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**FUNDING LIQUIDITY RISK IN A QUANTITATIVE
MODEL OF SYSTEMIC STABILITY**

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FINANCIAMIENTO DEL RIESGO DE LIQUIDEZ EN UN MODELO CUANTITATIVO DE ESTABILIDAD SISTÉMICA

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Resumen

Este documento muestra cómo la introducción de retroalimentación por el lado del pasivo afecta las propiedades de un modelo de riesgo sistémico. La versión preliminar del modelo, aún en curso, se basa en balances contables detallados de bancos del Reino Unido y abarca el riesgo de crédito global, el riesgo asociado al ingreso por intereses y otros, interacciones de red y efectos de retroalimentación. Se introduce el riesgo de liquidez de financiamiento permitiendo rebajas en la clasificación de riesgo e incorporando un marco simple en el que variables de solvencia, perfil de financiamiento y confianza pueden desencadenar el cierre total de los mercados crediticios. En la presentación de los resultados, nos centramos en la forma en que las autoridades podrían utilizar el modelo con referencia tanto a la distribución agregada como al análisis de un escenario en el que una pérdida grande en algunos bancos puede ser magnificada por retroalimentación de pasivos, generando una inestabilidad sistémica.

All authors are Bank of England except Prasanna Gai (Australian National University). The corresponding author is: sujit.kapadia@bankofengland.co.uk. The RAMSI project represents a major investment of Bank of England resources and we are grateful to many people both inside and outside the Bank of England for their contributions. In particular the OeNB have been very generous in providing guidance and significant analytical contributions. The analysis in this paper has benefited from encouragement and contributions from Viral Acharya, Niki Anderson, Marnoch Aston, Richard Barwell, Emily Beau, Michael Boss, John Carmichael, Ethan Cohen-Cole, Geoff Coppins, Sebastiano Daros, Paul Doran, Mathias Drehmann, John Elliott, Helmut Elsinger, David England, Phil Evans, Antonella Foglia, Celine Gauthier, Brenda Gonzalez-Hermosillo, Charles Goodhart, Andy Haldane, Simon Hall, Jen Han, Florence Hubert, Gregor Irwin, Nigel Jenkinson, Rob Johnson, Charles Kahn, Sandhya Kavar, Will Kerry, Jack McKeown, Alex McNeil, Andrew Mason, Colin Miles, Pierre Monnin, Haroon Mumtaz, Emma Murphy, Gareth Murphy, Rain Newton-Smith, Joseph Noss, Spyros Pagratis, Andrew Patton, Adrian Penalver, Silvia Pezzini, Laura Piscitelli, Claus Puh, Victoria Saporta, Til Schuermann, Miguel Segoviano, Jack Selody, Hyun Shin, Steffen Sorensen, George Speight, Marco Stringa, Martin Summer, Ryland Thomas, Dimitri Tsomocos, Iman van Lelyveld, Nick Vause, Lewis Webber, Simon Wells and Peter Westaway. Harry Goodacre, Tony Lee and Emma Mattingley provided excellent research assistance. We would also like to thank seminar participants at the Bank of England, the Financial Services Authority, the European Central Bank, the Bundesbank, the 12th Annual Conference of the Central Bank of Chile on 'Financial Stability, Monetary Policy and Central Banking' (Santiago, 6-7 November 2008), the Bundesbank / Technical University of Dresden Conference on 'Measuring and Forecasting Financial Stability' (Dresden, 15-16 January 2009), the 11th Annual Bowles Symposium on 'Liquidity, Valuation, and Financial Crisis', Atlanta, 12 February 2009, and the MMF, Barrie and Hibbert Conference on 'Challenges for Risk Management' at CASS on 27 February 2009 for helpful comments and suggestions.

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Abstract

We demonstrate how the introduction of liability-side feedbacks affects the properties of a quantitative model of systemic risk. The preliminary version of the model, which is still in its development phase, is based on detailed balance sheets for UK banks and encompasses macro-credit risk, interest and non-interest income risk, network interactions, and feedback effects. Funding liquidity risk is introduced by allowing for rating downgrades and incorporating a simple framework in which concerns over solvency, funding profile and confidence may trigger the outright closure of funding markets. In presenting results, we focus on how policymakers could use the model with reference to both aggregate distributions and analysis of a scenario in which large losses at some banks can be exacerbated by liability-side feedbacks, leading to system-wide instability.

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1 Introduction

The global financial crisis of 2007-2009 has illustrated the importance of including funding liquidity feedbacks within any model systemic risk. This paper illustrates how we have incorporated such channels into a Risk Assessment Model for Systemic Institutions (RAMSI), and outlines the Bank of England's plans to use RAMSI to sharpen its assessment of institution-specific and system-wide vulnerabilities. The model focuses on the health of core banks in the UK financial system. For these banks the model provides a coherent quantitative framework for assessing how shocks transmit through balance sheets, allowing for macro-credit risk, interest and non-interest income risk, network interactions, and feedback effects arising on both the asset and liability side of the balance sheet. Systemic risks stem from the connectivity of bank balance sheets via interbank exposures (counterparty risk); the interaction between balance sheets and asset prices (fire sale effects); and confidence effects that may affect funding conditions.

Central banks and regulators are increasingly seeking to use formal models to support their financial stability work, and various approaches have emerged in recent years (Jenkinson, 2007). Senior policymakers at the Bank of England have for some time expressed a desire for an integrated approach to assessing systemic risk (Gieve, 2007). Gai and Haldane (2007) provide motivation for a new approach which emphasises the importance of distinguishing probability and impact when conducting risk assessment work, and the Bank of England's preliminary implementation of such a framework is discussed by Haldane et al (2007).

RAMSI aims to deliver a suite of models that should support a substantial enhancement in the Bank of England's ability to conduct risk assessment in a rigorous and consistent quantitative framework, thus helping to sharpen the analysis of key vulnerabilities and to improve the Bank's capability to influence and strengthen the management of these risks. Internally, RAMSI will help discussions of key risks on a bank-by-bank and system-wide basis, and will be of help in examining the impact of various policy measures. Externally, the outputs from the suite of models will help in communicating risk assessment messages to risk managers in the financial sector, thereby helping shape their attitudes to risk.

The analytical foundations of RAMSI draw in particular on two strands of literature. First, it employs elements of the traditional stress testing literature, which tend to focus on credit risk on a

bank's balance sheet (see Foglia, 2009 and Borio and Drehmann, 2009). Second, it draws on recent theoretical work on modelling systemic financial crises. Allen and Gale (2000) explore the spread of contagion in a banking network and Cifuentes et al (2005) examine how default across the network is amplified by asset price effects. Gai and Kapadia (2008, 2009) examine the nonlinearities implied by these externalities and suggest that financial innovation may have increased the severity of crises.¹

The modular approach involves feeding shocks and scenarios from a macro-model through several distinct balance sheet-based models that describe how risk profiles evolve throughout banks' business operations. It is influenced by the framework developed by the Oesterreichische Nationalbank (OeNB, 2006) for the Austrian banking system (see also Elsinger et al, 2006a), which integrates balance-sheet based models of credit and market risk with a network model to evaluate the probability of bank default. In presenting a prototype version of RAMSI, Alessandri et al (2009) extended and developed the single-period Austrian model in a number of dimensions. In a multi-period setting, they incorporated net interest income and feedback effects associated with asset fire sales following bank default.

This paper extends the RAMSI prototype in several ways, including the use of richer balance sheets, a more powerful macro-model, better modelling of credit risk, and a model of non-interest (non-trading) income. But the main innovation that this paper focuses on relates to the role of liability-side feedbacks. We develop a two-pronged framework for modelling funding liquidity risk. In the first stage, we apply an empirical model to project individual bank ratings, and use the results to calibrate how funding costs may rise as the position of a bank worsens. In the second stage, we calibrate the onset of funding crises and outright closure of funding markets to particular institutions based on a series of indicators. To inform our analysis, we draw on theoretical models, information from banks' own liquidity policies and evidence from past episodes of funding stress as well as the recent experience, including the failure of Northern Rock.

¹ This result is reinforced by Gai et al (2008) who demonstrate how financial innovation and macroeconomic stability may have intensified the robust-yet-fragile nature of the banking system.

RAMSI's framework is particularly attractive to central banks because of its 'story-telling' capacity. Alternative approaches to the analysis of systemic risk offer particular strengths, either in terms of micro-foundations,² or in terms of consistency with market-based pricing of risk.³ Although RAMSI's framework relies on reduced-form estimation and behavioural 'rules of thumb', it offers a flexible and operational means of capturing a wide range of risks and transmission channels, and allows for a more articulated analysis and interpretation of the outputs of stress testing exercises.

The structure of the paper is as follows. Section 2 describes the current components of RAMSI and explains how they fit together. Section 3 discusses the aggregate distributions obtained from stochastic simulation and conducts a detailed analysis of a particular realisation in which funding liquidity feedbacks contribute to system-wide stress. Section 4 discusses how RAMSI will improve the quality of risk assessment work, and Section 5 concludes.

2 The Modelling Framework

2.1 Overview, Sequencing and Balance Sheets

Figure 1 illustrates the modular structure of RAMSI and the mapping from shocks to systemic risk. The transmission dynamics hinge crucially on two factors – the nature and scale of shocks and the structural characteristics of the financial system. In such an environment, balance sheet interdependencies and asset and liability-side feedbacks make for complex, non-linear behaviour. RAMSI produces asset distributions for individual banks and for the aggregate banking system by linking together the shaded modules presented in Figure 1. The unshaded module – feedbacks to the macro-economy – is mentioned briefly in the conclusion but left for future work. In what follows, we discuss the overall modelling strategy in RAMSI before briefly discussing each of its components.

² For example, Goodhart et al (2006) provide a general equilibrium framework, but the model is stylised and difficult to operationalise.

³ The 'asset pricing' approach extracts risk from observed security prices. This approach can be applied to individual banks (Segoviano and Padilla, 2006; Elsinger et al, 2006b; Frisell et al, 2007) or to sectors of the economy (Gray et al, 2007). These models provide timely updates to banks' risk profiles, albeit on the basis of strong assumptions on market completeness and efficiency. Furthermore, market prices may embed the possibility of official support, so the asset pricing approach may be unable to identify the extent to which intervention helps to mitigate systemic risks (Birchler and Facchinetti, 2007).

At the core of RAMSI are detailed end-2007 balance sheets of the largest UK banks (ten at end-2007).⁴ These link the modules to the structure of individual UK banks. The balance sheets are highly disaggregated, with approximately 650 balance sheet entries (including 400 asset classes and 250 liability classes). Each of the asset and liability classes are further disaggregated into five maturity buckets and six repricing buckets.⁵ Data are mainly extracted from regulatory accounts but are supplemented from regulatory returns. This modelling of individual bank balance sheets supports an analytically rich model and allows us to examine, in detail, the likely sources of profits and losses on a disaggregated and aggregated basis. Not all of the balance sheet entries are available so we use rules of thumb based on other information or extrapolations on the basis of our knowledge of similarities between banks to fill in the data gaps. Much of the granularity arises from decomposition of the trading book and available for sale (AFS) assets. Since the focus of this paper is on the role of funding liquidity risk, we do not model these exposures here. However, this part of the balance sheet has played an important role in the ongoing financial crisis, and we believe that no systemic risk model can credibly ignore it. Trading book and AFS models are currently under development and will be introduced in the next version of RAMSI.

The model is run over a three year horizon, sufficient time for some adverse shocks to be reflected in credit losses (Bunn et al, 2005; DNB, 2006), and consistent with the horizon central banks often use when stress testing their financial systems (Hagen et al, 2005, Bank of England, 2007, and Sveriges Riksbank, 2007). The sequence of events is illustrated in Figure 2. Outcomes from a macroeconomic model determine a yield curve and probabilities of default and loss-given default on banks' credit exposures. For each combination of risk factors, we model the first-round effects on each bank, with distinct modules accounting for credit losses, net interest income, other income and operating expenses.

If the fundamentals of a bank deteriorate, its rating may be downgraded, increasing its future funding costs. In severe circumstances, funding conditions may deteriorate to such an extent that the bank is shut out from short-term funding markets. It then fails, triggering a feedback loop. Because of bankruptcy costs, a fraction of the failed bank's assets are lost, reducing the amount available to its creditors on the interbank network. Some of the banks' assets are sold at fire sale

⁴ 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.

⁵ We do not have six repricing buckets for each of the five maturity buckets.

prices, creating asset-side feedbacks that cause remaining banks to suffer temporary (intra-period) mark-to-market losses. Funding markets suffer 'confidence contagion' that render banks with similar characteristics to the failed bank more vulnerable to being shut out of funding markets. If a further bank fails after we account for the second round effects, then the loop repeats until the default cascade ends.

Figure 1: RAMSI framework

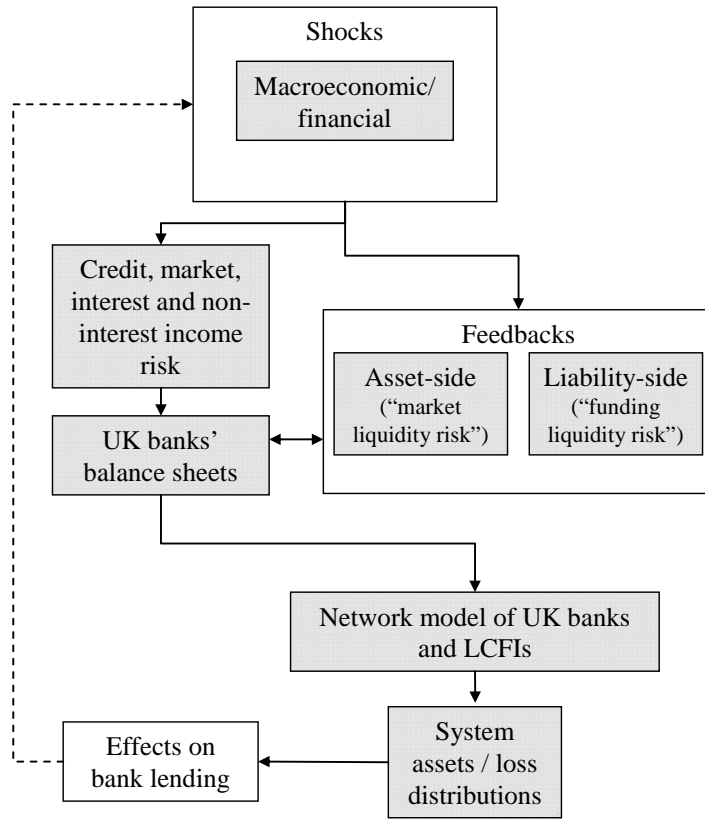
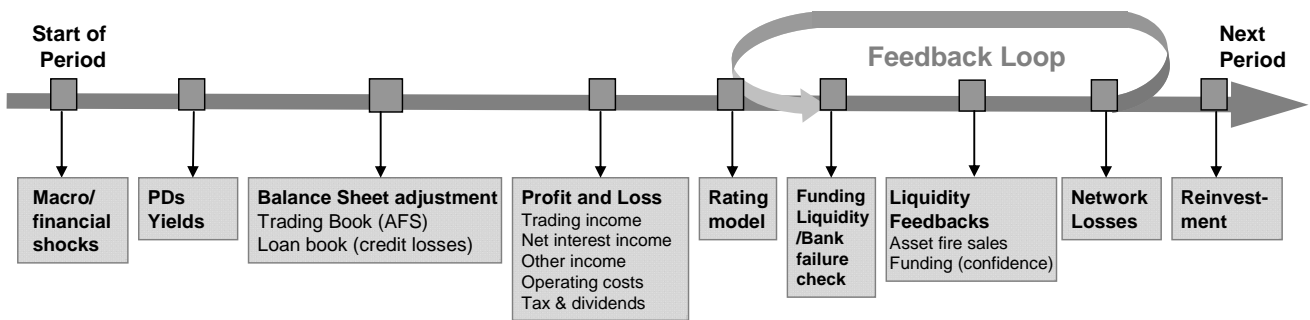


Figure 2: Model dynamics*



* The trading book and available for sale (AFS) assets are not included in this version of RAMSI.

In the absence of bank failures (or after the feedback loop has completed), we update the balance sheets of surviving banks using a rule of thumb for reinvestment behaviour. Banks target pre-

specified Tier 1 capital ratios, and invest in assets and increase liabilities in proportion to their shares on their initial balance sheet.

Throughout the paper, we assume that there is no regulatory or other policy intervention, aside from the interest rate response that is endogenous to the macroeconomic model. This is partly because modelling the policy reaction to extreme events is inherently difficult, especially given that there is no single, standard response to financial crises. The model therefore provides an assessment of how the financial system would fare without any policy response. This allows for judgements to be drawn on the potential benefits and costs of intervening.

2.2 *The Macroeconomic Model*

The link between the macro-economy and the various risks on banks' balance sheets is central to RAMSI. We use a large-scale Bayesian VAR (BVAR) to capture the evolution of macro and financial variables. The BVAR is the only source of shocks in RAMSI, thereby preserving a one-for-one mapping from macro-variables to default risk, which is useful for story-telling purposes.⁶

The BVAR is estimated on quarterly data over the sample period 1972Q2-2007Q4. The model includes 24 domestic and foreign (US and EU) variables (see Table 1) and has two lags. We use quarterly growth rates of all variables, barring those denoted with an asterisk. The resulting vector of time series variables to be modelled therefore contains a mixture of levels and growth rates (i.e. quarterly GDP growth, the level of the 3-month T-Bill rate etc). Our prior treats every variable in the system as a white noise process centred around a constant. This is a special case of the Minnesota prior popularised by Litterman (1986): essentially, we adapt the standard Minnesota prior to the case where all unit roots have been eliminated by data transformations.⁷

The BVAR performs well according to usual diagnostics. First, it has reasonable in-sample fit, capturing much of the variation over time in most series – the average R^2 across the 24 equations was 66 per cent. The equations for asset prices had the poorest fit: equities, sterling ERI, and particularly oil prices (R^2 of 12 per cent). Second, for the most part, the forecasts are reasonable:

⁶ It is of course possible to run stress scenarios in order to determine the impact of adjusting non-macro variables and model parameters.

⁷ In a Bayesian context, all parameters are treated as random variables and the data are used to estimate their probability distribution rather than to obtain point estimates. We abstract from model uncertainty and use the means of the estimated posterior parameter distributions.

most variables are projected to either regress back to their average historical growth rates, or to gradually converge on their sample means. Third, the model also produces reasonable impulse responses following shocks to UK GDP, UK 3-month interest rates, UK house prices and real oil prices.

Table 1: List of BVAR variables

UK	US
Real GDP	Real GDP
CPI inflation	CPI
£ERI	3-m T-Bill rate*
Real FTSE All Share	10-yr govt bond rate*
3-m T-Bill rate*	
3-yr govt bond rate*	EA
10-yr govt bond rate*	Real GDP
Unemployment*	CPI
Real house prices	3-m T-Bill rate*
Real comm. prop. prices	10-yr govt bond rate*
Income gearing*	
Corporate lending*	World
3-month LIBOR spread*	Real oil prices
10-yr corporate spread*	Real world equity prices

For simplicity, we approximate the yield curve by linearly interpolating the short and long-term interest rates implied by the BVAR (two for the United Kingdom and one each for the Euro Area and United States). This is the source of all risk-free rates used in the model. And, since the BVAR does not forecast the LIBOR spread particularly well, we currently assume that it evolves according to the path implied by forward spreads.

2.3 *First-round Impact on Banks*

2.3.1 *Credit Risk*

The credit risk module treats aggregate default probabilities (PDs) and loss given default (LGD) as a function of the macroeconomic and financial variables from the BVAR. Credit losses are derived as the product of the relevant aggregate PD times LGD times each bank's total exposure to the

sector,⁸ though we adjust the aggregate write-off rate for each bank to account for heterogeneity in the riskiness of banks' portfolios.⁹ We model credit losses arising from exposures to UK households (mortgages, credit card, and other unsecured borrowing), UK corporates, plus households and corporates in the US, EA and Rest of the World.¹⁰ For brevity, we only report results for UK mortgages and corporate loans.

Basing the model on Whitley et al (2004), we relate the PD on a representative pool of mortgages to the unemployment rate, the level of income gearing (i.e. interest payments relative to disposable income), and undrawn equity in housing stock (i.e. the residual proportion of housing wealth net of the stock of mortgage debt). Our dependent variable is the fraction of borrowers who are three months or more in arrears. We model arrears as these provide a forward-looking indicator of actual defaults. We estimate a transition rate based on the average historical relationship between these variables. The model is estimated on a sample running from the early 1980s, reflecting the structural change in retail credit markets following the removal of direct controls on bank lending in 1980 (the 'Corset'). The LGD on this pool is assumed to be driven by residential property prices.

Our preferred model of the corporate liquidations rate is driven by: real output growth, the real (ex post) cost of borrowing, commercial property prices and a measure of the cyclical variation in corporate debt (based on Vlieghe, 2001). The LGD on a corporate loan is assumed to depend on the value of commercial property prices.

The estimated coefficients in both equations are all signed according to our priors. Both models capture the broad movements in the data reasonably well, but there are clear areas for improvement. The mortgage arrears equation, for instance, only accounts for around half of the pick up in arrears in the early 1990s. And the performance of the corporate PD equation deteriorates from 2002 onwards.¹¹

⁸ That is, we model 'expected credit losses', and trace out variation in expected credit losses driven by macro fundamentals.

⁹ These adjustments are made on the basis of historical differences between write-off rates of individual banks and aggregate write-off rates. This implies that a relatively 'safer' bank continues to incur lower credit losses than the typical bank.

¹⁰ Data availability poses a major challenge. It would be desirable to capture sectoral concentrations and lumpiness in corporate exposures by modelling a finer breakdown of exposures (e.g. commercial property lending etc). Currently, our assumption is that portfolios are infinitely granular.

¹¹ Possible explanations include: the (until recent) prolonged stability of the macroeconomy; the cleansing effect of earlier recessions; legislative changes (the 2000 Insolvency Act and 2002 Enterprise Act); and the (until recent) easy availability of credit.

2.3.2 Net interest income

For most of the loan book, interest income is modelled endogenously. Banks price their loans 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. However, banks' repricing ability is constrained by the maturity structure of their balance sheets. Since assets and liabilities typically do not have matched maturities, these constraints generate significant income risk. The possibility of shifts in the yield curve intensifies this risk.

We use the risk-neutral asset pricing model of Drehmann et al (2008) to capture both sources of income risk in a consistent fashion. Consider a risky asset, A , with a repricing maturity equal to T , implying that the asset pays a fixed coupon C over the next T periods. The economic value of the asset today is the risk-adjusted discounted value of future coupon payments and the principal:

$$EV(A_0) = \sum_{t=1}^T D_t C A_0 + D_T A_0, \quad (1)$$

where the discount factors are given by:

$$D_t = \prod_{l=1}^t (1 + R_{l-1,l})^{-1} \quad (2)$$

$$R_{l-1,l} = \frac{r_{l-1,l} + PD_{l-1,l} * LGD_{l-1,l}}{1 - PD_{l-1,l} * LGD_{l-1,l}}$$

and $r_{l-1,l}$, $PD_{l-1,l}$, $LGD_{l-1,l}$ represent respectively the forward risk-free interest rate, expected PD and expected LGD between time $l-1$ and l .¹² We can use the first equation to calculate a “fair” time-zero coupon that guarantees that $EV(A_0) = A_0$:

$$C = (1 - D_T) / \sum_{t=1}^T D_t \quad (3)$$

Whenever the bank can update C (i.e. at time $T, 2T, \dots$), it will do so using the equation above, so that expected interest income covers expected losses and book and economic value coincide.

Between 0 and T , though, interest rates, PDs and LGDs may change whereas the coupon is fixed: any change in discount factors that is unexpected as of time-zero will thus prevent the zero profit condition from holding. For each bank, we use balance sheet information to determine what fraction of assets and liabilities can be repriced at any point in time. The model implies that the pricing

¹² The risk-free yield curve is known at the time of pricing; we assume that banks take future PDs and LGDs to be equal to the most recent observations.

structure of the balance sheet, and particularly the mismatch between assets and liabilities, influences a bank's vulnerability to interest rate and PD shocks.

The model-implied coupons are calibrated to better accord with actual observed spreads as these may also partly reflect compensation for fixed costs associated with arranging loans and oligopolistic profits derived by banks. In particular, for household and non-financial sector corporate assets, the model-implied coupon is increased by 50 basis points.

For other parts of the balance sheet, including all of the liability side, we simply calibrate spreads based on market rates and other data. For example, we assume that interbank assets and liabilities receive/pay the risk-free rate plus the LIBOR spread, whilst banks pay negative spreads relative to the risk-free rate on some household and corporate deposits (if the negative spread implies a negative interest rate, the interest rate paid is assumed to be zero). As discussed below, spreads on certain liability classes may also depend on the rating of the bank in question.

2.3.3 Non-interest (non-trading) income and operating expenses

Non-interest, non-trading income (henceforth non-interest income) was just under half of UK banks' operating income in 2007.¹³ It includes fees and commissions (see Table 2). Stiroh (2004) finds non-interest income to be procyclical, which appears plausible given that its components include securitisations. Bank-specific and structural determinants may also be important. The rise in the share of non-interest income may be seen in the context of new intermediation technologies such as internet fees; financial derivatives; loan securitisations; or by selling back-up lines of credit. Capital is not required for many such fee-based activities, even though some, such as derivatives and trust services, take place on-balance sheet, so increased reliance on non-interest income could be associated with higher leverage (DeYoung and Rice, 2004)).

¹³ One reason for separating the modelling of trading income from that of the other components of non-interest income is that trading income is the most volatile. It contributes to a large part of the variance of total non-interest income, which itself has increasingly contributed to the variance of overall operating income growth. Stiroh (2004) showed that for US banks the non-interest income contributed 80% of the volatility of operating income in the 1990s.

Table 2: US and UK non-interest income and expenses (ratio of operating income)

US ¹	1984-89	1990-99	2000-07	UK ²	1997-03	2004-06	2007 interim
Net interest income	0.72	0.64	0.57	Net int. inc.	0.58	0.42	0.39
Non-interest income	0.28	0.36	0.43	Non-int. inc.	0.43	0.58	0.61
Fiduciary	0.05	0.05	0.05	Net fees & com	0.27	0.20	0.21
Service charge	0.06	0.07	0.07	Dividend income	0.003	0.004	0.005
Trading	0.02	0.03	0.03	Dealing profits	0.05	0.11	0.13
Other	0.15	0.21	0.27	Other	0.10	0.27	0.26
Non-int. expenditure	0.68	0.64	0.59	Non-int. exp.	0.56	0.62	0.59
Memo:							
Non-int, non-trad. Inc	0.26	0.33	0.40	Non-int, non-trad. Inc	0.38	0.47	0.48

¹ A caveat is that the components of non-interest income are not directly comparable between the US and the UK. For example, fees and commissions are included in other non-interest income in the US.

²In the UK, the change to IFRS accounting standards in 2004 boosted the share of insurance income. For example, Lloyds TSB's non-interest income as a share of its operating income jumped from 47% in 2003 to 74% in 2004.

Data paucity and inconsistencies rule out estimation based on UK data and we instead use US data. This seems reasonable given the similarities between the UK and US and, in particular, the similar shares of non-interest income as a share of operating income (around 42% for UK banks and 38% for US banks, see Table 2). As in Stiroh (2004), we use aggregate quarterly US data that covers over 7000 FDIC-insured commercial banks, covering the period 1984Q1 to 2007Q3. The use of aggregate data prohibits a search for bank-specific effects.

The results for the favoured equation are shown below. As in Stiroh (2004), non-interest income is quite strongly pro-cyclical. A one percentage point increase in real GDP above baseline implies that real non-interest income rises by 2.7 percentage points initially, and 2.0 eventually.¹⁴ We find insufficiently strong evidence for factors such as balance sheet asset growth, equity returns and equity volatility to include them in RAMSI. However, in some specifications (not shown) there was evidence that non-interest income increases with leverage and decreases with the slope of the yield curve.

¹⁴ We also tried an error correction mechanism specification in attempt to identify a long run relationship. But it did not forecast as well as the dynamic equation.

$$\begin{aligned} \Delta \ln(\text{Non - interest income}_t) &= 0.003 - 0.338 \Delta \ln(\text{Non - interest income}_{t-1}) - 0.246 \Delta \ln(\text{Non - interest income}_{t-2}) \\ &\quad \begin{matrix} (0.27) & (2.94) & (2.06) \end{matrix} \\ + 0.027 \Delta \ln(\text{Non - interest income}_{t-3}) &- 0.003 \Delta \ln(\text{Non - interest income}_{t-4}) + 2.721 \Delta \ln(GDP_t) + 0.878 \Delta \ln(GDP_{t-1}) \\ &\quad \begin{matrix} (0.22) & (0.02) & (3.44) & (1.03) \end{matrix} \\ - 0.114 \Delta \ln(GDP_{t-2}) &- 1.357 \Delta \ln(GDP_{t-3}) + 1.003 \Delta \ln(GDP_{t-4}) \\ &\quad \begin{matrix} (0.13) & (1.61) & (1.19) \end{matrix} \end{aligned}$$

Joint significance of GDP and lagged GDP (p - value) : 0.004. Observations. 90. Adjusted $R^2 = 0.18$

We validate the US-based model on UK data by checking its forecasting performance. We generate non-interest income forecasts for each UK bank based on its initial level and increment that with the predicted values of real non-interest income growth from the estimated equation. When calibrated to UK banks, the out of sample forecasting performance is satisfactory. Between 2005 and 2007 the model predicts a 16.5% increase over the two years compared with an outturn of 16.2%.

For non-interest expenses (i.e. operating expenses), we suppose that banks target cost ratios. This is supported by empirical estimates of an equation for non-interest costs based on the same aggregate US data that were used to estimate non-interest income. Costs are found to be less procyclical than operating income, reflecting the proposition that banks are unable to immediately adjust expenses. The equation for operating expenses is:

$$\left(\frac{\text{Operating expense}}{\text{Operating income}} \right)_t = 0.053 + 0.920 \left(\frac{\text{Operating expense}}{\text{Operating income}} \right)_{t-1} - 0.487 \Delta \ln(GDP_t)$$

$\begin{matrix} (2.16) & (23.64) & (1.45) \end{matrix}$

Observations : 94. Adjusted $R^2 = 0.86$

2.3.4 Profits, Taxes and Dividends

In order to generate plausible profit figures, we assume that each bank earns a trading income that is proportional to the size of its portfolio, using 2007 data to calibrate the ratio. This assumption will obviously become redundant when we introduce trading book and AFS models. Profits are then computed as the sum of all sources of income, net of expenses and credit losses. We deduct taxes and dividends from profits, assuming that the tax rate and ratio of dividends to profits are in line with recent history.

Post-tax, post-dividend profits (or losses) are assumed to increase (or erode) Tier 1 capital directly. Updated Tier 1 capital ratios may then be computed by dividing capital by risk-weight assets, where

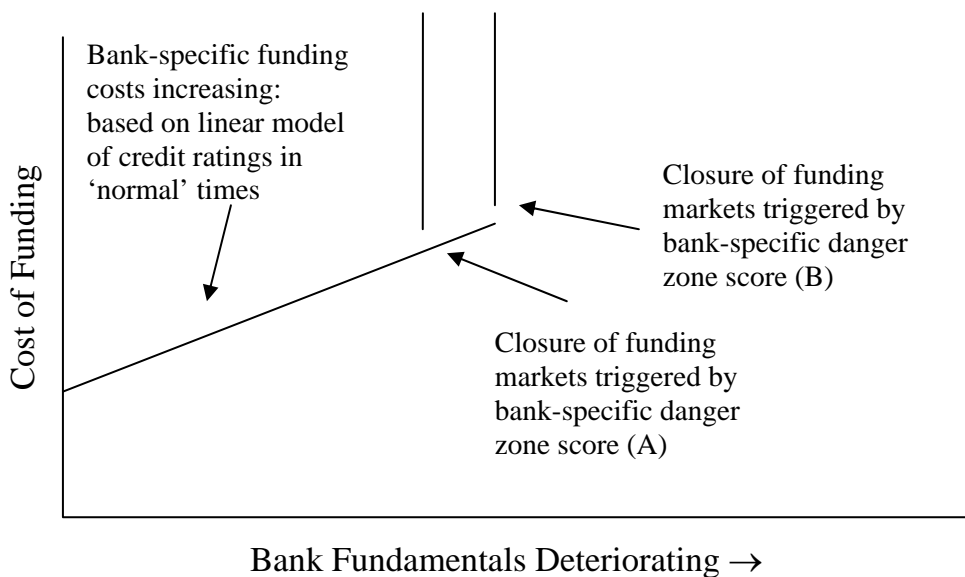
the latter are computed by applying Basel II standardised risk weights or approximations to them where we have insufficient information (e.g. corporate loans, for which we do not know the ratings of the borrowers).

2.4 Funding Liquidity Risk and Bank Failure

The ongoing credit crisis has illustrated starkly how increased funding costs and the closure of funding markets can trigger bank failure. We have integrated two complementary channels to capture funding liquidity effects. First, we apply an empirical model to project individual bank ratings, and use the results to calibrate how funding costs may change with the fundamentals of a bank. Second, we use a separate ‘danger zone’ model in which a range of indicators determine whether a bank suffers stress so severe that it is shut out of unsecured funding markets.

We consider it important to model the outright closure of funding markets in a distinct framework. Figure 3 illustrate this point. Though there may be a relatively linear relationship between a deterioration in bank fundamentals and increased funding costs in relatively ‘normal’ times, it is hard to use this approach to identify the closure of funding markets in extreme circumstances given that this is an inherently non-linear process, and could occur at different ratings and funding costs (A or B), depending on the circumstances. Hence we feel that the danger zone approach is more appropriate for identifying the region in which funding markets are likely to shut. Nevertheless, we intend to use the funding cost / ratings model as a cross-check on the danger zone approach.

Figure 3: The operation of funding liquidity risk



2.4.1 Bank ratings and funding costs

We model banks' funding costs in two stages. First, we use an ordered probit model (adapted from Pagratis and Stringa, 2008) to examine the sensitivity of Moody's senior (long term) unsecured ratings to a number of key bank performance indicators and macroeconomic variables. The index produces ratings for each bank at each quarter using the estimated coefficients from Table 3.

Ratings are found to improve when: (i) profitability increases; (ii) the lower is the ratio of (illiquid) customer loans to short-term liabilities; (iii) the higher the market share of lending by a bank; (iv) the higher the cost efficiency (proxied by operating expenses/total assets); (v) the higher the asset quality (proxied by credit losses/net interest income); (vi) economy-wide output and credit rise above trend, and the yield curve steepens.

Table 3: Ordered probit estimated coefficients for the bank ratings model

The model is estimated using a data panel of 1369 observations, for the period 1999-2006. The data panel includes published accounts data of 293 banks from 33 countries (grouped in 14 regions), and macroeconomic information. The constant (6.187) is the sum of coefficients for the United Kingdom regional dummy (0.441), the Aaa-Aa1 sovereign rating dummy (6.809), a dummy for IFRS reporting by banks (-0.577) and a dummy for the 4th quartile in the banks' sample distribution ranked by total assets.

DEPENDENT VARIABLE:	<i>Number of lags (in years)</i>	<i>Investment-grade bank</i>		<i>Sub-investment grade bank</i>	
		Coefficient	Robust Std. Error	Coefficient	Robust Std. Error
INDEPENDENT VARIABLES:					
BANK FINANCIAL INDICATORS					
Profitability: 100*(Profits before tax + Credit losses) / Total assets	1	0.200***	0.075	0.048**	0.076
Asset quality: 100*Credit losses / Net interest income	1	-0.002***	0.001	-0.002***	0.001
Cost efficiency: 100*Operating expenses / Total assets	0	-0.127***	0.039	-0.127***	0.039
Funding gap: 100*(Customers loans - Short term liabilities) / Customer loans	0	-0.002***	0.000	0.002***	0.000
Market share: ln(100*Loans / Total loans by banks in the network)	0	0.179***	0.050	0.179***	0.050
Capital dummy: 1 if (Equity / Total assets) falls below target, 0 otherwise	0	-0.261***	0.064	-0.261***	0.064
MACROECONOMIC VARIABLES					
Yield curve slope: (10-year gov. bond rate) – (3-month T-bill rate)	1	0.078***	0.030	0.078***	0.030
Economic downturn dummy: 1 if real output gap is negative, 0 otherwise	1	0.054	0.084	0.054	0.084
Credit boom dummy: 1 if credit gap is positive, 0 otherwise	2	0.038	0.087	0.038	0.087
Economic downturn * Credit boom	1,2	-0.222**	0.109	-0.222**	0.109
Subinvestment-grade dummy: 1 if rating Baa2 and below	1	-	-	-3.038***	0.119
Constant	-	6.187***	-	6.187***	-

Note. ** significant at 5%; *** significant at 1%. The first column in Table3 reports the lag structure of explanatory variables in the adapted Pagratis and Stringa (2008) model. For interaction effects we report two lags, one for each interacting variable. The second column reports the estimated coefficients of explanatory variables in the model. The third column reports White robust standard errors. The fourth column reports the estimated coefficients of interaction effects between explanatory variables and a dummy that takes the value 1 if the banks previous rating was of subinvestment grade (Baa2 and below) and 0 otherwise. Note also that we have replaced the insignificant coefficients on the economic downturn dummy and the credit boom dummy to be zero in the code.

The assigned ratings are mapped to credit spreads using Merrill Lynch’s bond indices of UK sterling bonds spreads associated with different credit ratings. These bank-specific spreads are applied to certain types of wholesale funding (including interbank and other non-retail deposits, commercial paper, certificates of deposit, and subordinated debt). This introduces a key feedback mechanism on the liability-side of balance sheets: if a bank gets downgraded, the associated rise in its funding costs will reduce its future profitability, leaving it more vulnerable to future downgrades and, ultimately, to a loss of access to wholesale funding markets.

2.4.2 *Modelling the closure of funding markets – a ‘danger zones’ approach*

Modelling the outright closure of funding markets presents significant challenges, both 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. We therefore adopt a simple, transparent (yet subjective) ‘danger zone’ approach under which banks accumulate points as liquidity conditions deteriorate, and face the prospect that certain funding markets may close to them as their score crosses particular thresholds.

Figure 4: Closure of Funding Markets in RAMSI

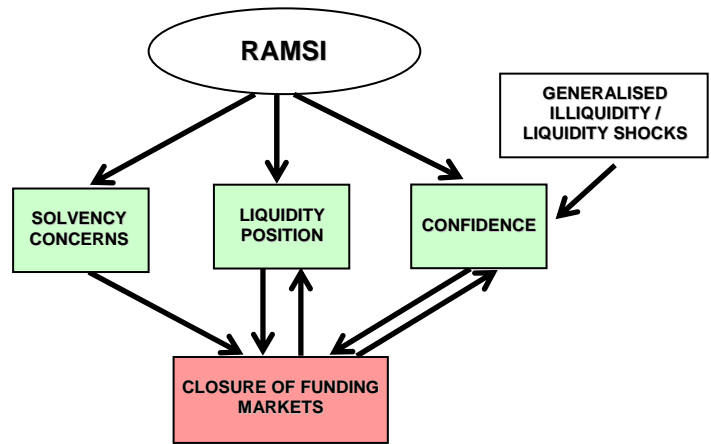


Figure 4 gives an overview of the approach. Outputs from the rest of the model are mapped into specific indicators of funding stress relating to three key areas that theoretical models (e.g. Chen, 1999; Goldstein and Pauzner, 2005) and evidence from case studies and banks’ own liquidity policies suggest are important – solvency, liquidity and confidence. The framework allows for feedback effects. In particular, the closure of certain 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. Recent events have emphasised that market-wide liquidity factors can also play an important role in affecting confidence and hence contributing to funding stress. To proxy for these factors, the framework captures a greater risk of funding stress in periods when the market interbank spread is elevated.

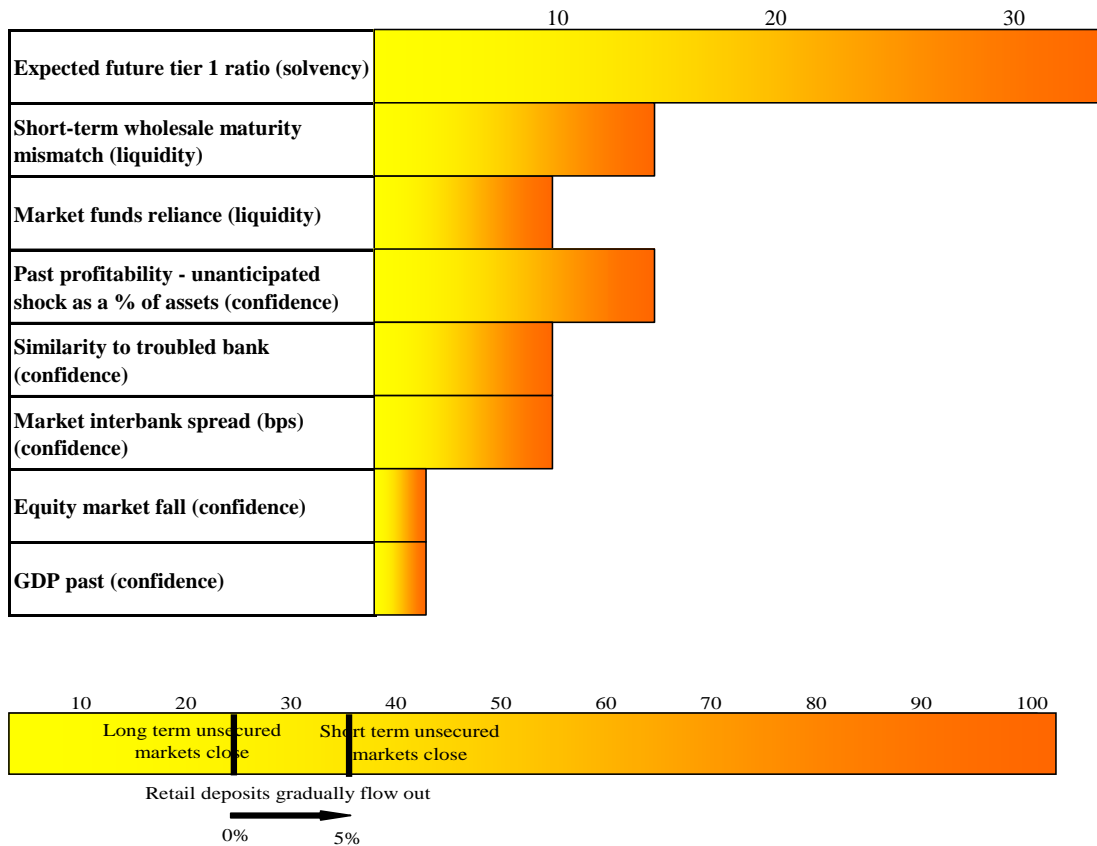
Figure 5 presents the set of eight indicators (the underlying factor that each is trying to proxy is mentioned in brackets), along with the aggregation scheme and the thresholds at which short-term and long-term unsecured funding markets are assumed to close to the bank.¹⁵ In constructing the weighting, we place roughly equal weight on three main factors that can trigger a funding crisis: (i) concerns about future solvency; (ii) a weak liquidity position/funding structure (e.g. high reliance on short-term wholesale unsecured funding); and (iii) institution-specific and market-wide confidence effects, over and above those generated by solvency concerns or weaknesses in liquidity positions. 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 judgments underpinning more specific aspects of the calibration and weighting schemes were informed by analysis of a range of case studies.¹⁶

Currently, the danger zones are incorporated into RAMSI in a simplified way. Since the model does not yet include model-consistent expectations, the current Tier 1 capital ratio is used instead of the expected ratio and the past profitability indicator is ignored as it is not possible to identify unanticipated losses. In addition, the threshold at 25 points is ignored and banks are simply assumed to default if their danger zone score reaches 35 and short-term secured markets close to them. When fully incorporated, a score of 25 or more will trigger the closure of long-term unsecured funding markets to the bank, which will be able to refinance in short-term unsecured funding markets or take other defensive actions such as selling or repoing assets. There will be no default at this point but there will be a snowballing effect, whereby the increased reliance on short-term funds will affect the bank’s score on the maturity mismatch indicator.

¹⁵ Secured funding markets are discussed below. For simplicity, we do not consider a more detailed breakdown of funding markets (e.g. we do not distinguish between foreign and domestic funding markets).

¹⁶ The case studies (still work in progress) include both episodes in which banks have failed (e.g. Franklin National Bank, Continental Illinois, Japanese banks, Northern Rock) and episodes in which banks have survived (e.g. Lehman Brothers during the LTCM crisis; Countrywide; Société Générale following the recent fraud).

Figure 5: Danger Zones – Basic Structure



The full danger zone framework will also allow for a number of extensions. First, there will be a gradual outflow of retail deposits after long term unsecured funding markets close to the bank, such that the outflow reaches 5% of retail deposits by the time short term unsecured markets close. This is intended to reflect behaviour of well-informed investors rather than a widespread (Northern Rock style) run. Second, we intend to define banks scoring less than five points as ‘safe’ and allow them to receive funding withdrawn from troubled banks; as such, they will help to close the system by capturing flight-to-quality effects. If there are no ‘safe’ banks, we will assume funds end up as increased reserves at the central bank. Finally, we plan to extend the framework to cover secured funding markets. For these, we will assume that if a bank cannot repo assets, it will be able to sell them at the prevailing market price. Critically, however, this could be a fire sale price and, in some instances, could even be zero, either because there are no buyers in the market or because of potential stigma effects which could be generated by a large asset sale in an illiquid market. The framework will thus highlight the importance of collateral quality in determining how a bank fares if secured funding markets close to it.

2.4.3 Example of a danger zone calibration: 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 very recent 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. Chart 1 scores Continental Illinois in each of these periods.

Chart 1: Continental Illinois Danger Zone Points



Continental scores heavily 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 raising 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. Increased reliance on short-term funding then serves to increase Continental's score over the next couple of years. 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.

2.4.4 Bank failure and bankruptcy costs

As just discussed, banks are assumed to default if they score 35 danger zone points and are shut out of short-term unsecured funding markets. When a bank defaults, we follow James (1991) and suppose that it incurs costs equivalent to 10% of its remaining assets. This is also in line with the mean figure reported in Bris et al (2006). These bankruptcy costs are designed to capture the direct legal, accounting and redundancy costs which are incurred upon default. They may also be viewed as capturing the erosion in the real value of a bank's assets that may occur upon default due to disruptions to established bank-borrower relationships or the loss of human capital. They imply that even if banks fail with positive shareholder funds, they will be unable to fulfil all of their obligations upon default.

2.5 Second-Round Effects and Contagion

2.5.1 Asset side feedbacks: fire sales

When a bank is in distress, it may sell assets, opening up the possibility of an important feedback channel operating via asset prices. In the current version of RAMSI, such fire sales only occur after a bank defaults, and not as a defensive action to stave off failure. A failing bank is assumed to liquidate all its available-for-sale (AFS) assets. The fire sale discount lasts for one quarter, and the resulting fall in asset prices may lead other banks to incur mark-to-market losses; hence in extreme circumstances these banks may then also fail.

The associated price impact given by equation (4) is applied to other banks' AFS assets. Consistent with Duffie et al (2007), we take the relationship between prices and the magnitude of fire sales to be concave. For asset j , the fire sale equation is:

$$P'_j = \max \left\{ 0, P_j \left(2 - \exp \left(\theta \frac{S_{ij}}{M_j + \varepsilon_j} \right) \right) \right\} \quad (4)$$

The price of asset j following the fire sale, P'_j , is the maximum of zero and the price before the fire sale, P_j , multiplied by a discount term. The discount term is a function of value of assets sold by bank i in the fire sale, S_{ij} , divided by the depth of the market in normal times, M_j , and scaled by a parameter θ that reflects frictions, such as search problems, that cause markets to be less than perfectly liquid. Market depth can also be shocked by a term ε_j to capture fluctuations in the depth of markets as macroeconomic conditions vary. There are three types of assets that can be affected by fire sales: equities, corporate debt securities, and asset and mortgage backed securities. Each has a different value of market depth.

Calibration of the parameters is made difficult by the paucity of empirical analyses that reveal the price impact for a given volume of assets sold in fire sales. Our calibration is guided in part by Mitchell *et al* (2007), who consider a fire sale of US convertible bonds by hedge funds in 2005. They estimate that 5% of the outstanding stock of US convertible bonds were sold at a maximum price discount of 2.7%. Similarly, Coval and Stafford (2007) analyse the price impact of fire sales involving US equity mutual funds. They find an average price impact of 2.2% for the fire sales they identify. Pulvino (1998) focuses on fire sales of aircraft and finds larger price impacts for these assets. He also finds that the price impact varies when the depth of the market fluctuates. However, none of this information is sufficient for precise calibration, since it is not possible to make a direct comparison of the size of the fire sale in relation to the overall market in the study and the potential size in the case of any liquidation of UK banks' assets.

Therefore, the calibration is guided both by this empirical evidence and a top down judgement regarding the plausible impact of a fire sale on capital.¹⁷ The calibration for θ is based on the results presented in Mitchell *et al* (2007). Given θ , a value of market depth M_j is chosen for each of the asset types so that when the UK bank with the largest holdings of an asset class in its trading portfolio and AFS assets sells all these assets, it generates prices falls of 2% for equities, 4% for corporate debt, and 5% for asset and mortgage backed securities.

¹⁷ The impact is likely to be stronger when the financial system is under stress and markets are less deep (Pulvino, 1998).

2.5.2 *Network model*

When a bank defaults, counterparty credit losses incurred by other banks are determined using a network model. A matrix of interbank exposures for the major UK banks, along with some smaller UK institutions and a selection of large, complex, financial institutions (LCFIs) is built using reported large exposure data where available. Since we also have information on total interbank asset and liability positions, we then use maximum entropy techniques to fill in missing gaps in the network, ensuring that none of the estimated entries exceed the reporting threshold for large exposures.¹⁸ If any interbank assets or liabilities are unallocated following this procedure, we assume that they are associated with a residual sector which cannot default. Once constructed, the estimated exposure matrix remains static over the forecasting horizon. To clear the network following the default of one or more institutions, we use the Eisenberg and Noe (2001) algorithm. This both determines contagious defaults and returns counterparty credit losses for each institution.

2.5.3 *Feedback loop*

After accounting for counterparty credit losses and mark-to-market losses on AFS assets, we update the danger zone scores for banks that survived initially (see Figure 2). In the event of another bank breaching the 35-point threshold, we iterate around the network and asset-side feedback mechanism again. If not, we update all balance sheets to account for counterparty credit losses. However, we assume that asset prices recover to pre-feedback levels, so mark-to-market losses are not carried forward. This reflects the idea that, once a crisis has passed, asset prices are likely to return to their fundamental values fairly quickly. A more gradual price adjustment process would impose higher systemic costs on the banking system, and we plan to allow for this in future work.

2.6 *Reinvestment*

Rules for adjusting balance sheets to account for profits and losses are necessary in a multi-period setting. As noted above, post-tax, post-dividend profits (or losses) are assumed to increase (or erode) Tier 1 capital. On the asset side, credit losses are simply booked against the relevant exposure for the loss. But other profit and loss items cannot be linked so directly to particular

¹⁸ The techniques adopted are similar to those discussed by Wells (2004), Elsinger et al (2006b) and OeNB (2006).

balance sheet lines. Therefore, to rebalance the balance sheet, we adopt a set of mechanical reinvestment rules.¹⁹ If operating income (which includes net interest income, non-interest income and trading income) exceeds operating expenses then, at the point of rebalancing, liabilities plus capital will exceed assets, and banks reinvest their surplus funds according to the following rules:

Rule (i): Banks have a bank-specific ‘target’ Tier 1 capital ratio which they aim to meet when investing their funds. (They are not permitted to buy back equity to meet their target.)

Rule (ii): Subject to rule (i), banks invest in assets in proportion to their shares on the bank’s initial balance sheet (e.g. mortgage banks will, ceteris paribus, invest in mortgage assets rather than trading assets).

Rule (iii): Rule (i) determines total assets after reinvestment and hence the amount of new liabilities which need to be raised. These net new liabilities are allocated in proportion to their shares on the bank’s initial balance sheet.

In the current version of RAMSI, defensive actions in response to declines in capital are very limited. In the case when a bank’s operating expenses exceed its operating income (so that assets exceed liabilities plus capital at the point of rebalancing), we assume that the bank is unable to disinvest or raise capital. Rather, it raises new liabilities according to rule (iii). The reinvestment rule therefore has the benefit of demonstrating transparently the implications when no mitigating actions are taken in the face of losses. But it is not necessarily realistic – for example, an alternative specification would allow banks to disinvest when making losses; this would reduce the likelihood of the bank suffering a liquidity crisis, but would introduce a further channel of macroeconomic feedbacks.

The primacy of the Tier 1 capital ratio rule is justifiable first, because five UK banks (Barclays, B&B, HBOS, HSBC and RBS) publish a Tier 1 capital ratio target; and second, because the mean ratio of capital to risk-weighted assets for the major UK banks was relatively stable in recent years (up to 2007) and institution-specific standard deviations of this ratio were low. For banks which have not published target capital ratios, we assume that they target a capital ratio equal to their end-2007 number.

¹⁹ Rules can be respecified in policy experiments, for example to assess the impact of targeting leverage, or of raising capital.

We are motivated to choose ‘neutral’ assumptions regarding portfolio allocation and the second and third rules are based on the presumption that initial balance sheets represent desirable equilibrium outcomes which banks seek to preserve in the face of changes in size. Drastic changes in portfolio are typically associated with a change in the bank’s business model – within a given business model, the rules seem reasonable, especially over the three year horizon considered in this paper.

The portfolio allocation rules are not entirely neutral, however. The liability rule precludes banks from responding to changes in funding costs. And on the asset side, our assumed rule may understate risk because it precludes the possibility that banks may skew their reinvestment towards areas in which they have recently been most profitable. Following positive macroeconomic outcomes, risky assets tend to generate the most profits and increase most in value. So risks would accumulate more quickly were we to employ an alternative re-investment rule in which banks reinvested profits in proportion to the nominal value of assets held on the balance sheet in the most recent period (rather than the initial period in our rule). We intend to conduct further validation to guide such choices.

There is no leverage target, so our reinvestment rules allow leverage to be determined according to developments elsewhere in RAMSI. As pointed out by Adrian and Shin (2007), leverage may be *pro-cyclical* when positive macroeconomic outcomes lead to a decline in the measured riskiness of banks’ existing assets (e.g. a decline in VaR or a fall in Basel II risk weights). Such pro-cyclicality will be built into RAMSI when we introduce endogenous Basel II risk weights which adjust to changes in PDs. Conversely, if banks choose to purchase relatively risky assets (with high risk weights), then leverage rises relatively *less*, since in order to achieve their Tier 1 capital ratio targets, banks can purchase fewer assets compared with the case in which they purchase assets with lower or zero risk weights, such as government bonds.

3 Simulations

We use data up to 2007Q4 (so that all balance sheet information is on the basis of end-2007 data) and run 500 simulations on a three year forecast horizon stretching to the end of 2010. The BVAR is currently the only source of exogenous randomness in the stochastic simulations; each simulation is thus driven by a sequence of macroeconomic shocks drawn from a multivariate normal

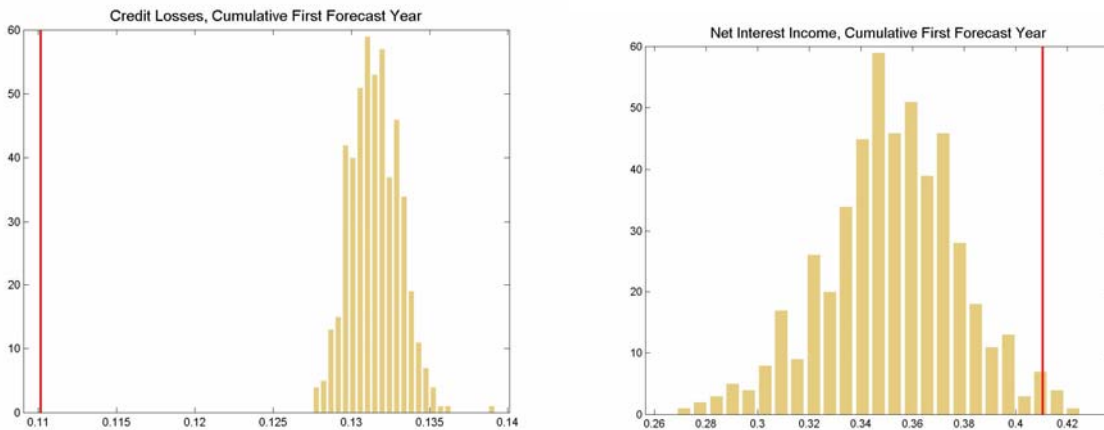
distribution.²⁰ It should be stressed, however, that the results are illustrative, reflecting model properties in this preliminary version rather than being the authors' view of likely responses of the banks in question.

3.1 Aggregate results

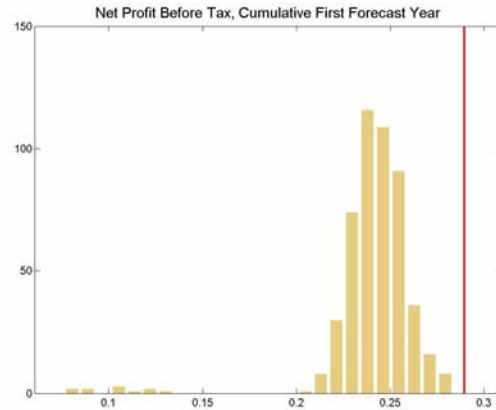
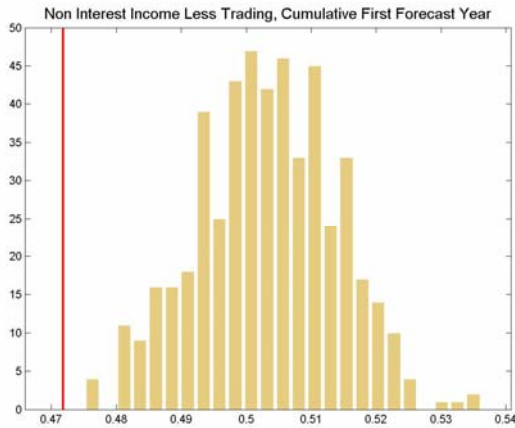
Throughout this section, we discuss results for the UK banking system in aggregate. Since individual banks' balance sheets are at the core of RAMSI, the model produces a rich set of information and may be used both to obtain baseline projections for specific institutions and to analyse their performance under stress. Such information can be used to assess the vulnerability of particular institutions to different risks and may thus feed into the internal institution-specific risk assessment work undertaken by regulators and central banks.

Chart 2 shows the simulated distributions of some key profit and loss items. For each variable, we calculate aggregate cumulative figures for the first year by adding over banks and quarters, and normalise by aggregate 2007 (i.e. "beginning of period") capital. The vertical line represents the corresponding figures from the 2007 published accounts, normalised by 2006 capital levels.

Chart 2: Simulated Distributions for Profit & Loss Items (percent of aggregate 2007 capital)



²⁰ 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.



The top-left hand panel shows that credit risk is projected to increase in 2008, reflecting a worsening of the macroeconomic outlook. However, since our credit risk model abstracts from portfolio concentrations (see Section 2.3.1), we arguably underestimate the variance of the credit risk loss distribution. Net interest income is projected to be weaker than 2007, reflecting contractual frictions that prevent banks from instantaneously passing on higher funding costs to their borrowers. The variance of net interest income may be unrealistically high as the model does not incorporate hedging of interest rate risk.²¹ Non-interest income (bottom-left hand panel) remains high, with a median projection above the reported 2007 level; this variable is pro-cyclical but adjusts relatively slowly to macroeconomic changes. The net impact on banks' profitability is summarised in the net profit chart (bottom-right hand panel). Profits were projected to be weaker than in 2007, and there is some evidence of bi-modality, insofar as there are a number of observations in the extreme tail of the distribution, which are typically associated with one or more banks defaulting.

3.2 *Dissecting the tail: The role of funding liquidity and contagion*

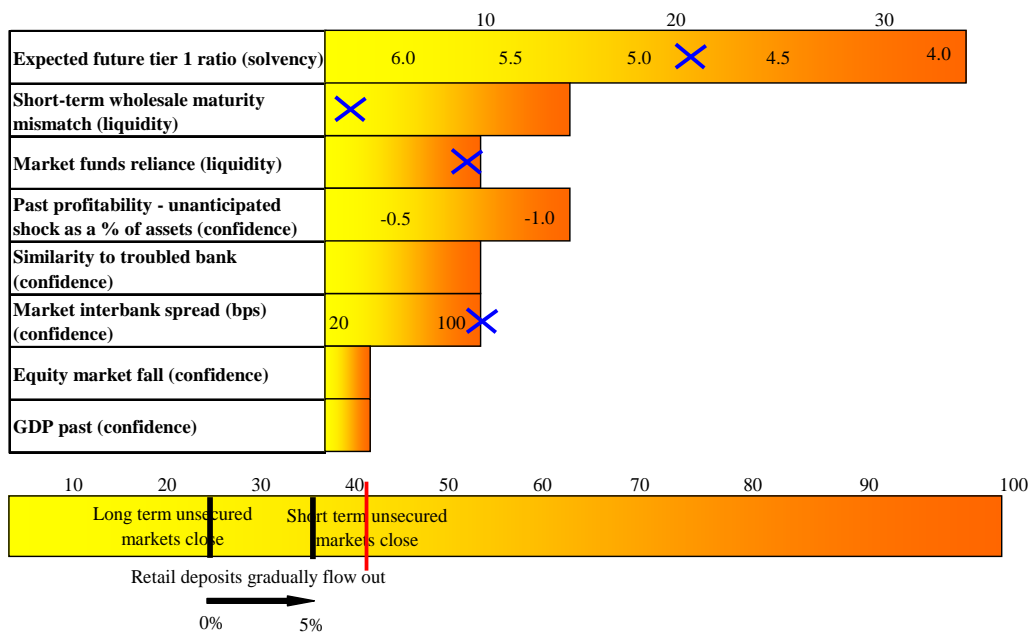
The crisis afflicting banks in the UK and internationally has illustrated the importance of funding liquidity. By their nature, the aggregate cumulative distributions in Chart 2 mask bank-by-bank heterogeneity. In bad draws taken from the BVAR, some banks incur large losses in some quarters/scenarios, which can erode those banks' Tier 1 capital ratios thereby increasing their danger zone points. With some banks scoring points on the liquidity indicators, the increased solvency concerns can, in extreme cases, be sufficient for a bank's score to reach 35 points, leading to the closure of short-term unsecured funding markets to that institution and its default. Note that

²¹ Banks can be penalised under the second pillar of Basel II for not hedging interest rate risk.

the introduction of funding liquidity risk into the framework is critical here. Looking at capital alone, the defaulting banks remain well above the 4% regulatory minimum. But a combination of mild solvency concerns, a weak liquidity position and elevated market interbank spreads is sufficient for wholesale depositors to withdraw funding.

The crosses in Figure 6 show danger zone scores for a defaulting bank. The bank fails because it scores points on a range of the indicators, including the Tier 1 capital ratio indicator. But its weak liquidity position, captured in the second and third indicators, contributes to its failure. As such, it is clear that the inclusion of danger zones into the framework makes banks more vulnerable. The results accord with reality in the sense that funding liquidity crises are triggered by a mixture of factors and can occur even if the bank is perceived to be solvent.

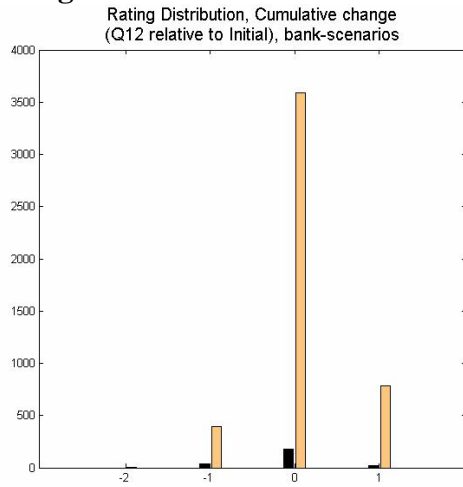
Figure 6: Danger zone scores for a defaulting bank



Contributing to bank heterogeneity are bank-specific funding spreads that depend on bank ratings. A bank is more likely to be downgraded as profitability falls and its capital falls below target. This serves to raise its funding costs, hurting profits further and making the bank more vulnerable to subsequent default. We observe this feedback relationship in Chart 3. This shows two distributions for bank rating changes at the end of the forecast horizon or at the point of default, relative to the initial rating. The total number of observations is therefore 500 simulations multiplied by 10 banks. The light-shaded distribution is for scenarios in which the bank does not default and the black-shaded distribution is for scenarios in which the bank defaults. As we expect, the defaulting bank-

scenarios distribution has more of its mass at lower ratings than does the non-defaulting bank distribution.

Chart 3: Rating Distribution – Cumulative Change

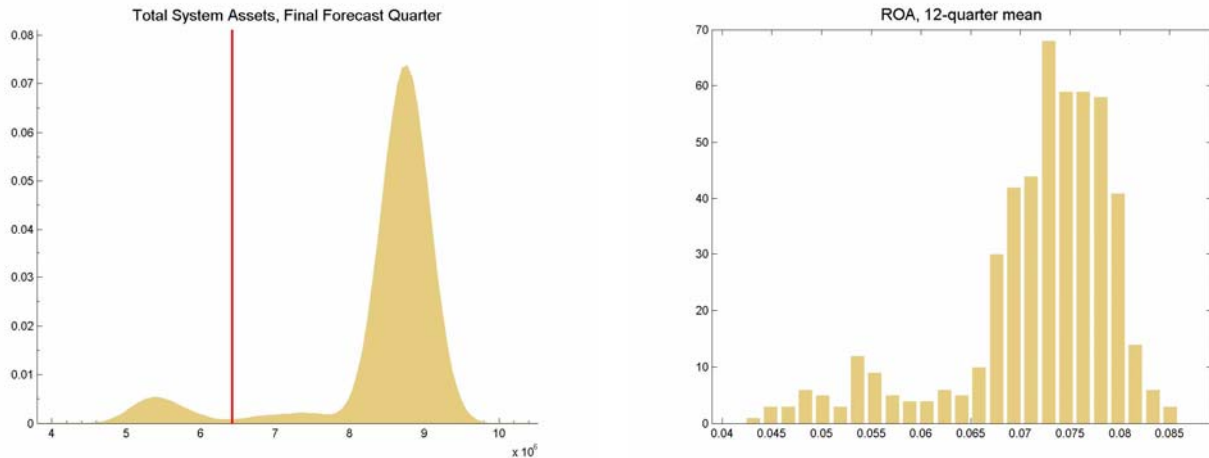


Note: light-shaded bars represent ratings for non-defaulting bank scenarios; black-shaded bars for defaulting bank scenarios)

Chart 4 shows the distribution of total assets in the last quarter of the simulation and the average aggregate return on asset (RoA) over the whole horizon. These charts highlight the role of contagion in RAMSI. The distributions are bimodal, with a main peak associated with a healthy banking sector and a considerably smaller second peak in the left tail.²² This is a direct consequence of bankruptcy costs and, in particular, network and asset-side liquidity feedbacks: since fundamental defaults can generate contagion, beyond a certain threshold "extreme" negative outcomes become relatively more likely than "moderate" negative outcomes. This result captures a phenomenon that is commonly perceived as a key feature of financial risk.

²² The bimodality is qualitatively robust and, we believe, crucial feature of the model. See Alessandri et al (2008) for more discussion of this bimodality.

Chart 4: Total System Assets – Final Quarter



The extent to which there is contagion in simulations in the left-hand tail is highlighted by the evolution of the danger zone points. For example, Table 4 presents the build up of points for two other banks following the failure of the bank shown in Figure 6. As already discussed, this bank (Bank 1) defaults in a fundamental sense because it receives a danger zone score greater than 35. Prior to the failure of Bank 1, Bank 2 only has a danger zone score of 26.5. But it is perceived to be so similar to Bank 1 that it is tipped into default by this pure confidence effect. Contagion then extends to Bank 3. It too suffers because of its perceived similarity to the failed banks. But the failure of Bank 2 and the associated fire sale of its assets result in Bank 3 also incurring significant interbank and mark-to-market losses that eat into its capital – indeed, Bank 3 is the bank that suffers the greatest counterparty credit loss as a percentage of Tier 1 capital prior to the default of Bank 1 of all the banks in the network from the failure of Bank 2. Both interbank and mark-to-market losses triggered by fire-sales are important sources of contagion. This process clearly illustrates how funding liquidity problems at one bank can spread to other banks in tail simulations.

Table 4: Funding liquidity and contagion

	Bank 1	Bank 2		Bank 3		
	Initial	Initial	After 1	Initial	After 1	After 2
			Default		Default	Defaults
Expected future tier 1 ratio	20.5	0	0	0	0	2
Short-term wholesale maturity mismatch	2	13	13	8	8	8
Market funds reliance	9	3.5	3.5	8	8	8
Past profitability	0	0	0	0	0	0
Similarity to troubled bank	0	0	9	0	7	10
Market interbank spread	10	10	10	10	10	10
Equity market fall	0	0	0	0	0	0
GDP past	0	0	0	0	0	0
Total	41.5	26.5	35.5	26	33	38

4 Policy Applications

The ultimate goal for RAMSI is to sharpen and add analytical rigour to the Bank of England’s risk assessment work. To be successful, the model must provide a well-grounded narrative of how potential risks may play out. And in order to improve external communication, it needs to use metrics that are familiar to supervisors and risk managers. This section assesses some channels through which improvements will transpire, and highlights some further issues in using RAMSI for policy analysis.

*Aggregate and bank specific fan charts for a wide variety of financial variables (losses, lending, credit spreads etc).*²³ In producing fan charts we face a potential trade-off. On the one hand, there are benefits from improving the accuracy of our fan charts by including additional sources of randomness to that arising from the BVAR, e.g. from the PD equations and liquidity risk. Such a

²³ RAMSI’s outputs may be used to provide alternative metrics of financial stability by recalibrating reinvestment rule. To gauge declines in credit supply, it would be necessary to specify a reinvestment rule in which banks respond to losses by taking defensive actions including reducing loans. Conversely, suppressing such mitigating actions would be a sensible option to assess the potential for individual bank failures.

distribution is (arguably) more likely to resemble that produced by commercial banks' own risk managers. On the other, increasing the number of sources of randomness greatly increases model run times and breaks the direct mapping from macro scenarios to outcomes, so reducing the clarity of story-telling.

Testing the stability of the banking system under stress scenarios. RAMSI will be of particular use in providing model-based estimates of the impact of the risks highlighted in the Bank of England's Financial Stability Report (FSR). It will also be useful for running stress tests. Relative to traditional stress-tests, RAMSI integrates more of the channels through which shocks could propagate and takes account of the contagion that may occur through interbank exposures, asset fire sales, funding liquidity and macro-feedbacks. Assessment of the second round effects has been identified by Haldane (2009) as an important area for development of stress testing in the financial system.

RAMSI will have the capacity to produce a ranking of banks in terms of overall vulnerability, and vulnerability to particular risks.

Decomposition by type of risk: RAMSI will provide the relative contributions to overall risk of the various modules (credit risk, market risk, funding risk, interest income risk and other risks). For extreme outcomes and scenarios, RAMSI's *interbank network* gauges counterparty risk.

Balance sheets: The granular balance sheets will greatly improve RAMSI's capacity to process risks. Going forward, the Bank of England will have increased powers to request balance sheet data from the FSA, in order to help it fulfil its new statutory objective for financial stability. RAMSI will be central to focusing such data requests to improve our balance sheet data and its consistency across banks.

Intermediate outputs: A number of RAMSI's outputs may be useful analytical tools, even when used in isolation of the rest of RAMSI. Examples include balance sheets, the credit loss model, the net interest income model, the ratings model, and the danger zone scores for funding liquidity crises.

Policy design: RAMSI can be used for counterfactual experiments in which regulatory changes could affect systemic risk (see for example Goodhart, 2008).²⁴ For example, we could analyse regulations that require banks to hold more capital or liquid assets, or make their holdings vary across the cycle. The impact on risk and profitability can be observed on either a bank-by-bank or an aggregate basis. The modular approach also affords the possibility of measuring the potential for diversification benefits for each bank.

Recapitalisation: RAMSI could be used to calibrate the extent to which the recent recapitalisation of the UK banking system reduces systemic risk.

²⁴ Pro-cyclicality will to some extent be built into the baseline of RAMSI when we introduce Basel II dynamic risk weights which adjust to changes in the probability of defaults. In addition to the regulatory experiments above, RAMSI can allow for the possibility of pro-cyclicality in terms of profits being re-invested into the most profitable (and risky) parts of the balance sheet.

5 Conclusion and Further Work

This paper incorporates funding liquidity risk into a quantitative model of systemic stability. By applying the model to the UK banking system based on the balance sheet vulnerabilities that existed at the end of 2007, we demonstrate how rising funding costs and liquidity concerns can amplify other sources of risk. The unified modelling approach sheds light on risks arising throughout banks' balance sheets. It also demonstrates how defaulting financial institutions may cause contagion by triggering default cascades through the interbank market; selling assets at fire sale prices; and through undermining confidence in other banks.

We intend to develop the model in a number of areas. A substantial area for further work is to analyse banks' cash flow constraints and consider how defensive actions in the face of funding stress may affect the rest of the financial system and the wider macro-economy. In principle, macroeconomic feedbacks could be introduced by linking realised banking-sector lending response to the price and quantity of loans in the BVAR, though we need to do more work to determine a coherent framework for embedding this important transmission channel. A further area for development will be to introduce more sources of randomness in the model beyond the BVAR, for example in PDs. Such developments would clearly add to the computational complexity of RAMSI, but would improve the realism of the various fan chart summaries of outcomes.

RAMSI has been one of the largest ever analytical projects at the Bank of England and it will go live in 2009. Ultimately, its future development will be determined to a large degree by the aspects of RAMSI that the Bank of England find most useful in enhancing its understanding and communication of financial vulnerabilities. Our hope is that the analytical framework RAMSI provides becomes central to the analysis of systemic risk in the United Kingdom, and perhaps in some other countries as well.

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