



BANK OF ENGLAND

Working Paper No. 456

Liquidity risk, cash-flow constraints and systemic feedbacks

Sujit Kapadia, Mathias Drehmann, John Elliott and Gabriel Sterne

June 2012

Working papers describe research in progress by the author(s) and are published to elicit comments and to further debate. Any views expressed are solely those of the author(s) and so cannot be taken to represent those of the Bank of England or to state Bank of England policy. This paper should therefore not be reported as representing the views of the Bank of England or members of the Monetary Policy Committee or Financial Policy Committee.



BANK OF ENGLAND

Working Paper No. 456

Liquidity risk, cash-flow constraints and systemic feedbacks

Sujit Kapadia,⁽¹⁾ Mathias Drehmann,⁽²⁾ John Elliott⁽³⁾ and Gabriel Sterne⁽⁴⁾

Abstract

The endogenous evolution of liquidity risk is a key driver of financial crises. This paper models liquidity feedbacks in a quantitative model of systemic risk. The model incorporates a number of channels important in the current financial crisis. As banks lose access to longer-term funding markets, their liabilities become increasingly short term, further undermining confidence. Stressed banks' defensive actions include liquidity hoarding and asset fire sales. This behaviour can trigger funding problems at other banks and may ultimately cause them to fail. In presenting results, we analyse scenarios in which these channels of contagion operate, and conduct illustrative simulations to show how liquidity feedbacks may markedly amplify distress.

Key words: Systemic risk, funding liquidity risk, contagion, stress testing.

JEL classification: G01, G21, G32.

(1) Bank of England. Email: sujit.kapadia@bankofengland.co.uk (corresponding author).

(2) Bank for International Settlements. Email: mathias.drehmann@bis.org

(3) Bank of England. Email: johnelliott1978@hotmail.co.uk

(4) Exotix. Email: gabriel.sterne@exotix.co.uk

This research was undertaken when John Elliott, Sujit Kapadia and Gabriel Sterne all worked at the Bank of England, and when Mathias Drehmann worked at the Bank of England and the Bank for International Settlements. The views expressed in this paper are those of the authors, and not necessarily those of the Bank of England, Financial Policy Committee members, or the Bank for International Settlements. The paper is forthcoming in Haubrich, J G and Lo, A W (eds), *Quantifying systemic risk*, University of Chicago Press.

We are grateful to the following people who have provided valuable contributions and comments: David Aikman, Piergiorgio Alessandri, Niki Anderson, Richard Barwell, Emily Beau, Geoff Coppins, Jason Dowson, Bruno Eklund, Prasanna Gai, Harry Goodacre, Simon Hall, Andy Haldane, Joseph Haubrich, Andrew Lo, Elizabeth Martin, Emma Mattingley, Will Kerry, Nada Mora, Emma Murphy, Mikhail Oet, James Purchase, Matthew Willison and two anonymous referees. We would also like to thank seminar participants at the Bank of England and the NBER/Federal Reserve Bank of Cleveland Research Conference on 'Quantifying Systemic Risk' (Boston, 6 November 2009) for helpful comments and suggestions.

The Bank of England's working paper series is externally refereed.

Information on the Bank's working paper series can be found at www.bankofengland.co.uk/publications/Pages/workingpapers/default.aspx

Publications Group, Bank of England, Threadneedle Street, London, EC2R 8AH
Telephone +44 (0)20 7601 4030 Fax +44 (0)20 7601 3298 email mapublications@bankofengland.co.uk

Contents

Summary	3
1 Introduction	5
2 Funding liquidity risk in a system-wide context: conceptual and theoretical issues	11
2.1 The cash-flow constraint	11
2.2 The trigger for funding problems at individual institutions	13
2.3 System dynamics of funding liquidity crises	15
3 Modelling liquidity risk for individual banks – a ‘danger zone’ approach	17
4 Modelling systemic liquidity feedbacks	21
4.1 Phase 1: Closure of long-term wholesale markets	21
4.2 Phase 2: Closure of short-term wholesale markets	24
4.3 Phase 3: Systemic impact of a bank’s failure	29
4.4 Summary of systemic feedback effects	29
5 Shocks to fundamentals and liquidity risk: simulations in RAMSI	29
6 Conclusions and future work	34
Appendix 1: An example of a danger zone calibration using Continental Illinois	36
References	38

Summary

Although the failure of a financial institution may reflect solvency concerns, it often manifests itself through a crystallisation of liquidity risk associated with a loss of funding. In such funding crises, the bank's solvency position no longer fully determines its survival; and its cash-flow constraint becomes critical.

This paper develops a framework that promotes an understanding of the triggers and system dynamics of liquidity risk during periods of financial instability and simulates the impact of these effects in a quantitative model of systemic risk. By using simple indicators and analysing bank-specific cash-flow constraints, we assess the onset and evolution of liquidity stress at individual institutions in various phases. And we capture several systemic feedbacks which may arise during funding liquidity crises, mostly linked to defensive actions taken by banks in distress, and many of which have been important during the current financial crisis. A key contribution of this paper is to demonstrate how systemic risk may escalate and contagion may spread to other institutions as a bank's funding conditions deteriorate, irrespective of whether the bank ultimately survives or fails. By applying the model to the UK banking system based on the balance sheet vulnerabilities that existed at the end of 2007, we illustrate how liquidity feedbacks may markedly amplify other sources of risk.

The severity of an individual bank's funding distress is calibrated using a simple 'danger zone' approach that scores each bank according to eight indicators that proxy solvency, liquidity profile, and confidence. Two indicators in particular play an important role in the transmission dynamics of funding crises modelled here. The first is short-term wholesale maturity mismatch (between contractually maturing liabilities and assets); a bank with a larger share of short-term borrowing faces greater funding liquidity risk. The second is that distress at one bank may adversely affect 'similar' banks through a pure confidence channel.

A danger zone score beyond a first threshold triggers the initial phase of distress, in which long-term unsecured funding markets close to the bank. The bank has to refinance a larger volume of liabilities in short-term markets each period, which further worsens its maturity mismatch score. The bank takes the defensive action of hoarding liquidity (reducing the maturity of its own intra-financial system lending), which improves its own mismatch score but worsens mismatch and increases danger zone scores at counterparty banks.

A second phase of distress is triggered beyond a further danger zone threshold. In the model, this results in shorter-term unsecured funding markets closing to the distressed bank, which then takes further defensive actions in an attempt to meet its cash-flow constraint. If profits earned over the period are insufficient to meet liquidity needs, the bank in the first instance withdraws all maturing intra-financial system assets, using the proceeds to pay off liabilities due. Its next line of defence is to sell or encumber its liquid assets. Finally, it resorts to fire-selling its illiquid assets, precipitating falls in asset prices and generating systemic feedbacks as other banks holding those assets are assumed to suffer temporary losses, worsening their solvency position and potentially increasing their danger zone score. If the combined effect of these defensive actions is insufficient for the bank to meet its cash-flow constraint, it fails. At this point, it defaults on its obligations to other banks, with the associated counterparty credit losses determined using a network model of bilateral interbank exposures. In extreme circumstances, the spillover effects linked to liquidity hoarding, asset fire sales, confidence channels and counterparty default may also generate sufficient contagion to cause other banks to suffer funding liquidity crises, and potentially fail.

The paper provides illustrative simulations using a version of the Bank of England's 'RAMSI' stress-testing model to highlight these dynamics quantitatively. RAMSI uses disaggregated balance sheets covering the largest UK banks. For the simulations, we use data up to 2007 Q4 and draw 500 realisations from a macroeconomic model on a three-year forecast horizon to end-2010. The results highlight the role of contagion due to the systemic feedbacks. The distribution of total system assets at the end of the simulation period has a long left-hand tail, which is a direct consequence of the feedbacks, which can in some cases cause several institutions to default. This fat tail emerges in spite of the underlying shocks to macroeconomic variables having no such tail. These illustrative results point towards the importance of considering funding liquidity risk and systemic feedbacks in quantitative models of systemic risk.

The model could be extended in several ways. For example, rather than generating all shocks from a macroeconomic model, it would be interesting to allow for direct shocks to banks' cash-flow constraints, perhaps linked to some market-wide liquidity shock. It would also be helpful to capture the evolution of systemic liquidity crises incorporating more developed behavioural assumptions, and over a shorter time period than the three months used here. Finally, it would be interesting to use the framework to explore the role that macroprudential policies such as time-varying liquidity buffers might be able to play in containing systemic risk.

1 Introduction

The global financial crisis has served to reiterate the central role of liquidity risk in banking. Such a role has been understood at least since Bagehot (1873). This paper develops a framework that promotes an understanding of the triggers and system dynamics of liquidity risk during periods of financial instability and illustrates these effects in a quantitative model of systemic risk.

The starting point of our analysis is the observation that although the failure of a financial institution may reflect solvency concerns, it often manifests itself through a crystallisation of funding liquidity risk. In a world with perfect information and capital markets, banks would only fail if their underlying fundamentals rendered them insolvent. In such a world, provided valuations are appropriate (eg adjusted to reflect prospective losses), then examining the stock asset and liability positions would determine banks' health, and solvent banks would always be able to finance random liquidity demands by borrowing, for example from other financial institutions. In reality, informational frictions and imperfections in capital markets mean that banks may find it difficult to obtain funding if there are concerns about their solvency, regardless of whether or not those concerns are substantiated. In such funding crises, the stock solvency constraint no longer fully determines survival; what matters is whether banks have sufficient cash inflows, including income from asset sales and new borrowing, to cover all cash outflows. In other words, the cash-flow constraint becomes critical.

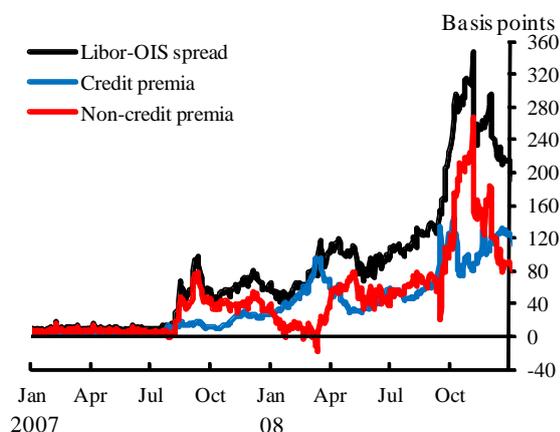
The lens of the cash-flow constraint also makes it possible to assess how banks' defensive actions during a funding liquidity crisis may affect the rest of the financial system. Figure 1 provides a stylised overview of the transmission mechanisms. For simplicity, it is assumed that the crisis starts with a negative shock leading to funding problems at one bank (bank A). The nature of the shock can be manifold, for example it could be a negative earnings shock leading to a deterioration of the bank's solvency position or a reputational shock. After funding problems emerge, confidence in bank A may deteriorate further either endogenously or linked to concerns about the shock (channel 1 in Figure 1).

In an attempt to stave off a liquidity crisis, the distressed bank may take defensive actions, with possible systemic effects (channels 2 and 3). For instance, it may hoard liquidity. Initially, it may be likely to start hoarding (future) liquidity by shortening the maturities of the interbank

Our modelling approach disentangles the problem into distinct steps. First, we introduce a ‘danger zone’ approach to model how shocks affect individual banks’ funding liquidity risk. This approach is simple and transparent (yet subjective) as we assume that certain funding markets close if the danger zone score crosses particular thresholds. The danger zone score, in turn, summarises various indicators of banks’ solvency and liquidity conditions. These include a bank’s similarity to other banks in distress (capturing confidence contagion) and its short-term wholesale maturity mismatch – since the latter indicator worsens if banks lose access to long-term funding markets, the framework also captures ‘snowballing’ effects, whereby banks are exposed to greater liquidity risk as the amount of short-term liabilities which have to be refinanced in each period increases over time. Second, we combine the ‘danger zone’ approach with simple behavioural reactions to assess how liquidity crises can spread through the system. In particular, we demonstrate how liquidity hoarding and asset fire sales may improve one bank’s liquidity position at the expense of others. Last, using the ‘RAMSI’ stress-testing model presented in Aikman *et al* (2009), we generate illustrative distributions for bank profitability to show how funding liquidity risk and associated contagion may exacerbate overall systemic risk and amplify distress during financial crises. In particular, we demonstrate how liquidity effects may generate pronounced fat tails even when the underlying shocks to fundamentals are Gaussian.

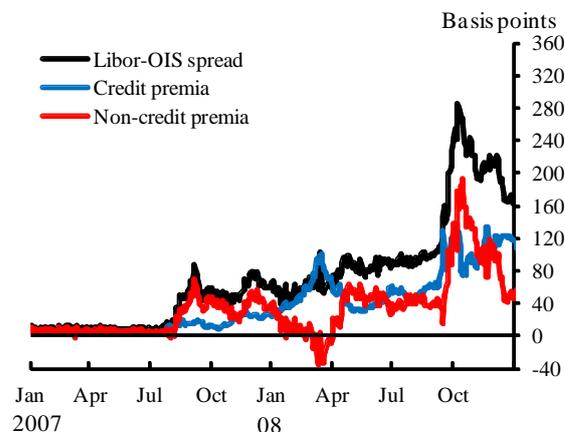
The feedback mechanisms embedded in the model all played an important role in the current and/or past financial crises. For example, the deterioration in liquidity positions associated with ‘snowballing’ effects was evident in Japan in the 1990s (see Figures 14 and 15 in Nakaso (2001)). And in this crisis, interbank lending collapsed from very early on. Spreads between interbank rates for term lending and expected policy rates in the major funding markets rose sharply in August 2007, before spiking in September 2008 following the collapse of Lehman Brothers (Figures 2(a)-2(c), black lines). Throughout this period, banks substantially reduced their lending to each other at long-term maturities, with institutions forced to roll over increasingly large portions of their balance sheet at very short maturities. Figure 3 highlights these snowballing effects between 2007 and 2008. At the same time, the quantity of interbank lending also declined dramatically and there was an unprecedented increase in the amounts placed by banks as reserves at the major central banks, indicative of liquidity hoarding at the system level.

Figure 2(a): Decomposition of the sterling twelve-month interbank spread^{(a)(b)}



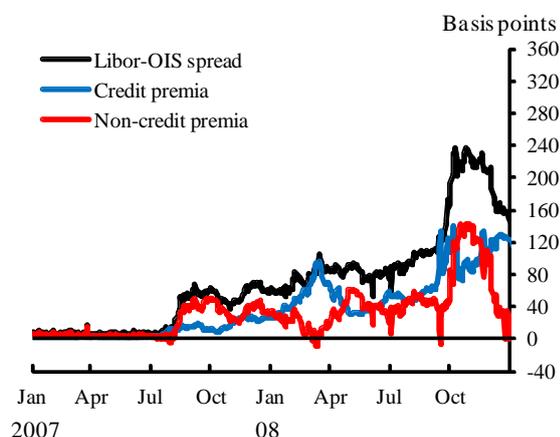
Sources: British Bankers' Association, Bloomberg, Markit Group Limited and Bank of England calculations.
 (a) Spread of twelve-month Libor to twelve-month overnight index swap (OIS) rates.
 (b) Estimates of credit premia are derived from credit default swaps on banks in the Libor panel. Estimates of non-credit premia are derived by the residual. For further details on the methodology, see Bank of England (2007).

Figure 2(b): Decomposition of the dollar twelve-month interbank spread^{(a)(b)}



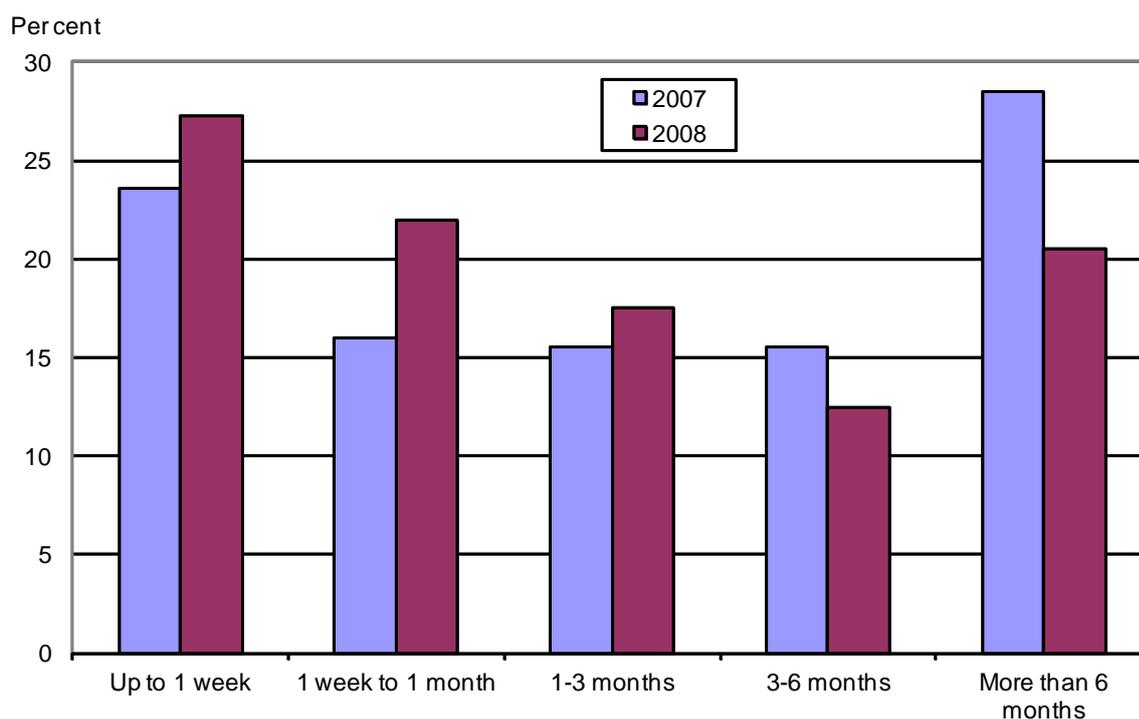
Sources: British Bankers' Association, Bloomberg, Markit Group Limited and Bank of England calculations.
 (a) Spread of twelve-month Libor to twelve-month OIS rates.
 (b) Estimates of credit premia are derived from credit default swaps on banks in the Libor panel. Estimates of non-credit premia are derived by the residual. For further details on the methodology, see Bank of England (2007).

Figure 2(c): Decomposition of the euro twelve-month interbank spread^{(a)(b)}



Sources: British Bankers' Association, Bloomberg, Markit Group Limited and Bank of England calculations.
 (a) Spread of twelve-month Libor to twelve-month OIS rates.
 (b) Estimates of credit premia are derived from credit default swaps on banks in the Libor panel. Estimates of non-credit premia are derived by the residual. For further details on the methodology, see Bank of England (2007).

Figure 3: Snowballing in unsecured markets^(a)



Source: European Central Bank.

(a) Maturity-weighted breakdown for average daily turnover in unsecured lending as a percentage of total turnover for a panel of 159 banks in Europe. Based on Chart 4, Section 1.2 of ECB (2008).

In principle, the collapse in interbank lending could have arisen either because banks had concerns over counterparty credit risk, or over their own future liquidity needs; it is hard to distinguish between these empirically. But anecdotal evidence suggests that, at least early in the crisis, banks were hoarding liquidity as a precautionary measure so that cash was available to finance liquidity lines to off balance sheet vehicles that they were committed to rescuing, or as an endogenous response to liquidity hoarding by other market participants. Interbank spread decompositions into contributions from credit premia and non-credit premia (Figures 2(a)-2(c)), and recent empirical work by Christensen *et al* (2009) and Acharya and Merrouche (2012), all lend support to this view.

It is also clear that the reduction in asset prices after Summer 2007 generated mark-to-market losses which intensified funding problems in the system, particularly for those institutions reliant on the repo market who were forced to post more collateral to retain the same level of funding (Gorton and Metrick (2010)). While it is hard to identify the direct role of fire sales in contributing to the reduction in asset prices, it is evident that many assets were carrying a large liquidity discount.

Finally, confidence contagion and counterparty credit losses came to the fore following the failure of Lehman Brothers. The former was evident in the severe difficulties experienced by the other US securities houses in the following days, including those which had previously been regarded as relatively safe. And counterparty losses also contributed to the systemic impact of its failure, with the fear of a further round of such losses via credit derivative contracts being one of the reasons for the subsequent rescue of American International Group (AIG).

There have been several important contributions in the theoretical literature analysing how liquidity risk can affect banking systems, some of which we refer to when discussing the cash-flow constraint in more detail in Section 2. But empirical papers in this area are rare. One of the few is van den End (2008), who simulates the effect of funding and market liquidity risk for the Dutch banking system. The model builds on banks' own liquidity risk models, integrates them to system-wide level and then allows for banks' reactions, as prescribed by rules of thumb. But the paper only analyses shocks to fundamentals and therefore does not speak to overall systemic risk.

Measuring systemic risk more broadly is in its infancy, in particular if information from banks' balance sheets is used (Borio and Drehmann (2009)). OeNB (2006) and Elsinger *et al* (2006) integrated balance-sheet based models of credit and market risk with a network model to evaluate the probability of bank default in Austria. Alessandri *et al* (2009) introduced RAMSI and Aikman *et al* (2009) extend the approach in a number of dimensions. RAMSI is a comprehensive balance-sheet model for the largest UK banks, which projects the different items on banks' income statement via modules covering macro-credit risk, net interest income, non-interest income, and operating expenses. Aikman *et al* (2009) also incorporate a simplified version of the 'danger zone' framework developed more fully in this paper. But in their model, contagion can only occur upon bank failure due to confidence contagion, default in the network of interbank exposures (counterparty risk), or from fire sales which are assumed to depress asset prices at the point of default. In particular, they do not allow for 'snowballing' effects or incorporate banks' cash-flow constraints, and do not capture behavioural reactions such as liquidity hoarding or pre-default fire sales, all of which are key to understanding the systemic implications of funding liquidity crises.

The paper is structured as follows. Section 2 provides the conceptual and theoretical framework for our analysis, focusing on the potential triggers and systemic implications of funding liquidity

crises through the lens of banks' cash-flow constraints. Sections 3 and 4 focus on our quantitative modelling – Section 3 provides details on how the danger zone approach captures the closure of funding markets to individual institutions; Section 4 presents details and partial simulation results of how behavioural reactions and the danger zone approach interact to create systemic feedbacks. Section 5 integrates these effects into RAMSI to illustrate how shocks to fundamentals may be amplified by funding liquidity risk and systemic liquidity feedbacks. Section 6 concludes.

2 Funding liquidity risk in a system-wide context: conceptual and theoretical issues

2.1 The cash-flow constraint

Liquidity risk arises because inflows and outlays are not synchronised (Holmström and Tirole (1998)). This would not matter if agents could issue financial contracts to third parties, pledging their future income as collateral. But given asymmetric information and other frictions, this is not always possible in reality. Hence, the timing of cash inflows and outflows is the crucial driver of funding liquidity risk and a bank is liquid if it is able to settle all obligations with immediacy (see Drehmann and Nikolaou (2012)).¹ This is the case if, in every period, cash outflows are smaller than cash inflows and the stock of cash held, along with any cash raised by selling (or repoing) assets:

$$\begin{aligned} & Liabilities_{(Due)} + Assets_{(New/Rolled\ over)} \\ & \leq \\ & Net\ Income + Liabilities_{(New/Rolled\ over)} + Assets_{(Due)} + Value\ of\ Assets\ Sold/Repoed. \end{aligned}$$

Breaking down these components further:

$$\begin{aligned} & WL_{Due} + RL_{Due} + WA_{New,Ro} + RA_{New,Ro} \\ & \leq \\ & Net\ Income + WL_{New,Ro} + RL_{New,Ro} + WA_{Due} + RA_{Due} + LA^S + \sum p_i * ILA_i^S \end{aligned} \tag{1}$$

where:

- WL are wholesale liabilities and WA are wholesale assets,
- RL are retail liabilities and RA are retail assets,
- LA^S are the proceeds from the sale of liquid assets such as cash or government bonds,
- ILA_i^S is the volume of illiquid asset i sold or used as collateral to obtain secured (repo) funding,

¹ Drehmann and Nikolaou (2012) discuss how this definition of funding liquidity risk relates to other definitions commonly used.

- p_i is the market price of illiquid asset i , which may be below its fair value and possibly even zero in the short run,
- subscripts $_{Due}$, $_{New}$ and $_{Ro}$ refer to obligations which are contractually due, newly issued or bought, and rolled over respectively.

We note several issues. First, assessing funding liquidity risk through a cash-flow constraint is common in practice (for a recent overview see Matz and Neu (2007)) and also forms the basis of elements of proposed new liquidity regulations (Basel Committee on Banking Supervision (2010)). Nonetheless, the literature has tended to model funding liquidity risk differently, even though most theoretical models can be recast in the cash-flow constraint as discussed below.

Second, the flow constraint is written in terms of *contractual* maturities as these are the ultimate drivers of funding liquidity risk in crises. But in normal times, the constraint might reasonably be thought of in terms of behavioural maturities that may differ from contractual ones. For example, many retail deposits are available on demand. In normal conditions, a bank can expect the majority of these ‘loans’ to be rolled over continuously, so RL_{Due} may roughly equal RL_{Ro} . But, in times of stress, depositors may choose to withdraw, so the behavioural maturity may collapse closer to the contractual one.

Third, equation (1) still makes some simplifying assumptions. For example, contingent claims are an important driver of funding liquidity risk. In particular, firms rely heavily on credit lines (see, for example, Campello *et al* (2010)). Equally, banks negotiate contingent credit lines with other banks. We do not include off balance sheet items separately because once drawn they are part of new assets or liabilities. Repo transactions are also an important component of banks’ liquidity risk management. Even though technically different, we treat them as part of the asset sales category because in both cases, the market price broadly determines the value that can be raised from the underlying asset, which may or may not be liquid.² Transactions with the central bank are also included under repo. These occur regularly, even in normal conditions as banks obtain liquidity directly from the central bank during open market operations.³

² In repo transactions, there may also be an additional haircut applied which would mean that the cash lent on the trade would be lower than the current market value of the security used as collateral. In principle, the flow constraint could be augmented to account for this.

³ Throughout this paper, we abstract from extraordinary policy intervention in crises, so the cash-flow constraint presumes that there is no intervention to widen central bank liquidity provision in a way which would allow banks to obtain more cash from the central bank than they could obtain through asset sales or repo transactions in the market.

Beyond this, different funding markets split into several sub-markets such as interbank borrowing, unsecured bonds, securitisations, commercial paper etc. And there is clearly also a distinction between foreign and domestic funding markets.⁴ These separate markets may have quite different characteristics that make them more or less susceptible to illiquidity. Not all factors relevant to funding market dynamics can be easily incorporated into a model of systemic risk. But there are two that we judge to be sufficiently important as well as empirically implementable to split them out separately. First, we differentiate retail funding, secured markets and unsecured markets. And second, we split unsecured funding into longer-term and shorter-term markets. We discuss these in more detail later in the paper.

Finally, note that, *ex post*, liquidity outflows will always equal inflows. If the bank is unable to satisfy the flow constraint, it will become illiquid and default. Conversely, if the bank has excess liquidity, it can sell it to the market, for example as WA_{New} , or deposit it at the central bank. *Ex ante*, however, banks are uncertain as to whether the flow constraint will be satisfied in all periods, ie they face funding liquidity risk. The right-hand side of equation (1) shows that this risk is influenced by banks' ability to raise liquidity from different sources for different prices, which will also change over time. The possibilities and implications of their choices are discussed in detail below. Before doing so, it is important to highlight a simple fact that is clear from equation (1): the maturity mismatch between (contractually) maturing liabilities and assets is a key driver for funding liquidity risk. It follows that, *ceteris paribus*, a bank with a larger share of short-term liabilities faces greater funding liquidity risk.

2.2 *The trigger for funding problems at individual institutions*

Under normal business conditions, banks are able to meet their cash-flow constraints in every period, as they can always obtain new wholesale funding or sell assets in a liquid market. But this may not be the case in a crisis. To understand crisis dynamics better, we first discuss the trigger events for funding problems at an individual institution before analysing how funding crises can spread through the system.

Many theoretical models can be cast in terms of the flow constraint. For example, Diamond and Dybvig (1983) assume there is only one illiquid investment project ILA_i which pays a high,

⁴ McGuire and von Peter (2009) identify a shortage of dollar funding as a key driver of non-US banks funding problems during the current crisis.

certain pay-off in period 2 but a low pay-off p_i if liquidated early in period 1 (the high period 2 return guarantees that the bank is always solvent). The bank is entirely funded by demand deposits (RL_{Due}). It is known that a fraction of (*early*) depositors only care about consumption in period 1, while other (*late*) agents (which cannot be distinguished by the bank) are patient and prepared to wait until period 2, though they can withdraw in period 1 if they wish. To satisfy withdrawals of early depositors, the bank invests a fraction of its deposits into liquid assets LA^S . For simplicity, the bank has to pay no costs and interest payments are subsumed into liabilities to depositors, ie *net income* = 0. Given that all other terms in the cash-flow constraint are also assumed to be zero, equation (1) in period 1 for the Diamond and Dybvig bank looks like:

$$RL_{Due}^{early} + RL_{Due}^{late} \leq RL_{Ro}^{late} + LA^S + p_i * ILA_i$$

Under normal circumstances, late depositors roll over their demand deposits ($RL_{Due}^{late} = RL_{Ro}^{late}$) and the bank can meet its cash-flow constraint as the investment in the short-term asset is sufficient to pay back early depositors. But if late depositors are unwilling to roll over and start a run on the bank ($RL_{Ro}^{late} = 0$), the bank is forced to start selling its illiquid assets at p_i , which is below the fair value of the asset. Given that the bank is fundamentally sound, bank runs should not happen. But, as pay-offs are low when all late depositors run, an equilibrium exists in which it is optimal for all agents to run. This generates the possibility of multiple equilibria, whereby fundamentals do not fully determine outcomes and confidence has an important role.

Even though very stylised, this model captures several key features of liquidity crises. First, contractual maturities matter in a liquidity crisis as the ‘behavioural’ maturities of late depositors collapse in stressed conditions from two periods to the contractual maturity of one period. Second, funding and market liquidity are closely related. If the bank’s assets were liquid, so that p_i equalled its fair value, the bank could always sell assets to satisfy unexpected liquidity demands and would never be illiquid but solvent. Third, confidence and beliefs about the soundness of an institution and the behaviour of others play an important role in the crystallisation of funding liquidity risk.

The result that confidence effects can, in isolation, drive self-fulfilling bank runs is not particularly realistic: runs only tend to occur when there are strong (mostly justified) doubts about the fundamental solvency of a bank, or the bank has a very weak liquidity position. Chari

and Jagannathan (1988) therefore introduce random returns and informed depositors in the model, which can induce bank runs driven by poor fundamentals. More recently, global game techniques have been applied to this problem (Rochet and Vives (2004); Goldstein and Pauzner (2005)). Our empirical strategy is in the spirit of these papers: liquidity crises only tend to occur in our simulations when bank fundamentals are weak, even though banks can still be illiquid but solvent.

2.3 System dynamics of funding liquidity crises

The main focus of our work is to capture the system-wide dynamics of liquidity crises. Figure 1 identified several channels through which a funding crisis at one bank could spread to the rest of the financial system. We now relate these dynamics to existing literature and, where appropriate, to the cash-flow constraint.

Confidence contagion (channel 4 in Figure 1) could be interpreted through fundamentals, whereby a liquidity crisis in one institution reveals some information on the likelihood of insolvency of other banks with similar investments (Chen (1999)).⁵ Alternatively, it could simply reflect panic, whereby investors decide to run on similar banks purely because of sentiment. More generally, system confidence effects can contribute to liquidity hoarding. For example, Caballero and Krishnamurthy (2008) show that (Knightian) uncertainty may be triggered by a small shock, which is not necessarily a funding problem at one bank but could simply be a downgrade of an important market player. Anticipating potential funding needs in the future, banks start to hoard liquidity.⁶

The possible systemic consequences of liquidity hoarding (channel 2 in Figure 1) are made clear by considering cash-flow constraints. For example, if a (stressed) bank hoards liquidity (either by shortening the maturity of loans it offers in the interbank market or withdrawing funding altogether), the flow constraints of counterparties will be tightened or put at greater future risk via a reduction in $WL_{New, Ro}$. This may intensify funding problems at institutions which are already stressed. And small banks may find it difficult to access alternative sources of funding even if they are not stressed: indeed, the potential loss of a major funding source for small

⁵ Contagious bank runs can also affect the investment incentives of banks, making system-wide banking crisis even more likely (see Drehmann (2002), and Acharya and Yorulmazer (2008)).

⁶ Liquidity hoarding by surplus banks may also be a result of asymmetric information and heightened counterparty credit risk following adverse shocks (Heider *et al* (2009)).

regional US banks was one of the reasons for the bail-out of Continental Illinois in 1984. Yet, despite its potential importance, this ‘funding contagion’ channel has only received limited attention in the literature, though recent theoretical work by Gai *et al* (2011) has shown how this type of action, especially if associated with key players in the network, can cause an interbank market collapse in which all banks stop lending to each other.

By contrast, asset fire sales (channel 3 in Figure 1) have been widely discussed. The potential feedback loop between distress selling and falling asset prices was first highlighted by Fisher (1933). After the failure of LTCM and the resulting liquidity crisis for Lehman Brothers in 1998, this idea was formalised by a wide range of authors (see Shim and von Peter (2007) for a survey). Cifuentes *et al* (2005) illustrate how mark-to-market losses associated with falling asset prices could raise solvency concerns at highly exposed institutions. And Brunnermeier and Pedersen (2009) show how downward spirals between asset fire sales and increased funding liquidity risk can emerge. Such a spiral can, for instance, start if a bank (or broker in the Brunnermeier and Pedersen model) is short of funding liquidity, cannot obtain it from the interbank market, and has to sell assets. If asset markets are characterised by frictions, (large) asset sales induce a fall in prices and thus the value of collateral. This, in turn, implies that the bank has to post higher margins, increasing liquidity outflows. To remain liquid banks have to sell even more assets, depressing market prices further.⁷ Their model can also be recast in terms of the flow constraint: higher margin calls are equivalent to higher liquidity demands ($WL_{New,Ro}$) while at the same time, lower asset prices, p_i , reduce available liquidity.⁸

Interbank market contagion via counterparty credit risk (channel 5 in Figure 1) has also been widely discussed in the literature (Allen and Gale (2000), Freixas *et al* (2000), Gai and Kapadia (2010) and Upper (2011)). Clearly, this may weaken the solvency and thus overall funding position of other banks. But it is also evident from the flow constraint that a loss of WA_{Due} could lead to a direct short-term funding problem at a bank even if it remains solvent.

Thus far, we have focused on the negative system-wide effects of funding liquidity crises. But it is important to note that when funds are withdrawn from a stressed bank, they must be placed elsewhere. So, unless the funds end up as increased reserve holdings at the central bank, some

⁷ Related papers on the amplification role of shocks to margins and haircuts on the securities which serve as collateral in repo transactions include Adrian and Shin (2010), Geanakoplos (2010) and Gorton and Metrick (2010).

⁸ Shocks to margins or haircuts could also be modelled more directly in the flow constraint by scaling down the value of the $\Sigma p_i * ILA_i^S$ term when interpreted as applying to repo transactions.

banks are likely to *strengthen* as a result of funding crises through an increase in WL_{New} and, possibly, RL_{New} . Indeed, Gatev and Strahan (2006) and Gatev *et al* (2009) identify this effect in the US banking sector, especially for larger institutions.⁹ However, the strength of this countervailing effect is likely to be highly dependent on the type of crisis: in a crisis precipitated by an idiosyncratic shock to one institution, we may expect it to be fairly strong; if much of the banking system is in distress, central bank reserves may end up increasing as has happened to a certain extent during this financial crisis. Moreover, such redistributive effects can only occur if funds are actually withdrawn – they do not help if there is a systemic shortening of the maturity of interbank lending across the system. Therefore, to maintain simplicity, we do not take these effects into account in our model.

3 Modelling liquidity risk for individual banks – a ‘danger zone’ approach

Modelling the liquidity risk of an individual bank quantitatively presents significant challenges. One might wish to construct a formal forecasting framework for predicting funding crises. But we do not have full information on the underlying cash-flow constraints. And it would be difficult to estimate the stochastic nature of each component because of the binary, non-linear nature of liquidity risk, and because liquidity crises in developed countries have been (until recently) rare events for which data are limited. Instead, we adopt a simple, transparent (yet subjective) ‘danger zone’ approach, in which we assume that certain funding markets close, if banks solvency and liquidity conditions – summarised by a danger zone score explained below – cross particular thresholds. In some respects, this is consistent with the broad methodological approach advocated by Gigerenzer and Brighton (2009) that simple heuristics can sometimes lead to more accurate inferences than approaches which use more information and computation.

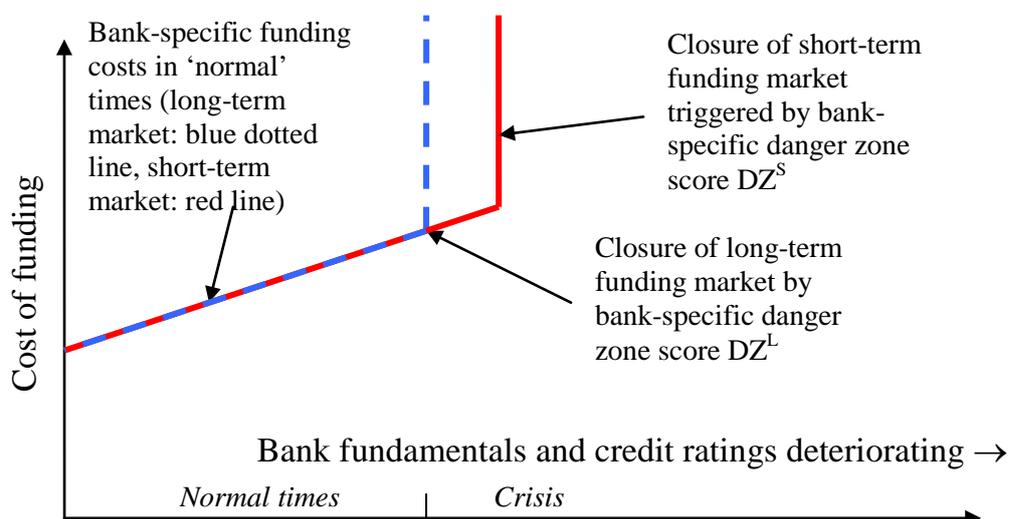
Our approach to modelling the closure of funding markets is somewhat stylised. In particular, as discussed in Section 2.1, we take a high-level view of the flow constraint and do not consider all different markets for liquidity. But we differentiate between retail, short-term unsecured wholesale and long-term unsecured wholesale markets. The closure of secured funding markets does not play an explicit role because it is assumed that banks will always be able to raise the same amount of cash by disposing the collateral at prevailing market prices. In reality, however,

⁹ It should, however, be noted that Pennacchi (2006) finds that demand deposit inflows cannot be observed prior to the introduction of deposit insurance, indicating that this effect may be driven by regulatory interventions rather than by the underlying structure of banks’ balance sheets.

sudden closures of secured funding markets may make it impossible to sell all of the collateral at a sufficiently high price to meet immediate funding needs.

We also only consider normal and crisis times for each funding market. Figure 4 illustrates this point. In normal times, funding is available in all markets. But banks with weaker fundamentals have to pay higher costs. Interbank markets usually do not differentiate widely between different banks (see Furfine (2002) or Angelini *et al* (2011)). As a first-order approximation, we therefore assume that, in ‘normal’ times, funding costs equal a market rate plus a credit risk premium which increases as ratings deteriorate.

Figure 4: A stylised view of funding liquidity risk for an individual bank



Once liquidity risk crystallises, the process in different markets is inherently non-linear and may occur at different ratings and funding costs. We model the non-linearity especially starkly, but in line with practitioners (see Matz and Neu (2007)): once fundamentals (as summarised in the danger zone (DZ) score) fall below a certain thresholds, the bank faces infinite costs to access the relevant market, ie the market is closed for this bank. Crises have, however, shown that different funding markets close at different times. For example, as discussed above, it may be rational for lenders to provide short-term funding even if they are not willing to grant long-term loans. Given this, we assume that a danger zone score above DZ^L will lead to a closure of long-term wholesale markets, whilst short-term wholesale markets remain open until the bank breaches the danger zone score DZ^S .

The previous discussion highlights that there is not one simple trigger for a funding liquidity crisis at an individual bank. For practical purposes, we supplement the insights from theory with information from summaries of individual banks' liquidity policies and contingency plans (ECB (2002), BIS (2006) and IIF (2007)), and evidence from case studies of funding liquidity crises from this and past crises. As shown in Figure 5, we assume that a set of eight indicators can proxy the three broad areas that theory and experience suggest are important: (i) concerns about future solvency; (ii) a weak liquidity position/funding structure; and (iii) institution-specific and market-wide confidence effects, over and above those generated by solvency concerns or weakness in liquidity positions.

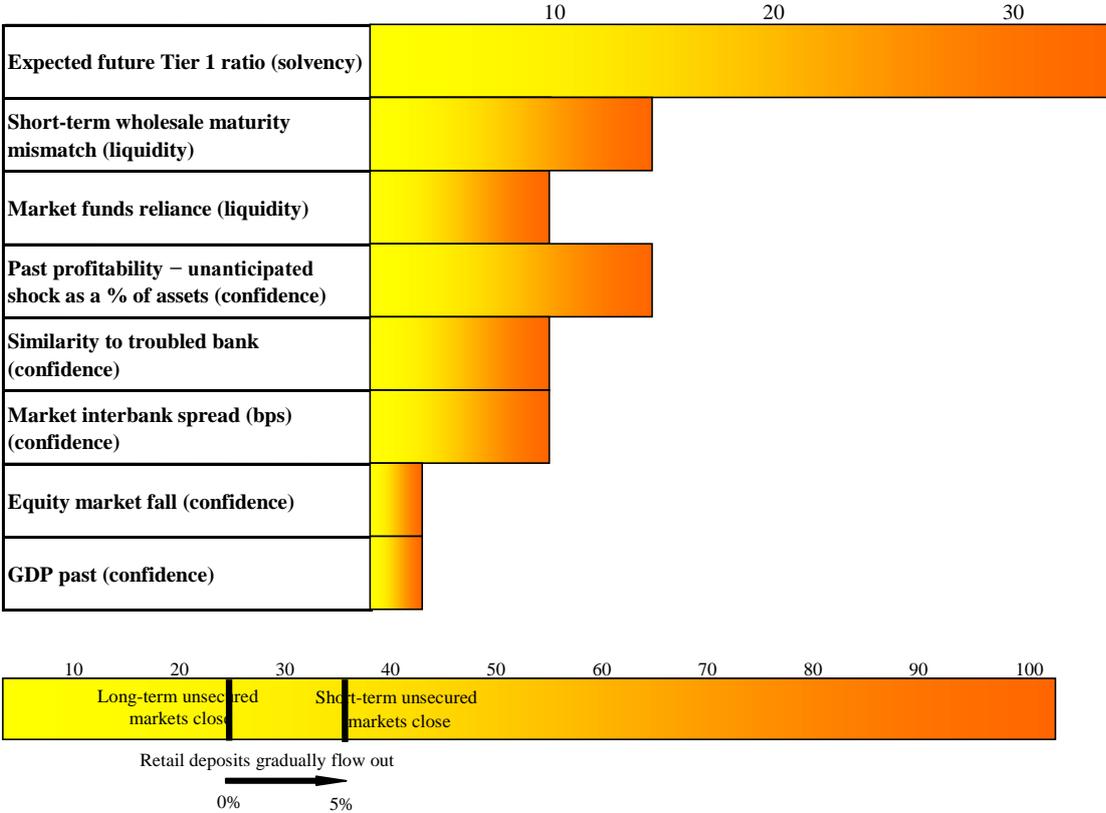
Solvency concerns are captured through a forward-looking Tier 1 capital ratio, based on regulatory measures. Weak liquidity positions and funding structures are captured through two metrics. First, a short-term wholesale maturity mismatch compares short-term wholesale liabilities with short-term wholesale assets (including maturing wholesale loans and liquid assets). Second, longer-term funding vulnerability is captured through a metric that measures reliance on market funds and shares some similarities to the (inverse of the) core funding ratio applied as a policy tool in New Zealand (Ha and Hodgetts (2011)). These metrics assume funds from wholesale counterparties and markets to be flightier than retail deposits. Confidence concerns are captured through a number of metrics: unexpected shocks to the previous quarter's profitability (distinct from solvency concerns, which are longer-term in focus); the possibility of confidence contagion which is captured through an assessment of how similar the institution is to other troubled banks; and three metrics looking at market prices and real economy data (the cost of interbank funding, the size of recent movements in equity markets, and the size of recent movements in GDP).

Note that the danger zone approach allows for some feedback effects. In particular, the closure of long-term funding markets to an institution: (i) may worsen that bank's liquidity position through 'snowballing' effects, whereby the bank becomes increasingly reliant on short-term funding; and (ii) may adversely affect 'similar' banks through a pure confidence channel.

Figure 5 also presents the aggregation scheme and the thresholds at which short-term and long-term unsecured funding markets are assumed to close to the bank. Noting that equal weights can predict almost as accurately as, and sometimes better than, multiple regression (Dawes and Corrigan (1974) and Dawes (1979)), we place roughly equal weight on the three main factors

(solvency, liquidity and confidence) that can trigger funding crises. In the aggregation, we allow for the possibility that a run could be triggered either by extreme scores in any of the three areas, or by a combination of moderate scores across the different areas. The judgements underpinning more specific aspects of the calibration and weighting schemes were informed by analysis of a range of case studies. As an example, Appendix 1 shows the danger zone approach ahead of the failure of Continental Illinois.

Figure 5: Danger zones – basic structure



Funding options become more restricted as a bank’s position deteriorates. At a score of $DZ^L = 25$ points, long-term unsecured funding markets close to the bank. The bank is also assumed to start experiencing gradual retail deposit outflows at this point (0.5% for every danger zone point above 25), intended to reflect behaviour of well-informed investors rather than representing a widespread (Northern Rock style) run. We refer to this as ‘Phase 1’ of funding market closure. There is no default during this phase since the bank is able to refinance in short-term unsecured funding markets and banks are assumed to have access to an infinite supply of short-term unsecured funding. Once the DZ score reaches $DZ^S = 35$, short-term funding markets close to

the bank, and the bank enters ‘Phase 2’ of funding market closure. But even a very high DZ score does not in itself trigger the failure of the bank – this only occurs if the bank’s capital falls below the regulatory minimum or if it is unable to meet its cash-flow constraint.

4 Modelling systemic liquidity feedbacks

As banks’ liquidity position deteriorates, they may undertake increasingly extreme defensive actions to try to bolster it. As noted above, such actions may have an adverse effect on other banks. In this section, we provide illustrative simulations using the RAMSI balance sheets to highlight these dynamics quantitatively.

The RAMSI balance sheets cover the largest UK banks and are highly disaggregated, with a wide range of different asset and liability classes. Each of the asset and liability classes is further disaggregated into a total of eleven buckets (five maturity buckets and six repricing buckets) and these are interpolated so that maturity information for each asset and liability class is available in a series of three-month buckets (0-3 months, 3-6 months, 6-9 months etc). Given the structure of these data, we define short-term assets and liabilities to be those with less than three months maturity throughout the simulations. RAMSI also exploits large exposure data to construct a matrix of bilateral interbank assets and liabilities for the major UK banks.¹⁰

In general, the balance sheet data are mainly extracted from published accounts but supplemented from regulatory returns. As some balance sheet entries are unavailable, rules of thumb based on other information or extrapolations on the basis of similarities between banks are used to fill in the data gaps. As the simulations in this paper are purely intended for illustrative purposes, they use balance sheet data for the ten largest UK banks as at end-2007.¹¹

4.1 Phase 1: Closure of long-term wholesale markets

The closure of long-term wholesale markets implies that the bank has to refinance a larger volume of liabilities in short-term wholesale markets each period. This increases the short-term wholesale maturity mismatch danger zone score (MM_T):

¹⁰ The techniques adopted are similar to those discussed by Wells (2004), Elsinger *et al* (2006) and OeNB (2006).

¹¹ Membership of the major UK banks group is based on the provision of customer services in the United Kingdom, regardless of country of ownership. At end-2007, the members were: Alliance & Leicester, Banco Santander, Barclays, Bradford & Bingley, Halifax Bank of Scotland, HSBC, Lloyds TSB, Nationwide, Northern Rock and Royal Bank of Scotland.

$$MM_t = \frac{LA_t + WA_t^{0-3} - WL_t^{0-3}}{TA_t},$$

The mismatch is constructed using liquid assets (LA_t) and wholesale assets (WA_t^{0-3}) and liabilities (WL_t^{0-3}) which have a remaining contractual maturity of less than three months, normalised by total assets (TA_t).¹² The danger zone scores for the short-term maturity mismatch indicator are shown in Table 1.

Table 1: Points score for short-term wholesale maturity mismatch

Calculated maturity mismatch	Danger zone points
Less than -5%	0
-5% to -8%	0-3
-8% to 11%	3-6
-11% to -14%	6-9
-14% to -17%	9-12
-17% to -20%	12-15

We demonstrate some of the feedback dynamics embedded in the model by presenting results from a stressed scenario in which various transmission channels are introduced in turn. Results are presented relative to a baseline in which no effects are switched on. We focus on three banks from the RAMSI peer group. The ‘distressed’ bank is initially set to have a DZ score exceeding 25, implying it is shut out of long-term funding markets. We also show the impact on two other banks (Banks A and B). Both are connected to the distressed bank through the interbank network and we demonstrate how the degree of connectivity affects the magnitude of the spillovers. To simplify the analysis, we hold the size of balance sheets constant as time progresses, and also hold all other DZ scores constant apart from the short-term wholesale maturity mismatch score.

(i) *Snowballing into shorter-term maturities (Figure 6.1)*: Once the distressed bank loses access to long-term unsecured wholesale funding markets and starts to experience gradual retail deposit outflows, it substitutes lost funding for short-term wholesale unsecured funding. This is the snowballing effect. Figure 6.1 illustrates that snowballing worsens the distressed bank’s short-term wholesale maturity mismatch each quarter as more of its liabilities mature and are rolled over only at short-term maturity. After three years, it deteriorates by around 4 percentage points.

¹² Liquid assets are defined as: cash and balances at central banks; items in the course of collection; Treasury and other eligible bills; and government bonds. Wholesale assets are defined as loans and advances to banks and other financial companies, financial investments available for sale (excluding items that are recognised as liquid assets) and reverse repos. Wholesale liabilities are defined as deposits from banks and other financial companies, items in the course of collection due to other banks, debt securities in issue and repos. Short-term is defined as less than three months due to the constraints of RAMSI’s balance sheet structure. Ideally, we would embellish the model with a more granular maturity split of liabilities but the same key dynamics and feedbacks would apply.

But most of the snowballing occurs in the first four quarters, with the effect tailing off over time, reflecting the concentration of liabilities in the shorter-maturity buckets. By design there is no impact on the other banks.¹³

Figure 6: The evolution of maturity mismatch under different assumptions

Figure 6.1: Impact of snowballing only

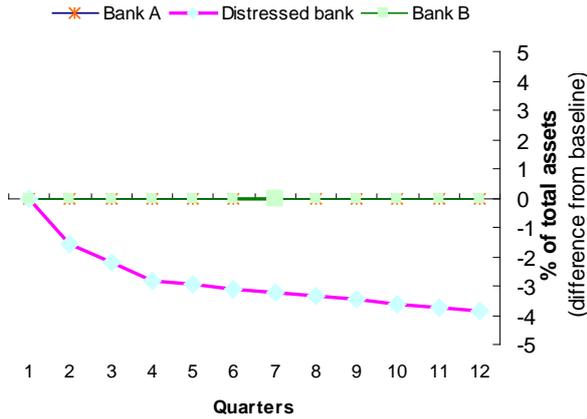


Figure 6.2: Impact of liquidity hoarding only

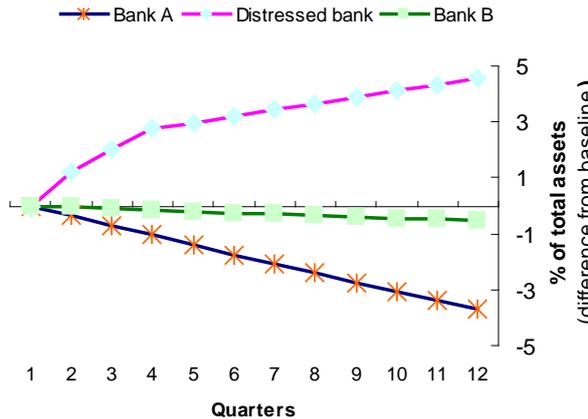
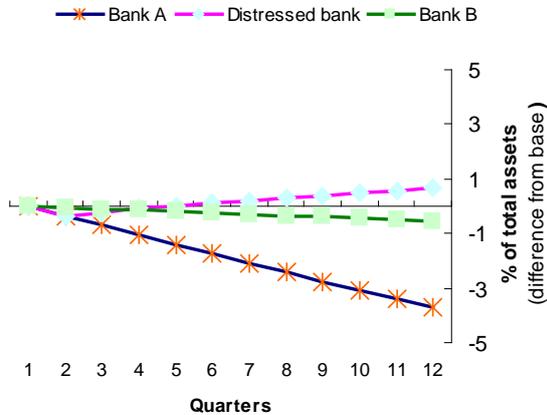


Figure 6.3: Impact of snowballing and liquidity hoarding



(ii) *Liquidity hoarding by shortening lending maturities (Figure 6.2):* As argued by Acharya and Skeie (2011), a bank that is nervous about its liquidity position may hoard (future) liquidity by only providing wholesale lending at short-term maturities. This has two effects. First, the additional short-term wholesale assets improve the distressed bank’s short-term wholesale maturity mismatch position as extra liquidity will be available on demand if needed. Abstracting from the snowballing effect, Figure 6.2 illustrates how such hoarding can improve the maturity

¹³ This includes a simplifying assumption that there is no corresponding shortening of the maturity of assets of other banks, since this is likely to be of only second-order importance in its impact on funding conditions.

mismatch position of the distressed bank by nearly 5 percentage points over the simulation. Second, this behaviour leads to a shortening of the interbank liabilities of other banks to which the distressed bank is lending – as the distressed bank hoards liquidity, some other banks effectively suffer a snowballing effect on a portion of their interbank liabilities. As the blue and green lines in Figure 6.2 illustrate, this worsens other banks' short-term wholesale maturity mismatch position. It thus serves to increase their DZ points scores – hence this type of liquidity hoarding has clear adverse spillovers for other banks in the system. Note that bank A's position deteriorates by more than bank B. This is because more of bank A's interbank liabilities are sourced from the distressed bank (based on data from the matrix of bilateral interbank exposures).

(iii) Snowballing and liquidity hoarding by shortening maturities (Figure 6.3): Allowing for both snowballing and liquidity hoarding is represented as a combination of (i) and (ii) above. In this case, after worsening initially, the distressed bank's maturity mismatch position eventually improves as the impact of liquidity hoarding becomes stronger than the impact of snowballing. Note that this is due to the specific balance sheet structure of this bank – in other cases, snowballing may prove to be the stronger effect. At the same time, other banks' maturity mismatch worsens, since they only experience the negative impact of the distressed bank's liquidity hoarding, identical to case (ii).

In most circumstances, a stressed bank will survive this phase of a funding crisis, since it can still access short-term funding markets. But if its mismatch position worsens, its danger zone score will be increasing. Therefore, the bank may be accumulating vulnerabilities which place it at greater risk of losing access to short-term funding markets in future periods.

4.2 Phase 2: Closure of short-term wholesale markets

The second phase of the liquidity crisis occurs when funding conditions deteriorate to such an extent that the bank is frozen out of both short and long-term funding markets. In our model, this occurs when a bank's DZ score exceeds 35 (see Figure 5). Although the bank's insolvency is not inevitable at this point, it becomes increasingly difficult for it to meet its cash-flow constraint. Therefore, it may need to take further defensive actions.

The possible systemic consequences of funding crises are made clear by considering the short-term (ie one-period) cash-flow constraint of a bank experiencing funding problems. In particular, suppose that a bank faces a liquidity crisis and cannot, or anticipates not being able to, access new funding from wholesale markets ($WL_{New,Ro} = 0$ in equation (1)). Then, short of defaulting, the bank has four options affecting the left or right-hand side of the cash-flow constraint. It can:

- 1) use profits (net income) earned over the period to pay off maturing liabilities;
- 2) choose not to roll over or grant new funding to other financial institutions ($WA_{New,Ro}$) (liquidity hoarding by withdrawal of funding);
- 3) sell or repo liquid assets;
- 4) sell illiquid assets ($\sum p_i * ILA_i^S$).

Note that, in practice, banks have further options, which we exclude in our simulations. First, they could draw down committed credit lines with other banks. In principle, this may be a preferred option, but experience in this and previous financial crises has demonstrated that a stressed bank cannot always rely on being able to draw on such lines. And any such drawdown may, in any case, send an adverse signal to the markets, further undermining confidence. Second, as set out in many contingency plans (see Matz and Neu (2007)), banks could securitise assets. But, this requires some time as well as previous presence in these markets. And, as the current crisis has demonstrated, it may not be possible in systemic crises. Third, banks could contract lending to the real economy. This will improve the flow constraint but with potentially severe repercussions for the macroeconomy.¹⁴ However, this is a very slow means of raising liquidity. And, as Matz and Neu (2007, page 109) put it, a strategic objective of liquidity risk management is to ‘ensure that profitable business opportunities can be pursued’. Given this, we assume that banks continue to replace maturing retail assets with new retail assets ($RA_{New} = RA_{Due}$).

It is unclear how banks would weigh up the relative costs of options 1-4. For a start, banks’ choice set is not as coarse as can be captured in the model. For example, banks hold a multitude of assets, some of which are less or more illiquid and therefore less or more costly to sell. Actions may also depend on specific circumstances. But we sequence defensive actions as ordered above in our simulations. As discussed below, this reflects an intuitive judgement of the costs imposed on the bank in distress by each action, information from summaries of banks’

¹⁴ For the impact of liquidity shocks on real lending during the current crisis see eg Ivashina and Scharfstein (2010). Huang (2009) provides evidence that distressed banks reduced the availability of pre-committed credit lines to non-wholesale customers.

contingency planning documents, and an assessment of the defensive actions actually taken by banks during this financial crisis.

4.2.1 *Simulating the implications of the various funding options*

Continuing from phase 1 of funding distress, we now explain how a bank's reaction to losing access to short-term wholesale funding markets may be simulated by using its cash-flow constraint. A preliminary check is made to determine if the bank can meet its cash-flow constraint in the complete absence of wholesale funding but without accounting for any net income earned over the period and assuming that banks aim to roll over interbank lending and avoid eroding liquid asset buffers or undertaking fire sales. If so, the constraint is satisfied and the bank survives to the next period. If not, then we consider the following sequence of defensive actions (options 1-4). Any bank that does not satisfy the flow constraint after all options are exhausted is defined as defaulted.¹⁵

Option 1: Using profits (net income) earned over the period to repay liabilities. In normal times, profits boost bank equity and may be matched on the asset side by higher lending. But banks may also use these proceeds to repay maturing liabilities. This is unlikely to have a significant adverse effect on funding markets' confidence in the bank, and so is ordered first. But banks are only likely to be able to raise limited funds in this way, especially in circumstances in which low profitability has contributed to funding difficulties.

Option 2: Liquidity hoarding by withdrawal of funding ($WA_{New, Ro} = 0$). In practice, liquidity hoarding has probably been the most frequently observed defensive action during this financial crisis. From the perspective of individual banks in distress, it allows funds to be raised quickly and may be perceived as only having a limited impact on franchise value. Furthermore, although such hoarding may involve some reputational costs, these may be seen as less severe than those resulting from other options.

In phase 1, a bank which loses access to long-term funding hoards liquidity by shortening the maturity of its wholesale lending. But, at this stage, we now suppose that it stops rolling over or issuing new wholesale loans completely. The proceeds from the maturing assets are used to

¹⁵ Throughout the simulation, we also assume that all retail liabilities can be refinanced beyond the 5% outflow already captured between 25 and 35 points (ie $RL_{New} = RL_{Due}$).

repay maturing wholesale liabilities. The balance sheet shrinks as a result. For simplicity, this version of the model assumes that there is no direct impact on counterparties – we assume that those that are below 35 DZ points can replace the lost funding with new short-term wholesale liabilities in the interbank market, while those that are above 35 points will already have lost access to short-term wholesale funding markets in any case. It should, however, be noted that in practice, such liquidity hoarding behaviour is likely to have adverse systemic consequences by tightening overall funding conditions and causing a deterioration in confidence.

Option 3: Sale or repo of liquid assets. If the cash-flow constraint still cannot be met, we assume that banks look to sell liquid assets or use them to obtain repo funding to replace liabilities due. Sales or repo of highly liquid assets are usually possible even in the most severe of crises, but are generally not the first line of defence. Their use depletes buffers, making banks more susceptible to failure in subsequent periods, when other options are exhausted (see Matz (2007)). That said, selling or repoing liquid assets is likely to be preferable to selling illiquid assets, due to the real costs imposed by the latter course of action.

In the simulations, this step is implemented by assuming liquid assets are repoed so that the size of the balance sheet does not change. But banks' liquid assets are recorded as encumbered rather than unencumbered and remain so for the next quarter, meaning that they can no longer be counted as liquid assets in the danger zone measures and can no longer be used in a defensive way if the bank experiences further outflows in subsequent periods.

Option 4: Asset fire sales. Finally, banks may raise liquidity by selling assets in a fire sale. Fire sales are likely to be associated with a real financial loss and a corresponding hit to capital. They may also be easily observable in the market, potentially creating severe stigma problems. Given this, we assume that they represent the last course of action.

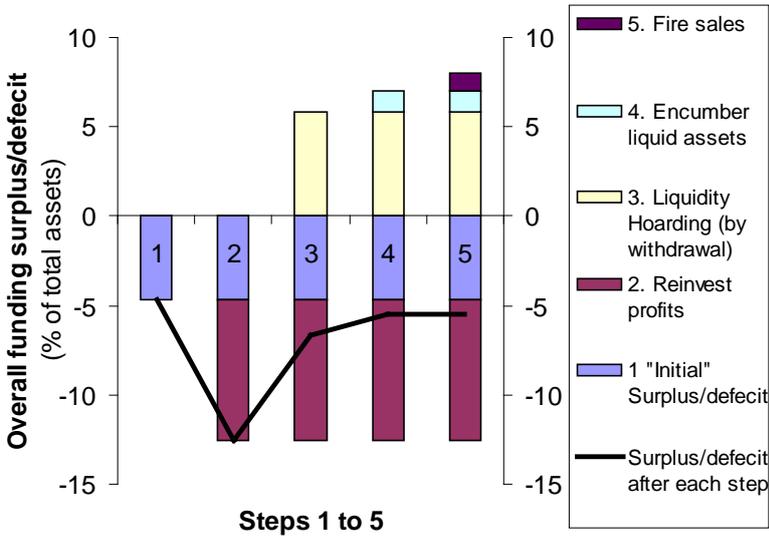
In principle, fire sales could apply across a wide range of asset classes, including in the trading book. But in the simulations, we restrict them to the bank's pool of available-for-sale (AFS) assets due to data limitations. If the bank does not have enough assets to sell to meet its flow constraint, then it fails. The restriction of fire sales to AFS assets makes individual bank failure more likely at this stage than may be the case in practice. But it also limits the extent of contagion to other banks.

The asset-side feedbacks associated with fire sales are modelled by assuming that other banks suffer temporary (intra-period) mark-to-market losses. This can increase their DZ score via the solvency indicator. In extreme circumstances, these banks may then also suffer funding liquidity crises. The pricing equations used to determine mark-to-market losses on different types of assets follow Aikman *et al* (2009) – the key difference with that approach is that fire sales and associated contagion occur *before* rather than upon bank failure.

4.2.2 Crisis funding, a graphical illustration

Figure 7 illustrates the above mechanisms with a simulation representing an outcome for one bank. Its cash-flow constraint is estimated using the RAMSI balance sheet data. Following a particular shock to fundamentals, the bank does not initially meet the flow constraint once it has been excluded from short and long-term funding markets. In the example, the bank has a shortfall of around 5% of total assets (the first bar in the chart). Hence the bank moves to Option 1. In the simulation example, the bank is not able to ameliorate its funding position from profits since it makes losses, which actually imply that it is further from meeting its flow constraint. The solid line in Chart 3 illustrates that the bank gets closer to meeting its flow constraint by withdrawing all maturing wholesale assets and using them to pay off liabilities due (Option 2); by encumbering its liquid assets (Option 3) and by selling illiquid assets in a fire sale (Option 4). But in this example, the combined effect of these actions is insufficient for the bank to meet its flow constraint and the bank fails.

Figure 7: Steps in flow constraint when wholesale funding withdrawn



4.3 Phase 3: Systemic impact of a bank's failure

If, after exhausting all potential options, a bank cannot meet its flow constraint, it is assumed to default. When a bank defaults, counterparty credit losses incurred by other banks are determined using a network model. This model operates on RAMSI's interbank matrix and is cleared using the Eisenberg and Noe (2001) algorithm. This returns counterparty credit losses for each institution.

Both fire sales and network feedbacks affect other banks' danger zone points scores by weakening their solvency position. If any of the banks reach 25 points as a result, then they suffer snowballing and start to hoard liquidity by shortening maturities, and this affects balance sheets in the next quarter as outlined under Phase 1. If the score of any bank crosses 35 points, then that bank enters Phase 2, in which case their defensive actions or failure may affect other banks. This process is continued in a loop until the system clears.

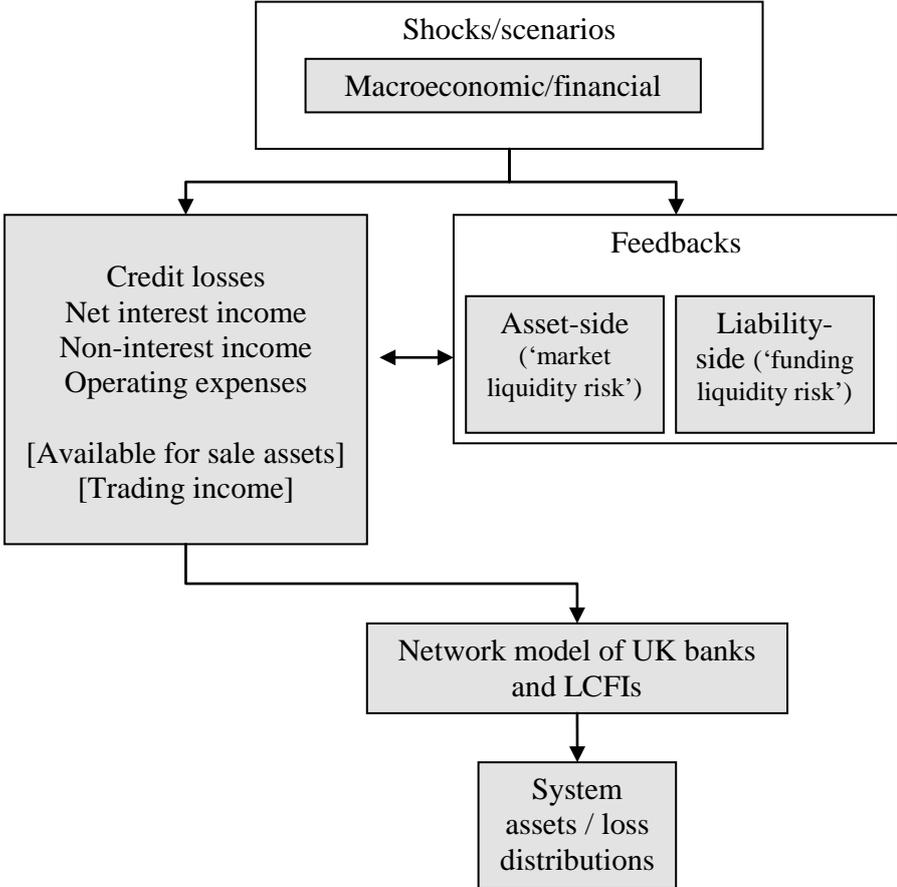
4.4 Summary of systemic feedback effects

To summarise, we can see how the framework captures all of the feedback effects depicted in Figure 1. Confidence contagion is modelled directly within the danger zone scoring system, while liquidity hoarding by shortening maturities is an endogenous response to a weak danger zone score which can, in turn, worsen other banks' danger zone scores. Pre-default fire sales can occur as a bank tries to meet its cash-flow constraint when it is completely shut out of funding markets, and counterparty credit risk crystallises upon default.

5 Shocks to fundamentals and liquidity risk: simulations in RAMSI

So far we have analysed liquidity risk and associated systemic feedbacks in an isolated fashion. To illustrate the impact of introducing liquidity risk and systemic feedbacks on overall system risk, measured here by the system-wide asset and loss distribution, we now integrate these mechanisms into the RAMSI stress-testing model which simulates banks' profitability from fundamentals. Figure 8 provides a high-level overview of RAMSI. We only provide a very brief discussion here – for further details, see Aikman *et al* (2009).

Figure 8: RAMSI framework



A key input into RAMSI are future paths of macroeconomic and financial variables. In the following experiments, these have been generated by a large-scale Bayesian VAR (BVAR). This is the only source of shocks, thereby preserving a one-for-one mapping from macroeconomic variables to default risk (as well as liquidity risk). The credit risk model treats aggregate default probabilities (PDs) and loss given default (LGD) as a function of the macroeconomic and financial variables from the BVAR. For most of the loan book, interest income is modelled endogenously. Banks price their loans to households and corporates on the basis of the prevailing yield curve and the perceived riskiness of their debtors: an increase in actual or expected credit risk translates into a higher cost of borrowing. For other parts of the balance sheet, including all of the liability side, spreads are calibrated based on market rates and other data. On certain liabilities, spreads also depend on the credit rating of the bank in question which is, in turn, endogenous to its fundamentals. RAMSI also includes simple models for non-trading income and operating expenses but, for simplicity, the version used in this paper assumes that trading income is fixed and excludes portfolio gains and losses on AFS assets. Net

profits are then computed as the sum of all sources of income, net of expenses, credit losses and, when profitable, taxes and dividends.

At this point, we have all the information we need to assess the danger zone score – for example, the projected profit and loss for each bank drives its solvency score and balance sheet characteristics its liquidity scores. We then simulate the sequence of events described in Section 4. In the absence of bank failures, or after the feedback loop has completed, we update the balance sheets of profitable surviving banks using a rule of thumb for reinvestment behaviour. Banks are assumed to target pre-specified capital ratios, and invest in assets and increase liabilities in proportion to their shares on their initial balance sheet, unless the bank faces high liquidity pressures and diverts some or all of its reinvestment funds to meet liquidity needs (Step 2 in Phase 2).

For the simulations, we use data up to 2007 Q4 (so that all balance sheets are on the basis of end-2007 data) and draw 500 realisations on a three-year forecast horizon stretching to the end of 2010. The BVAR is the only source of exogenous randomness in the stochastic simulations; each realisation is thus driven by a sequence of macroeconomic shocks drawn from a multivariate normal distribution.¹⁶ The results are purely intended to be illustrative rather than being the authors' view of the likely impact on the banks in question.

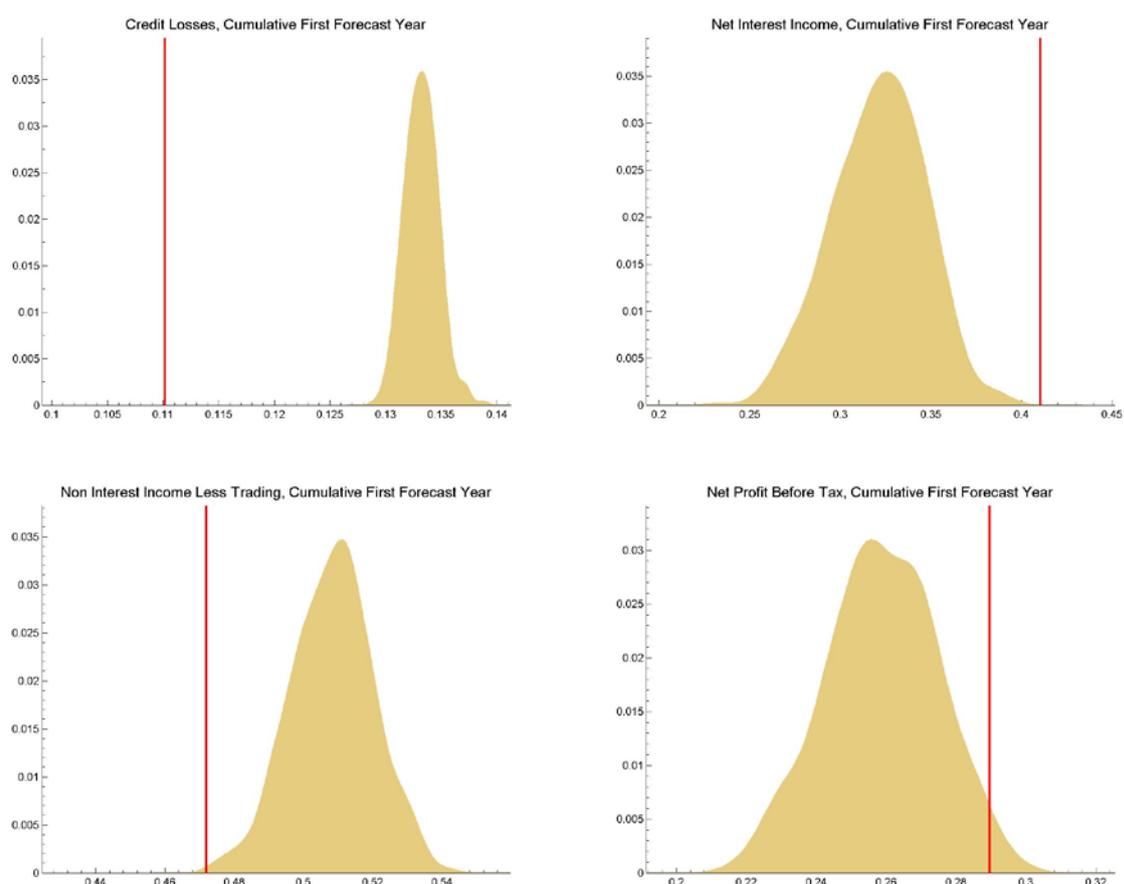
Figure 9 shows the simulated distributions of some key profit and loss items when systemic liquidity feedbacks are not included. For each variable, we calculate aggregate cumulative figures for the first year by adding over banks and quarters, and normalise by aggregate 2007 ('beginning of period') capital. The vertical line represents the corresponding figures from the 2007 published accounts, normalised by 2006 capital levels.

The top left-hand panel shows that credit risk is projected to increase in 2008, reflecting a worsening of the macroeconomic outlook. Net interest income is projected to be weaker than in 2007, reflecting higher funding costs and contractual frictions that prevent banks from instantaneously passing on these costs to their borrowers. The variance of net interest income may be unrealistically high as the version of the model used does not incorporate hedging of

¹⁶ In other words, we draw 500 realisations of the macroeconomic risk factors in the first quarter. In subsequent periods, we draw a single set of macroeconomic risk factors for each of the 500 draws.

interest rate risk.¹⁷ Non-interest income (bottom left-hand panel) remains high, with a median projection above the reported 2007 level; this variable is procyclical but adjusts relatively slowly to macroeconomic changes. The net impact on banks' profitability is summarised in the net profit chart (bottom right-hand panel). As can be seen, profits were projected to be weaker than in 2007.

Figure 9: Simulated distributions for profit and loss items: no liquidity effects



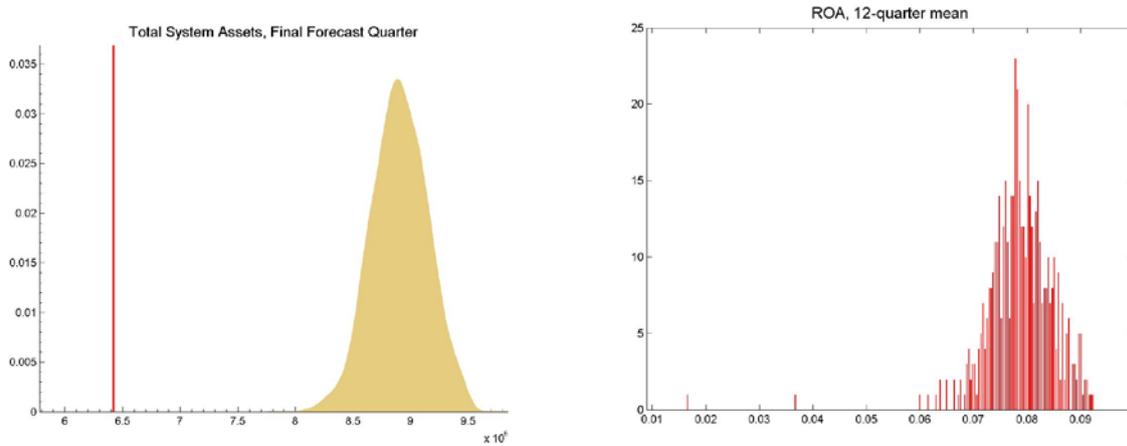
Note: In per cent of aggregate 2007 capital. Red vertical line represents the corresponding figures from the 2007 published accounts, normalised by 2006 capital levels.

Figure 10 shows the distribution of total assets in the last quarter of the simulation and the average *quarterly* aggregate return on assets (RoA) over the whole three-year horizon with funding liquidity risk and systemic liquidity feedbacks excluded from the model. This implies that institutions can only default if they become insolvent because their capital falls below the regulatory minimum. It also implies that there is no contagion. As can be seen, the RoA chart has negative skew and some observations in the extreme tail. The negative skew reflects cases

¹⁷ Banks can be penalised under Pillar 2 of Basel II for not hedging interest rate risk in their banking book.

where one institution defaults for pure solvency reasons; the extreme observations reflect cases where more than one institution defaults for pure solvency reasons.

Figure 10: Total system assets – final quarter (no liquidity effects)



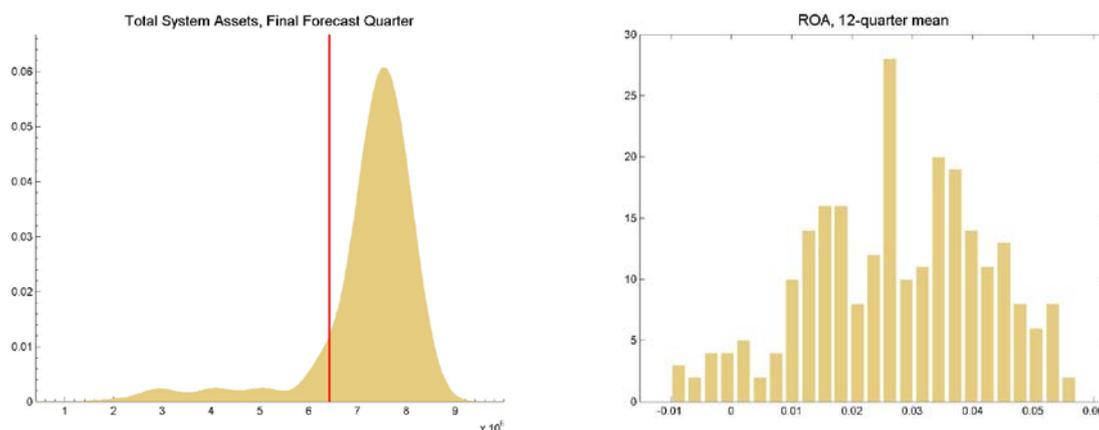
Note: Red vertical line represents total system assets from the 2007 published accounts. RoA on a quarterly basis, in per cent.

Figure 11 presents the results incorporating funding liquidity risk and systemic liquidity feedbacks. It is immediately evident that the final projected outcomes are considerably worse. This is partly driven by a higher incidence of failure due to the possibility that an institution may default because it is unable to meet its cash-flow constraint. But the charts also highlight the role of contagion due to the systemic feedbacks. The distributions have a long left-hand tail, which is a direct consequence of the feedbacks, which can in some cases cause several institutions to default. This fat tail emerges in spite of the Gaussian nature of the underlying shocks to macroeconomic fundamentals. These illustrative results point towards the importance of considering funding liquidity risk and systemic feedbacks in quantitative models of systemic risk.

By adding on various components individually, the model can be used to identify how different mechanisms contribute to the profile of systemic risk. For example, the introduction of the danger zone framework permits failure even if a bank’s capital does not fall below the regulatory minimum and thus worsens the loss distribution. Confidence contagion, counterparty defaults, liquidity hoarding and asset fire sales all amplify distress in the tail but allowing for hoarding and fire sales increases the survival chances of individual banks. It is possible to dissect the tail to identify the particular contributions of these different feedbacks – for an

exercise in this spirit which tries to disentangle the effects of (post-failure) fire sales and counterparty default, see Alessandri *et al* (2009).

Figure 11: Total system assets – final quarter (with liquidity effects)



Note: Red vertical line represents total system assets from the 2007 published accounts.

6 Conclusions and future work

The main contribution of this paper has been to discuss and model how systemic risk may escalate and contagion may spread to other institutions as a bank's funding conditions deteriorate, irrespective of whether the bank ultimately survives or fails. Quantitative simulations illustrate how liquidity feedbacks can amplify other sources of risk.

Our model captures several channels of systemic funding liquidity crises. By using simple indicators and analysing bank-specific cash-flow constraints, we assess the onset and evolution of liquidity stress in various phases. As distressed banks lose access to longer-term funding markets, their liabilities snowball into shorter maturities, further increasing funding liquidity risk. Stressed banks take defensive actions in an attempt to stave off a liquidity crisis, which may, in turn, have a systemic impact. In particular, liquidity hoarding shortens the wholesale liability structure of other banks; while asset fire sales may affect the value of other banks' assets, which, in turn, can affect their funding conditions. Beyond this, spillovers between banks may occur due to confidence contagion or via default cascades in the interbank network.

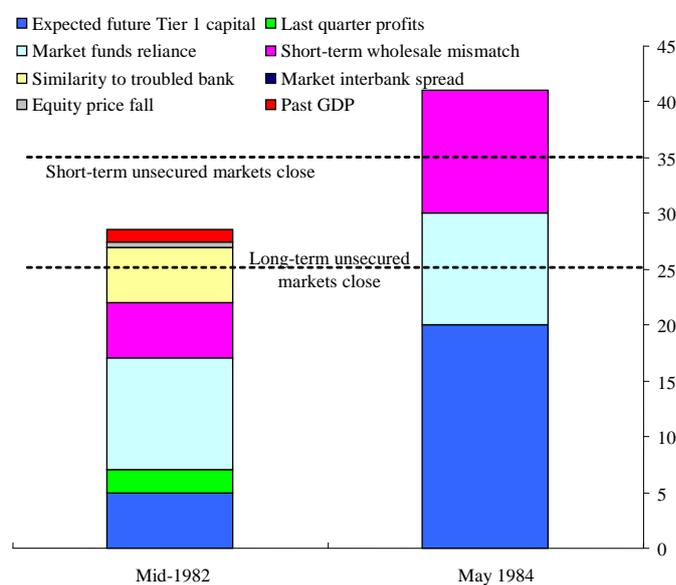
The model could be extended in several ways. For example, rather than generating all shocks from a macroeconomic model, it would be interesting to allow for direct shocks to banks' cash-

flow constraints, perhaps linked to some underlying aggregate liquidity shock. It would also be helpful to capture the evolution of systemic liquidity crises on a more granular basis incorporating more developed behavioural assumptions. With sufficient data, more detailed analysis of liquidity feedbacks over a time period of less than three months should be possible in this framework. But further extensions are likely to be more challenging as modelling the optimal endogenous response to shocks is a highly complex problem as banks would need to optimise over different asset classes and maturity structures taking account of shocks to fundamentals and behavioural reactions of all other market participants. Finally, it would be interesting to use the framework to explore the role that macroprudential policies such as time-varying liquidity buffers (see Bank of England (2011)) might be able to play in containing systemic risk.

Appendix 1: An example of a danger zone calibration using Continental Illinois

Case studies indicate that the danger zones approach performs relatively well, especially in terms of capturing the ranking of institutions under most stress. We have considered case studies beyond the current crisis. An example is the case of Continental Illinois, which, at least in terms of funding liquidity pressure, can be divided into two periods: the closure of longer-term domestic funding markets to it in July 1982 and the global run in May 1984. Figure 12 scores Continental Illinois in each of these periods.

Figure 12: Applying danger zones to the failure of Continental Illinois



Reflecting its high dependence on wholesale funding, Continental scores highly on the market-funds reliance indicator. But solvency concerns also played a crucial role for Continental. In particular, the July 1982 run may be identified with mild concerns over future solvency stemming from anticipated losses on risky speculative loans to the energy sector. Many of these loans had been originated by Penn Square, a much smaller bank which failed earlier that month. Aside from rising solvency concerns, Continental scores points following Penn Square's failure both because of its similarity and because of a significant unanticipated loss due to a direct exposure. Overall, Continental scores enough points for the first danger zone threshold to be crossed.

After 1982, Continental had greatly reduced access to long-term funding markets. Therefore, increased reliance on short-term funding served to increase Continental's DZ score over the next

couple of years (the snowballing effect). But the final trigger for the second run is the fallout from the Latin American debt crisis – this substantially raised future solvency concerns during the first part of 1984 so that by May, Continental exceeds the second danger zone threshold and ultimately fails.

References

- Acharya, V and Merrouche, O (2012)**, 'Precautionary hoarding of liquidity and inter-bank markets: evidence from the sub-prime crisis', *Review of Finance*, forthcoming.
- Acharya, V and Skeie, D (2011)**, 'A model of liquidity hoarding and term premia in inter-bank markets', *Journal of Monetary Economics*, Vol. 58(5), pages 436-47.
- Acharya, V and Yorulmazer, T (2008)**, 'Information contagion and bank herding', *Journal of Money, Credit and Banking*, Vol. 40, pages 215-31.
- Adrian, T and Shin, H S (2010)**, 'Liquidity and leverage', *Journal of Financial Intermediation*, Vol. 19(3), pages 418-37.
- Aikman, D Alessandri, P, Eklund, B, Gai, P, Kapadia, S, Martin, E, Mora, N, Sterne, G and Willison, M (2009)**, 'Funding liquidity risk in a quantitative model of systemic stability', *Bank of England Working Paper No. 372*.
- Alessandri, P, Gai, P, Kapadia, S, Mora, N and Puhr, C (2009)**, 'Towards a framework for quantifying systemic stability', *International Journal of Central Banking*, Vol. 5(3), pages 47-81.
- Allen, F and Gale, D (2000)**, 'Financial contagion', *Journal of Political Economy*, Vol. 108(1), pages 1-33.
- Angelini, P, Nobili, A and Picillo, C (2011)**, 'The interbank market after August 2007: what has changed, and why?', *Journal of Money, Credit and Banking*, Vol. 43(5), pages 923-58.
- Bagehot, W (1873)**, *Lombard Street: a description of the money market*, London: HS King.
- Bank of England (2007)**, 'An indicative decomposition of Libor spreads', *Bank of England Quarterly Bulletin*, Vol. 47, No. 4, pages 498-99.
- Bank of England (2011)**, *Instruments of macroprudential policy*. Discussion paper, December.
- Basel Committee on Banking Supervision (2010)**, *Basel III: International framework for liquidity risk measurement, standards and monitoring*, Basel, December.
- BIS (2006)**, *The management of liquidity risk in financial groups*, The Joint Forum of the Basel Committee on Banking Supervision, May.
- Borio, C and Drehmann, M (2009)**, 'Towards an operational framework for financial stability: 'fuzzy' measurement and its consequences', *BIS Working Paper No. 284*.
- Brunnermeier, M K and Pedersen, L H (2009)**, 'Market liquidity and funding liquidity', *Review of Financial Studies*, Vol. 22(6), pages 2,201-38.
- Caballero, R J and Krishnamurthy, A (2008)**, 'Collective risk management in a flight to quality episode', *Journal of Finance*, Vol. 63, pages 2,195-236.
- Campello, M, Giambona, E, Graham, J R and Harvey, C R (2010)**, 'Liquidity management and corporate investment during a financial crisis', *NBER Working Paper No. 16309*.

Chari, V and Jagannathan, R (1988), ‘Banking panics, information, and rational expectations equilibrium’, *Journal of Finance*, Vol. 43(3), pages 749-61.

Chen, Y (1999), ‘Banking panics: the role of the first-come, first-served rule and information externalities’, *Journal of Political Economy*, Vol. 107(5), pages 946-68.

Christensen, J, Lopez, J and Rudebusch, G (2009), ‘Do central bank liquidity facilities affect interbank lending rates?’ *Federal Reserve Bank of San Francisco Working Paper No. 2009-13*.

Cifuentes, R, Ferrucci, G and Shin, H S (2005), ‘Liquidity risk and contagion’, *Bank of England Working Paper No. 264*.

Dawes, R M (1979), ‘The robust beauty of improper linear models in decision making’, *American Psychologist*, Vol. 34, pages 571-82.

Dawes, R M and Corrigan, B (1974), ‘Linear models in decision making’, *Psychological Bulletin*, Vol. 81, pages 95-106.

Diamond, D and Dybvig, P (1983), ‘Bank runs, deposit insurance, and liquidity’, *Journal of Political Economy*, Vol. 91, pages 401-19.

Drehmann, M (2002), ‘Will an optimal deposit insurance always increase financial stability?’, *Bonn Econ Discussion Paper No. 28/2002*.

Drehmann, M and Nikolaou, K (2012), ‘Funding liquidity risk: definition and measurement’, *Journal of Banking and Finance*, forthcoming.

ECB (2002), ‘Developments in banks’ liquidity profile and management’, May.

ECB (2008), *Euro Money Market Survey*, September.

Eisenberg, L and Noe, T (2001), ‘Systemic risk in financial systems’, *Management Science*, Vol. 47(2), pages 236-49.

Elsinger, H, Lehar, A and Summer, M (2006), ‘Risk assessment for banking systems’, *Management Science*, Vol. 52, pages 1,301-41.

Fisher, I (1933), ‘The debt-deflation theory of great depressions’, *Econometrica*, Vol. 1(4), pages 337-57.

Freixas, X, Parigi, B M and Rochet, J C (2000), ‘Systemic risk, interbank relations, and liquidity provision by the central bank’, *Journal of Money, Credit, and Banking*, Vol. 32(3), pages 611-38.

Furfine, C (2002), ‘The interbank market during a crisis’, *European Economic Review*, Vol. 46, pages 809-20.

Gai, P, Haldane, A and Kapadia, S (2011), ‘Complexity, concentration and contagion’, *Journal of Monetary Economics*, Vol. 58(5), pages 453-70.

Gai, P and Kapadia, S (2010), ‘Contagion in financial networks’, *Proceedings of the Royal Society A*, Vol. 466, No. 2120, pages 2,401-23.

- Gatev, E, Schuermann, T and Strahan, P E (2006)**, ‘Managing bank liquidity risk: how deposit-loan synergies vary with market conditions’, *Review of Financial Studies*, Vol. 22(3), pages 995-1,020.
- Gatev, E and Strahan, P E (2006)**, ‘Banks’ advantage in hedging liquidity risk: theory and evidence from the commercial paper market’, *Journal of Finance*, Vol. 61(2), pages 867-92.
- Geanakoplos, J (2010)**, ‘Solving the present crisis and managing the leverage cycle’, *Economic Policy Review*, Federal Reserve Bank of New York, August, pages 101-31.
- Gigerenzer, G and Brighton, H (2009)**, ‘Homo heuristicus: why biased minds make better inferences’, *Topics in Cognitive Science*, Vol. 1(1), pages 107-43.
- Goldstein, I and Pauzner, A (2005)**, ‘Demand-deposit contracts and the probability of bank runs’, *Journal of Finance*, Vol. 60(3), pages 1,293-327.
- Gorton, G and Metrick, A (2010)**, ‘Haircuts’, *Federal Reserve Bank of St. Louis Review*, November/December, Vol. 92(6), pages 507-20.
- Ha, Y and Hodgetts, B (2011)**, *Macro-prudential instruments for New Zealand: a preliminary assessment*, Reserve Bank of New Zealand.
- Heider, F Hoerova, M and Holthausen, C (2009)**, ‘Liquidity hoarding and interbank market spreads: the role of counterparty risk’ *European Central Bank Working Paper No.1126*.
- Holmström, B and Tirole, J (1998)**, ‘Private and public supply of liquidity’, *Journal of Political Economy*, Vol. 106, pages 1-40.
- Huang, R (2009)**, ‘How committed are bank lines of credit? Experiences in the subprime mortgage crisis’, *Federal Reserve Bank of Philadelphia Working Paper No. 10-25*.
- Institute of International Finance (2007)**, ‘Principles of liquidity risk management’, *IIF*, May.
- Ivashina, V and Scharfstein, D S (2010)**, ‘Bank lending during the financial crisis of 2008’, *Journal of Financial Economics*, Vol. 97(3) pages 319-38.
- Matz, L (2007)**, ‘Contingency planning’, in Matz, L and Neu, P (eds), *Liquidity risk: measurement and management*, Wiley Finance.
- Matz, L and Neu, P (2007)**, *Liquidity risk: measurement and management*, Wiley Finance.
- McGuire, P and von Peter, G (2009)**, ‘The US dollar shortage in global banking’, *BIS Quarterly Review*, March, pages 47-63.
- Nakaso, H (2001)**, ‘The financial crisis in Japan during the 1990s: how the Bank of Japan responded and the lessons learnt’, *BIS Papers, No 6*, available at www.bis.org/publ/bppdf/bispap06.pdf?noframes=1.
- OeNB (2006)**, ‘Systemic risk monitor: risk assessment and stress testing for the Austrian banking system’, Oesterreichische Nationalbank, *mimeo*.
- Pennacchi, G (2006)**, ‘Deposit insurance, bank regulation and financial system risk’, *Journal of Monetary Economics*, Vol. 53, pages 1-30.

Rochet, J-C and Vives, X (2004), ‘Coordination failures and the lender of last resort: was Bagehot right after all?’, *Journal of the European Economic Association*, Vol. 2(6), pages 1,116-47.

Shim, I and von Peter, G (2007), ‘Distress selling and asset market feedback: a survey’, *BIS Working Paper No. 229*.

Upper, C (2011), ‘Simulation methods to assess the danger of contagion in interbank markets’, *Journal of Financial Stability*, Vol. 7(3), pages 111-25.

van den End, J W (2008), ‘Liquidity stress-tester: a macro model for stress-testing banks’ liquidity risk’, *DNB Working Paper No. 175*.

Wells, S (2004), ‘Financial interlinkages in the United Kingdom’s interbank market and the risk of contagion’, *Bank of England Working Paper No. 230*.