pi)(\alpha+\eta(1-\alpha))+(1-\eta)(1-\alpha)}\right) \\ y_s^* &= C+\pi(1-C)(\alpha+\eta(1-\alpha)) \\ d_s^* &= (1-C)\left(\tfrac{\eta}{\alpha}+1-\eta\right) \end{aligned} \quad (3.6)$$

Since liquidity demand is relatively higher in State 1 than in State 0, asset price is higher in State 0, ie. $p_{0s}^* > p_{1s}^*$. The expected value of the screening strategy V_s^* in the screening equilibrium is

$$\begin{aligned} V_s^* &= \ln((1-C)(\alpha+\eta(1-\alpha))) \quad (3.7) \\ &\quad -(1-\eta)(\ln(\alpha)+(1-\pi+\pi(1-\alpha))\ln(p_{0s}^*)) - \eta(1-\pi)\ln(p_{1s}^*) \end{aligned}$$

3.2 Non-screening strategy

If a bank chooses the non-screening strategy, it may face eight different situations from date 1 onwards. In addition to bank-specific and aggregate liquidity shocks, the success or failure of the projects underlying the bank's bad assets determine the situation of the bank. If all the bank's projects succeed in spite of non-screening, the expected utility of its customers depend

[9] Similarly, market-clearing conditions for date 2 ensure that the cumulative consumption of the consumers equal the total production in the economy in each state.

on the bank-specific and aggregate shocks in the similar way as in the screening strategy except that the bank avoids the screening cost C

$$\begin{aligned}
W_n(s,0,0) &= \ln\left(\tfrac{y}{p_0} + R(1-y)\right) \\
W_n(s,1,0) &= \alpha \ln(d) + (1-\alpha)\ln\left(\frac{\frac{y_n-\alpha d}{p_0}+R(1-y)}{(1-\alpha)}\right) \\
W_n(s,0,1) &= \ln\left(\frac{y}{p_1} + R(1-y)\right) \\
W_n(s,1,1) &= \ln(y + p_1 R(1-y)).
\end{aligned} \tag{3.8}$$

If the bank's bad projects fail, however, the utility of the depositors differ more from the screening case. First, if the bank with failing bad projects does not face a bank-specific liquidity shock in State 0, the utility of its depositors is $W_n(f,0,0) = \ln\left(q\left(\frac{y}{p_0} + R(1-y)\right)\right)$. Even though only the good projects succeed and yield to the bank only fraction q of the full return, the bank has excess liquidity at date 1 (qy) and invests it in long assets at price p_0. At date 2, the value of the bank's asset returns are paid out to the depositors who are all late consumers. Second, if the bank with failing bad projects faces a bank-specific shock in State 0, a bank run is triggered, all the bank's (good) long assets are sold in the interbank market and the present value of the bank's assets is paid to the depositors. The utility of the depositors is $W_n(f,1,0) = \ln(q(y + p_0 R(1-y)))$. Third, in State 1, if the bank with failing bad projects does not face a bank-specific liquidity shock, the utility of its depositors is $W_n(f,0,1) = \ln\left(q\left(\frac{y}{p_1} + R(1-y)\right)\right)$. Due to the aggregate shock, the bank with excess liquidity is now able to buy good long assets at date 1 at price p_1. Finally, if the bank with failing bad projects faces a bank-specific liquidity shock in State 1, a bank run is triggered and the depositors are paid out the present value of the bank's assets with the price level p_1. The utility of the depositors is $W_n(f,1,1) = \ln(q(y + p_1 R(1-y)))$.

With the possible outcomes as defined above, each bank maximizes the expected utility of its depositors as follows

$$\begin{aligned}
&\max_{y_n,d_n} \lambda\{(1-\eta)((1-\pi)W_n(s,0,0) + \pi W_n(s,1,0)) \\
&+\eta((1-\pi)W_n(s,0,1) + \pi W_n(s,1,1))\} \\
&+(1-\lambda)\{(1-\eta)((1-\pi)W_n(f,0,0) + \pi W_n(f,1,0)) \\
&+\eta((1-\pi)W_n(f,0,1) + \pi W_n(f,1,1))\}
\end{aligned} \tag{3.9}$$

So, a bank run can occur on a bank facing a bank-specific liquidity shock for two reasons. First, in State 1, even if the projects of a bank succeed, all depositors of the bank withdraw already at date 1 due to an aggregate liquidity shock. Second, if the bad projects funded by the bank fail, a bank run occurs irrespective of the aggregate liquidity demand.

Given the asset price levels, p_0 and p_1, each bank maximizes (3.9) with respect to y and d, giving the following choices

$$\begin{aligned}
y_n &= \tfrac{-(1-p_1R)p_0+(p_0-p_1)(1-\eta)}{(1-p_1R)(1-p_0R)} R \\
d_n &= \tfrac{(1-\eta)R}{1-p_1R}(p_0-p_1)
\end{aligned} \tag{3.10}$$

Now, the expected value of the non-screening strategy V_n given the asset prices is obtained by substituting the values of y and d from (3.10) in the expected utility function in the maximization problem (3.9)

$$\begin{aligned} V_n &= (1-\eta)\left(\ln\left(\tfrac{(1-\eta)R(p_0-p_1)}{1-p_1 R}\right) - (1-\pi+\lambda\pi(1-\alpha))\ln(p_0)\right) \\ &+\eta\left(\ln\left(\tfrac{\eta R(p_0-p_1)}{p_0 R-1}\right) - (1-\pi)\ln(p_1)\right) + (1-\lambda)\ln(q) \end{aligned} \tag{3.11}$$

Now, if all the banks follow the non-screening strategy, the market clearing conditions for date 1 are in State 0

$$\pi(\lambda\alpha d_n + (1-\lambda)q(y_n + p_{0n}R(1-y_n))) \leq (\lambda + (1-\lambda)q)y_n \tag{3.12}$$

and in State 1

$$\pi(\lambda + (1-\lambda)q)(y_n + p_{1n}R(1-y_n)) \leq (\lambda + (1-\lambda)q)y_n \tag{3.13}$$

As above, I focus on cases where asset prices are below unity in each state in equilibrium by assumption (see section 2.5 and appendix 1) and thereby none of the banks is willing to buy short assets at date 1 because long assets provide return higher than one from date 1 to date 2. Thus, (3.12) and (3.13) hold as equalities and combining them with (3.10) yields the non-screening equilibrium outcome (marked with asterisk)

$$\begin{aligned} p_{0n}^* &= \frac{1}{R}\left(1 + \frac{\lambda(1-\alpha)\eta(q(1-\lambda)+\lambda)}{(q(1-\lambda)+\alpha\lambda)\left(q(1-\lambda)+\left(\eta+\left(\alpha+\frac{1-\alpha}{1-\pi}\right)(1-\eta)\right)\lambda\right)(1-\pi)}\right) \\ p_{1n}^* &= \frac{1}{R}\left(1 - \frac{\lambda(1-\eta)(1-\alpha)}{\left(q(1-\lambda)+\left(\eta+\left(\alpha+\frac{1-\alpha}{1-\pi}\right)(1-\eta)\right)\lambda\right)(1-\pi)}\right) \\ y_n^* &= \pi\left(1 - \frac{\lambda(1-\eta)(1-\alpha)}{q(1-\lambda)+\lambda}\right) \\ d_n^* &= 1 + \frac{\lambda(1-\alpha)\eta}{q(1-\lambda)+\alpha\lambda}. \end{aligned} \tag{3.14}$$

Similarly to the pure screening equilibrium, since liquidity demand is relatively higher (and demand for long asset is lower) in State 1 than in State 0, asset price is higher in State, ie $p_{0n}^* > p_{1n}^*$. Comparing (3.6) and (3.14) reveals that $p_{0s}^* > p_{0n}^*$ and $p_{1s}^* < p_{1n}^*$.

The expected value of the non-screening strategy V_s^* in the non-screening equilibrium is

$$\begin{aligned} V_n^* &= (1-\eta)\left(\ln\left(\tfrac{q(1-\lambda)+(\alpha(1-\eta)+\eta)\lambda}{q(1-\lambda)+\alpha\lambda}\right)\right. \\ &\quad \left. - (1-\pi+\lambda\pi(1-\alpha))\ln(p_{0n}^*)\right) \\ &\quad +\eta\left(\ln\left(\tfrac{q(1-\lambda)+(\alpha(1-\eta)+\eta)\lambda}{q(1-\lambda)+\lambda}\right) - (1-\pi)\ln(p_{1n}^*)\right) + (1-\lambda)\ln(q) \end{aligned} \tag{3.15}$$

3.3 Choice of strategy

Now that the outcomes of a bank's two possible strategies with respect to screening have been established, let us analyse how changes in bank-specific and aggregate liquidity shocks affect the bank's incentives to choose between strategies.

An atomistic bank takes as given the expected asset price levels in each possible state of the world, and given the prices it chooses the strategy with the largest expected value to its depositors. In practice, the bank computes the difference of the expected values of the strategies to its depositors (given in (3.3) and (3.11))

$$V_s - V_n = \ln(1 - C) - (1 - \lambda)\ln(q) - (1 - \eta)\,\pi\,(1 - \lambda)(1 - \alpha)\ln(p_0) \quad (3.16)$$

The difference between the expected value of strategies consists of three terms. First, investment in screening reduces the value of the screening strategy as it cuts the bank's investments in productive assets. Second, possible credit losses reduce the expected value of the non-screening strategy. Finally, the third term is due to the fact that if a bank chooses the non-screening strategy a larger part of the bank's depositors are expected to withdraw deposits at date 1 than if the bank chooses the screening strategy. These withdrawals are costly since they have to be financed by selling long assets at price $p_0 < 1$. The difference in the expected number of withdrawing depositors is created by the bank runs caused by the combination of credit losses and bank-specific liquidity shocks in State 0. So, the relative expected value of the screening strategy increases because the strategy prevents bank runs in State 0.

The effects of the probability of liquidity shocks on the relative value of the strategies works works through their effects on the proportion of those depositors who withdraw at date 1 because of bank runs in a non-screening bank in State 0 and on the price p_0 that measures the cost of the withdrawals.

3.3.1 Bank-specific shocks

The probability of a bank-specific liquidity shock affects the difference between the expected values of the strategies in two ways

$$\begin{aligned} \frac{d(V_s - V_n)}{d\pi} &= \tfrac{\partial(V_s - V_n)}{\partial \pi} + \tfrac{\partial(V_s - V_n)}{\partial p_0}\tfrac{\partial p_0}{\partial \pi} \\ &= -(1 - \eta)(1 - \lambda)(1 - \alpha)\left(\ln(p_0) + \tfrac{\pi}{p_0}\tfrac{\partial p_0}{\partial \pi}\right) \end{aligned} \quad (3.17)$$

First, as a direct effect, if the probability of bank-specific shocks grows, the expected share of those depositors withdrawing in a bank run in State 0 in a non-screening bank increases because of the probability of bank runs rise. Consequently, the relative expected value of the screening strategy clearly increases. Second, however, there is an indirect effect whenever the probability of bank-specific liquidity shocks affects the price level in the asset market. This effect depends on the impact of π on the asset price in State 0.

Combining the effects of a bank-specific liquidity shock on the expected relative value of screening in the two pure equilibria determined above results in the first main result of the paper.

Proposition 3.1 *Both in the screening equilibrium and in the non-screening equilibrium, provided that the parameter restrictions are not violated:*

a) The incentives of banks to screen the borrowers are increasing in the probability of bank-specific liquidity shocks if aggregate liquidity shocks or bank-specific liquidity shocks are unlikely enough.

b) The incentives of banks to screen the borrowers are decreasing in the probability of bank-specific liquidity shocks if aggregate liquidity shocks and bank-specific liquidity shocks are likely enough.

Proof. See Appendix 2. ■

Given that liquidity shocks are not too common, Proposition 1 implies that a bank has less incentives to screen when its bank-specific liquidity outlook is favourable and have more incentives to screen if there is a greater risk of a bank-specific liquidity shock. This is because an increase in the bank-specific liquidity shock increases the probability of costly bank runs on banks with credit losses. That is, the increasing probability of subsequent bank runs amplifies the costs of credit losses and makes banks more eager to avoid them by screening.

While the situation where the probability of liquidity shocks are relatively infrequent can be characterised as being normal, the bank-specific and aggregate liquidity shocks might be more likely for instance in a crisis period of a troubled economy. In such an exceptional case, Proposition 1 suggests that an increase in π might even reduce banks' incentives to screen the borrowers. This results from the negative indirect effect of π on the relative value of the screening through the equilibrium asset price in State 0. If π increases, banks respond by investing more in short assets, which results in an increase in the supply of liquidity and equilibrium asset price p_0^* in State 0 when demand for liquidity is relatively low. An increase in p_0^* reduces the costs of bank runs in State 0 and thereby the incentives to choose the screening strategy. In a period with a high probability of liquidity shocks, this effect becomes relatively more important and may reverse the direction of effect of π on the screening choice.

Even though an increase in the probability of bank-specific liquidity shock adds banks' incentives to screen and thereby mitigates credit risk, it does not necessarily increase the expected utility of depositors. On the contrary, at least when liquidity shocks are not too common, it can be shown that both $\frac{dV_s}{d\pi}$ and $\frac{dV_n}{d\pi}$ are negative.

3.3.2 Aggregate liquidity shocks

As in the case of bank-specific shocks, the impact of the probability of aggregate liquidity shocks on the relative value of screening is twofold

$$\begin{aligned} \frac{d\left(V_s - V_n\right)}{d\eta} &= \frac{\partial(V_s - V_n)}{\partial\eta} + \frac{\partial(V_s - V_n)}{\partial p_0}\frac{\partial p_0}{\partial\eta} \\ &= \pi\left(1-\lambda\right)\left(1-\alpha\right)\left(\ln\left(p_0\right) - \frac{1-\eta}{p_0}\frac{\partial p_0}{\partial\eta}\right) \end{aligned} \tag{3.18}$$

Note that the probability of aggregate liquidity shocks affects the relative expected value of screening by changing the probability and costs of bank runs in State 0. Instead, it has no effects through the events in State 1 since the choice of strategy does not change the probability of a bank run in State 1 with the aggregate liquidity shock.

As a direct effect, an increase in η reduces the probability of bank runs due to the combination of a bank-specific liquidity shock and credit losses in State 0. This happens simply because an increase in the probability of an aggregate liquidity shock means a decline in the probability of State 0. Indirectly, the probability of an aggregate liquidity shock changes price level p_0 and thereby the costs of bank runs in State 0. Combining these effects results in the second major result of the paper.

Proposition 3.2 *Both in the screening equilibrium and in the non-screening equilibrium, the incentives of banks to screen the borrowers are decreasing in the probability of aggregate liquidity shocks.*

Proof. In both the screening and non-screening equilibria, $p_0^* < 1$ by assumption, implying $\ln(p_0^*) < 0$. Moreover, $\frac{1-\eta}{p_{0s}^*}\frac{\partial p_{0s}^*}{\partial \eta} = \frac{(1-\alpha)(1-\eta)}{(\eta+\alpha(1-\eta))(1-\pi(\eta+\alpha(1-\eta)))} > 0$ and $\frac{1-\eta}{p_{0n}^*}\frac{\partial p_{0n}^*}{\partial \eta} = \frac{\lambda(1-\alpha)(1-\eta)(q(1-\lambda)+\lambda)}{(q(1-\lambda)+(\eta+\alpha(1-\eta))\lambda)(q(1-\pi)(1-\lambda)+\lambda(1-\pi(\eta+\alpha(1-\eta))))} > 0$. Thus, $\left(\ln(p_0^*) - \frac{1-\eta}{p_0^*}\frac{\partial p_0^*}{\partial \eta}\right) < 0$ and, as defined in (3.18), $\frac{d(V_s-V_n)}{d\eta} < 0$ in both equilibria. ■

As the direct and indirect effect of π on screening now work in the same direction, the result in Proposition 2 applies for all possible parameter values. Due to an increase in the probability of an aggregate liquidity shock it becomes more likely that screening does not help bank avoiding a bank run, and the value of screening thereby decreases. This effect is still amplified as the increase in the probability of an aggregate liquidity shock raises the asset price level in State 0, which reduces the costs of bank runs in State 0.

4 Discussion

The results of the model can be interpreted in the context of turbulence in the global financial markets in 2007–2008. During the period of a few years before the crisis, the liquidity situation in the international financial markets has been characterized as especially favourable, with little threat of liquidity problems to banks. In addition, securitization and other types of financial innovations have improved the liquidity outlook of banks. At the same time, banks and other market participants have been involved in remarkable risk-taking ('hunt for yield') and the risk aversion reduced. According to Proposition 1, banks' generally benign liquidity outlook may have been at least one factor weakening their incentives to mitigate credit risks.

After the beginning of the market turbulence in 2007, a clear rise in risk aversion has been observed in the banking market. Banks have remarkably tightened their credit standards (see eg ECB 2007) and most likely increased screening of the borrowers. This development might be interpreted in the present model so that the probability of bank-specific liquidity shocks has increased, which has given banks an additional incentive to mitigate their credit risks. Naturally, one could also ask whether the probability of an aggregate liquidity shock has increased, which could weaken the incentives to mitigate credit risks.

Both propositions in the paper rest on the assumption that liquidity available to banks has an impact on asset pricing (in terms of the model, even $p_0 < 1$) or assets follow the 'cash-in-the-market' pricing. Results that are to some extent similar to this paper have been presented in Wagner (2007) where an increased liquidity of banks' assets gives banks incentives to take additional risks. However, Wagner considers a case where asset prices are given exogenously whereas asset prices are determined within the model in this paper. Before Wagner, eg Diamond and Rajan (2000, 2001) have discussed the issue that illiquid bank assets may discipline bank managers. In another recent paper by Gârleanu and Pedersen (2007), there can be a feedback effect where investors' tighter risk management results in market illiquidity, and illiquidity tightens risk management, as happens in the present paper.

Although the model gives important insights about the links between banks' liquidity outlook and screening incentives, there are a number of dimensions in which the assumptions of the model could be questioned and the model could be further developed.

In particular, Proposition 1 relies on the assumption that credit losses of a bank with failing bad projects are large enough to make the bank so vulnerable that a bank-specific liquidity shock triggers a bank run, but not large enough to trigger a run on a bank without other shocks.

In an alternative scenario, with credit losses large enough to provoke a run on a bank with failing bad projects, it could be shown that banks' incentives to screen decrease in the probability of a bank-specific liquidity shock,[10] contrasting with Proposition 1. In such a case, an increase in the probability of a bank-specific shock would not increase the probability of a run on banks with credit losses. Therefore, such an increase would not amplify the incentives of banks to avoid credit losses so as to avoid bank runs. On the other hand, an increase in the probability of a bank-specific shock would reduce the expected utility of depositors in those banks that evade a bank run. Since bank runs on screening banks were less frequent than those on non-screening banks, the expected adverse effects of an increase in the probability of a bank-specific shock would be stronger in the screening strategy. Thus, the effect of an increase in probability of a bank-specific liquidity shock on the screening incentives would always be negative.

In the end, it remains an empirical question whether credit losses are large enough to provoke a run alone on a bank avoiding other shocks. There are, however, some arguments for the relevance of cases where there must be a liquidity shock contributing to a bank run. First of all, the bank-specific liquidity shocks in the present model are in fact shocks that may force banks to sell assets at a reduced price due to constrained liquidity. Empirical evidence, on the other hand, suggests that asset prices are one of the main explanations for banking crisis (see discussion in Allen and Gale, 2007, eg ch. 1 & ch. 9),

[10]The computations for this scenario are available from the author.

Although there is a large empirical literature that suggests that banking crises are chiefly based on bank fundamentals (see eg Gorton, 1988, or Calomiris and Gorton, 1991), it does not exclude the role of asset prices in the emergence of banking runs. Anyhow, when the result on the link between liquidity shocks and screening incentives is interpreted, it must be remembered that it does not hold for situations where bank runs are caused purely by banks' solvency problems.

In addition, it could be argued that liquidity shocks should not be exogenous, but eg somehow related to the banks' asset returns or credit risks in the model. In fact, if the occurrence of bank-specific liquidity shocks were fully correlated with banks' credit losses, the outcome of the model would converge to that in the scenario above where credit losses alone provoked a bank run. However, the model's qualitative predictions would not change if bank-specific liquidity shocks were only moderately correlated with the occurrence of credit losses. In practice, it seems plausible that there is a positive, but imperfect correlation between the bank-specific liquidity shocks and credit losses.

5 Conclusion

In conclusion, the model suggests that banks' liquidity outlook has clear implications for banks' incentives to mitigate their credit risks. Bank-specific liquidity shocks that contribute to a bank run on banks with credit losses disciplines banks in normal conditions to screen more to avoid credit losses. On the contrary, aggregate liquidity shocks that provoke a bank run even without credit losses reduce banks' incentives to screen. In the light of these results, banks' high credit risks underlying the emergence of the subprime mortgage crisis may have been promoted by favourable global liquidity environment in the years preceding the crisis. However, the effects of banks' liquidity outlook on screening incentives should not be overestimated as there are several other factors with probable impact on screening.

The results of the model could be considered from the viewpoint of financial stability analysis if bank failures are seen to have negative externalities. From the policy perspective, the model's results suggest that for instance an optimal central bank intervention policy aimed at reducing the likelihood of aggregate liquidity shocks with a possibility of runs on solvent banks but not necessarily bank-level liquidity shocks with a possibility of runs on insolvent banks. In a liquidity crisis, where liquidity shocks were likely, it might also be optimal to reduce the frequency of bank-specific shocks.

Another interpretation of the model is that credit risk taking may be encouraged by structural developments in financial markets that make assets more liquid by nature and thereby bank-specific liquidity shocks less likely. Obviously, both policy interventions and financial market innovations should be included in the model to understand better their effects on banks' incentives. This analysis would offer an important avenue for future research.

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Appendix 1

Assumptions on parameter restrictions

In order to focus on the cases where there are runs only on banks with both a bank-specific liquidity shock and credit losses in State 0 and on banks with a bank-specific liquidity shock in State 1, the following parameter restrictions have to be assumed.

First, if a bank follows the screening strategy, bank-specific shocks must not cause a bank run in State 0. Moreover, in the screening strategy without credit losses, a bank run cannot occur in any state of the world without a bank-specific liquidity shock. Both requirements are satisfied when $p_0 \leq 1$. Note that there is a bank run on all banks with a bank-specific liquidity shock by definition in State 1.

Second, if a bank follows the non-screening strategy, a bank-specific liquidity shock must not cause a bank run in State 0 without credit losses and a bank run cannot occur in any state of the world without a bank-specific liquidity shock. The first requirement is satisfied when $p_0 \leq 1$ while the latter one is satisfied when $p_0 \leq 1$ and $p_1 \leq 1$. In addition, credit losses must not trigger a bank run without a bank-specific liquidity shock. This requires that $p_0 \leq q$ for State 0 and $p_0 \leq q$ and $p_1 \leq q$ for State 1. On the other hand, credit losses and a bank-specific shock together must trigger a bank run in State 0. This requires that $p_0 > \frac{q-\alpha}{1-\alpha}$. Note again that there is a bank run on all banks with a bank-specific liquidity shock by definition in State 1. Altogether, it is required that the prevailing asset price level satisfies $\frac{q-\alpha}{1-\alpha} < p_0 \leq q$ in State 0 and $p_1 \leq q$ in State 1.

I consider two types of pure strategy equilibria in the model. Either a) all banks follow the screening strategy in a pure screening equilibrium, b) all banks follow the non-screening strategy in a pure non-screening equilibrium. The State 0 asset price is at highest in the pure screening equilibrium and at lowest in the pure non-screening equilibrium, ie. $p^*_{0s} > p^*_{0n}$ while the State 1 asset price is at highest in the pure non-screening equilibrium and at lowest in the pure screening equilibrium, ie. $p^*_{1s} < p^*_{1n}$. In both equilibria, asset prices are higher in State 0 than in State 1, ie. $p^*_0 > p^*_1$.

With these characteristics of equilibria, $p^*_{0s} \leq q$ and $p^*_{0n} > \frac{q-\alpha}{1-\alpha}$ have to hold to ensure that all the equilibria are possible. Using the equilibrium prices, the following assumption is necessary in terms of the yield of a successful long project, R

$$\begin{aligned} &\frac{1}{q}\left(1+\frac{(1-\alpha)\eta}{((1-\pi)(1-(1-\eta)(1-\alpha))+(1-\eta)(1-\alpha))\alpha}\right) \\ &\leq R < \\ &\frac{1-\alpha}{q-\alpha}\left(1+\frac{\lambda(1-\alpha)\eta(q(1-\lambda)+\lambda)}{(q(1-\lambda)+\alpha\lambda)\left(q(1-\lambda)+\left(\eta+\left(\alpha+\frac{1-\alpha}{1-\pi}\right)(1-\eta)\right)\lambda\right)(1-\pi)}\right) \end{aligned} \tag{A1.1}$$

To focus on the two possible strategies where bank runs occurs in a combination of bank-specific liquidity shocks and other shocks as defined in section 2.5, it is necessary to rule out a non-screening strategy where the bank still avoids bank runs in State 0 even when hit by credit losses and a bank-specific liquidity shock by offering a low enough d.

We consider the possibility of this alternative strategy by asking with which parameter restrictions banks do not have an incentive to deviate from the non-screening strategy in the pure non-screening equilibrium. First, the following assumption in implicit form is necessary to ensure that a bank had to reduce d from the free optimum to avoid a bank run in case of a bank-specific liquidity shock and credit losses in State 0

$$\alpha \geq -\frac{p_{0n}^*\left(1-p_{0n}^*-(1-q)\lambda\right)}{\left(1-p_{0n}^*\right)\left(1-p_{0n}^*-(q+(1-q)\lambda)\right)} \tag{A1.2}$$

where $p_{0n}^* = \frac{1}{R}\left(1+\frac{\lambda(1-\alpha)\eta(q(1-\lambda)+\lambda)}{(q(1-\lambda)+\alpha\lambda)\left(q(1-\lambda)+\left(\eta+\left(\alpha+\frac{1-\alpha}{1-\pi}\right)(1-\eta)\right)\lambda\right)(1-\pi)}\right)$ is the screening equilibrium price level. Given this assumption, the final step is to guarantee that given the asset price level in the equilibrium, the difference between the expected value of the non-screening strategy and the expected value of the alternative strategy where the bank sets $d = \frac{q(y+p_0R(1-y))}{\alpha+(1-\alpha)p_0}$ and avoids bank runs in State 0 is non-negative as in (A1.3)

$$(1-\eta)\left(\begin{array}{c} -\ln(a) \\ +\lambda\left(\pi\left(\alpha\left(-\ln\left(\frac{q}{\alpha+(1-\alpha)p_{0n}^*}\right)\right)+(1-\alpha)\left(-\ln\left(\frac{\left(1-\frac{\alpha q}{\alpha+(1-\alpha)p_{0n}^*}\right)}{(1-\alpha)}\right)\right)\right)\right) \\ +(1-\lambda)\left(\pi\left(-\ln\left(\frac{1}{\alpha+(1-\alpha)p_{0n}^*}\right)\right)\right) \end{array}\right) \tag{A1.3}$$

$$-\ln\left(\frac{1}{\eta+a(1-\eta)}\right) \geq 0$$

where $a = (1-\pi)+\pi(1-\alpha)\left(\frac{\lambda}{1-\frac{\alpha q}{\alpha+(1-\alpha)p_{0n}^*}}+\frac{1-\lambda}{1-\frac{\alpha}{\alpha+(1-\alpha)p_{0n}^*}}\right)$. Restrictions (A1.1), (A1.2) and (A1.3) together define a set of parameter values ensuring that banks choose between the screening strategy and the non-screening strategy and the strategies result in bank runs as described in section 2.5. By numerical experiments, it can be shown that the set of possible parameter values is non-empty.

Appendix 2

Proof of Proposition 3.1

In the pure screening equilibrium, $p_0 = p_{0s}^*$ and $\frac{\partial p_{0s}^*}{\partial \pi} = \frac{1}{R}\frac{(1-\alpha)\eta(\eta+\alpha(1-\eta))}{\alpha(1-\pi(\eta+\alpha(1-\eta)))^2}$ which is clearly positive so that the sign of $\frac{d(V_s-V_n)}{d\pi}$ given in (3.17) is not uniquely determined. Now, $\lim_{\eta\to 0}\frac{d(V_s-V_n)}{d\pi} = -(1-\alpha)(1-\lambda)\ln(p_{0s}^*)$ that is strictly positive by assumption. Since $\frac{\partial\left(\ln\left(p_{0s}^*\right)+\frac{\pi}{p_{0s}^*}\frac{\partial p_{0s}^*}{\partial\pi}\right)}{\partial\eta} = \frac{1-\alpha}{(\eta+\alpha(1-\eta))(1-\pi(\eta+\alpha(1-\eta)))^2}$ is finite, $\frac{d(V_s-V_n)}{d\pi} > 0$ when η is close enough to 0. If parameter restrictions allow η increase enough, $\frac{d(V_s-V_n)}{d\pi}$ becomes negative because $\frac{\partial\left(\ln\left(p_{0s}^*\right)-\frac{(1-\pi)}{p_{0s}^*}\frac{\partial p_{0s}^*}{\partial\pi}\right)}{\partial\eta} > 0$. Moreover, $\lim_{\pi\to 0}\frac{d(V_s-V_n)}{d\pi} = -(1-\eta)(1-\lambda)(1-\alpha)\ln(p_{0s}^*)$ which is strictly positive by assumption. Since $\frac{\partial\left(\ln\left(p_{0s}^*\right)+\frac{\pi}{p_{0s}^*}\frac{\partial p_{0s}^*}{\partial\pi}\right)}{\partial\pi} = \frac{(1-\alpha)\eta((1-\alpha)(1+\pi(1-\eta))+(1-\pi)(1+\alpha))}{(1-\alpha+(1-\pi)\alpha)^2((1-\pi)\eta+(1-\alpha+(1-\pi)\alpha)(1-\eta))^2}$ is finite, $\frac{d(V_s-V_n)}{d\pi} > 0$ when π is close enough to 0. Again, if parameter restrictions allow π increase enough, $\frac{d(V_s-V_n)}{d\pi}$ becomes negative because $\frac{\partial\left(\ln\left(p_{0s}^*\right)+\frac{\pi}{p_{0s}^*}\frac{\partial p_{0s}^*}{\partial\pi}\right)}{\partial\pi} > 0$.

In the pure non-screening equilibrium, $p_0 = p_{0n}^*$ and $\frac{\partial p_0}{\partial\pi} = \frac{1}{R}\frac{\lambda(1-\alpha)\eta}{(q(1-\lambda)+\alpha\lambda)}$ $\frac{(q(1-\lambda)+\lambda)(q(1-\lambda)+(\eta+\alpha(1-\eta))\lambda)}{(q(1-\pi)+((1-q)(1-\pi)+(1-\alpha)(1-\eta)\pi)\lambda)^2}$ which is clearly positive so that the sign of $\frac{d(V_s-V_n)}{d\pi}$ given in (3.17) is not uniquely determined. First, $\lim_{\eta\to 0}\frac{d(V_s-V_n)}{d\pi} = -(1-\alpha)(1-\lambda)\ln(p_{0n}^*)$ that is strictly positive by assumption. Since $\frac{\partial\left(\ln\left(p_{0n}^*\right)+\frac{\pi}{p_{0n}^*}\frac{\partial p_{0n}^*}{\partial\pi}\right)}{\partial\eta} = \frac{\lambda(1-\alpha)(q+\lambda-q\lambda)^2}{(q(1-\lambda)+(\eta+\alpha(1-\eta))\lambda)(q(1-\pi)+((1-q)(1-\pi)+(1-\alpha)(1-\eta)\pi)\lambda)^2}$ is finite, $\frac{d(V_s-V_n)}{d\pi} > 0$ when η is close enough to 0. If parameter restrictions allow η increase enough, $\frac{d(V_s-V_n)}{d\pi}$ becomes negative as $\frac{\partial\left(\ln\left(p_{0n}^*\right)+\frac{\pi}{p_{0n}^*}\frac{\partial p_{0n}^*}{\partial\pi}\right)}{\partial\eta} > 0$. Moreover, $\lim_{\pi\to 0}\frac{d(V_s-V_n)}{d\pi} = -(1-\eta)(1-\lambda)(1-\alpha)\ln(p_{0n}^*)$ which is strictly positive by assumption. Since $\frac{\partial\left(\ln\left(p_{0n}^*\right)+\frac{\pi}{p_{0n}^*}\frac{\partial p_{0n}^*}{\partial\pi}\right)}{\partial\pi} = \frac{\lambda(1-\alpha)\eta(q+\lambda-q\lambda)^2(2q(1-\pi)(1-\lambda)+((1-\alpha)(1+\pi(1-\eta))+(1-\pi)(1+\alpha))\lambda)}{(q(1-\pi)(1-\lambda)+(1-\alpha+(1-\pi)\alpha)\lambda)^2(q(1-\pi)+((1-q)(1-\pi)+(1-\alpha)(1-\eta)\pi)\lambda)^2}$ is finite, $\frac{d(V_s-V_n)}{d\pi} > 0$ when π is close enough to 0. Again, if parameter restrictions allow π increase enough, $\frac{d(V_s-V_n)}{d\pi}$ becomes negative as $\frac{\partial\left(\ln\left(p_{0n}^*\right)+\frac{\pi}{p_{0n}^*}\frac{\partial p_{0n}^*}{\partial\pi}\right)}{\partial\pi} > 0$.

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