Optimal deposit insurance in a macroeconomic model with runs*

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Abstract

This paper examines the effects of deposit insurance in a quantitative macroeconomic model that incorporates the risk of deposit runs faced by banks. During systemic sunspot panic episodes, uninsured depositors tend to withdraw their funds from banks they perceive as vulnerable. While deposit insurance reduces banks' susceptibility to such runs, it may also weaken their risk management incentives, resulting in a U-shaped relationship between insurance coverage and the risk of bank failure. The model suggests that the welfare-maximizing level of deposit insurance coverage for the U.S. in 2008 aligns closely with the observed level.

Keywords: Deposit insurance, bank runs, moral hazard

JEL Classification: E61, G01, G21, G28, G32

*I am deeply indebted to Javier Suarez for inspiration, guidance, and support throughout this project, and to Rafael Repullo and Josep Pijoan-Mas for their generous advice. This paper also benefited from helpful comments and suggestions from Jorge Abad, Sebastian Fanelli, Florian Heider, Rajkamal Iyer, Federico Kochen, Loriana Pelizzon, and Ansgar Walther, as well as from participants at the Frankfurt Summer School. I acknowledge financial support from Grant PRE2021-099907, funded by MCIN/AEI/ 10.13039/501100011033 and by "ESF +", the Maria de Maeztu Unit of Excellence CEMFI MDM-2016-0684, funded by MCIN/AEI/10.13039/501100011033, and CEMFI.

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1 Introduction

The seminal work of Diamond and Dybvig (1983) provides the first rigorous foundation for rational bank runs. At the heart of their analysis is a canonical bank balance sheet: illiquid loans on the asset side and demand deposits on the liability side. The ensuing maturity mismatch gives rise to an inherent vulnerability: the prospect of a failure following the losses incurred in early liquidation of the loans may precipitate self-fulfilling depositor runs. In the four decades since, empirical studies have made great progress in understanding the severe macroeconomic consequences of bank runs (Baron, Verner, and Xiong, 2021; Jamilov, König, Müller, and Saidi, 2024).

Deposit insurance provision by the government is considered the leading solution to reduce depositor incentives to run on their banks. In fact, Diamond and Dybvig show that in an economy without fundamental risk, a government that insures deposits in whole can *costlessly* eliminate the possibility of bank runs. Yet in practice, banks are exposed to exogenous and endogenous sources of risk and may fail even without runs, and this makes the public insurance of deposits fiscally costly. Further, the risk-insensitive pricing of insured deposits may provide the bank with incentives to lever up excessively and/or take excessive risk (Kareken and Wallace, 1978) and, more generally, be detrimental to the discipline associated with financial fragility (Calomiris and Kahn, 1991; Diamond and Rajan, 2001).

Since its introduction in the United States in 1933, the extent to which deposits should be covered by (federally provided) deposit insurance has been an object of intense debate. Against the polar alternatives of unlimited deposit insurance and no insurance at all, the U.S. and most other countries with an explicit deposit insurance scheme provide coverage to bank deposits up to certain limits (typically in the form of a gross covered amount per account holder and bank).[1] What is the impact of moving those limits on banks' exposure to runs? How does it affect credit provision and macroeconomic performance more generally, especially around bank panic episodes? How big are the fiscal and loss-of-discipline costs associated with a more generous coverage? Under which conditions is the socially optimal deposit insurance coverage different from zero or effectively unlimited?

Addressing these questions requires a quantitative framework that captures well the severity and persistence of macroeconomic losses from bank runs, as well as the impact of deposit insurance on banks' risk taking incentives. To meet these requirements, I develop a quan-

[1] See Demirgüç-Kunt, Kane, and Laeven (2015), who provide a recent, comprehensive account of deposit insurance systems around the world.

titative dynamic general equilibrium model with banks in which panic runs can occur as a recurring equilibrium phenomenon. In my model, the banking sector is characterized by three features. First, there are investment opportunities that depend on bank financing. Second, banks' unobservable risk management. With low effort, a bank's risk management fails and its investment is affected by an idiosyncratic shock. A bank with risky assets has a positive probability of becoming fundamentally insolvent. Third, banks issue demand deposits which makes them potentially exposed to run risk. Specifically, there are depositors who will withdraw their uninsured deposits from banks that they perceive as sufficiently vulnerable to runs. When accommodating early withdrawals, a bank incurs liquidation losses which can turn them insolvent, opening the possibility of having rational self-fulfilling runs.

The model, which is calibrated to match important data moments of the U.S. economy and its banking sector over the business cycle, yields two key insights. First, I find a U-shaped relationship between the level of deposit insurance coverage and the risk of bank failure. This finding is the result of a large decline in panic-induced failures from increasing the level of coverage when starting from low levels, which is eventually dominated by increasing risk of fundamental insolvencies from a weakening of banks' risk management incentives. Second, the welfare-maximizing level of deposit insurance coverage for the U.S. in 2008 – roughly 60% of aggregate deposits insured by U.S. FDIC – aligns closely with the level observed in the data. This level weighs less severe deadweight costs and macroeconomic losses during the infrequent episodes of bank panics against higher deadweight costs due to fundamental bank insolvencies in normal times.

The analysis reveals nuanced effects of deposit insurance on banks' risk management incentives. On the one hand, higher insurance coverage makes the pricing of a larger portion of deposits insensitive to default risk, reducing banks' funding costs. With the fraction of deposit funding limited by capital requirements, making deposits cheaper reduces the repayment obligations of the banks, effectively reducing their leverage and having a positive effect on risk management effort. On the other hand, reducing the losses implied by panics reduces the disciplinary effect of runs and, ceteris paribus, induces banks to exert lower risk management effort. In the calibrated model, the latter force is stronger than the former, resulting in the weakening of banks' overall risk management incentives in response to increasing deposit insurance.

To quantitatively evaluate the effects of deposit insurance, I augment a standard business-cycle model with banks. In the model banks finance some bank-dependent investment activities. Banks can reduce the riskiness of those investments by exerting a privately observable risk management effort. Specifically, this effort reduces the probability with which their investments are affected by some bank-idiosyncratic shocks. Effort is costly, as modeled by a standard convex cost function. Banks are financed with a combination of equity issued to some *bankers*, and demand deposits issued to households. They are subject to a capital requirement that imposes a minimum proportion of equity funding per unit of assets.

Households' deposits with banks are *insured up to a limit* by a governmental deposit insurance agency. In between any two periods, a proportion of so-called *alert* households become cognizant of the banks whose risk management has failed and consider the early withdrawal of their deposits on the basis of that information. As in the literature, a household's incentives to run are driven by first-mover-advantages associated with a sequential service constraint. Due to some underlying costs of early withdrawals, alert depositors run on the banks to which they attribute a sufficiently large probability of becoming insolvent by next period. I focus on situations in which this requires (i) banks being known to be risky, and (ii) alert depositors anticipating that other alert depositors will attempt to withdraw early too. Condition (ii) engenders the possibility of multiple equilibria as in Diamond and Dybvig (1983) and, as in Gertler and Kiyotaki (2015), I solve the indeterminacy of equilibrium by assuming that alert depositors coordinate to panic following a sunspot that occurs with some exogenous probability.

I match the model to quarterly U.S. data from the Federal Deposit Insurance Corporation (FDIC), Bureau of Economic Analysis (BEA), and the Flow of Funds Accounts (FoF) corresponding to the period 1984-2006. Over this period, the U.S. FDIC effectively insured an average of 67% of aggregate bank deposits. My baseline calibration sets the deposit insurance limit in the model to replicate this feature of the data.[2] The capital requirement is set at 8%, matching the standards set by the Basel agreements (prior to the reforms initiated in 2009).

The model matches key balance sheet and income statement moments from banks, together with macroeconomic aggregates. Moreover, its dynamics are consistent with many business-cycle correlations in the U.S. data that my calibration does not target. For example, it captures the procyclicality of the share of bank financing in the economy, as well as the countercyclicality of the aggregate share of insured bank deposits and banks' equity issuance. Using lending standards as an empirical proxy for banks' risk taking, I show that

[2] In practice, the FDIC provided an insurance coverage on nominal deposits up to $100,000 per account holder and bank over the entire period. Under a fixed nominal insurance limit but with variations in the amount and composition of deposits over time, the aggregate share of insured deposits in the data is time-varying (and in fact countercyclical).

the model reproduces the strong procyclicality in banks' incentives for risk taking.

After quantitatively validating the model in this way, I analyze the macroeconomic implications of varying deposit insurance coverage. The effects of deposit insurance on the incidence and severity of bank runs are quantitatively large. Comparing an economy with no deposit insurance to the baseline economy with a 67% share of insured deposits, the proportion of bank failures during panics reduces from 7.6% to 0.8%. The macroeconomic implications associated with this decline are considerable. Credit-to-GDP declines by 12 percentage points (p.p.) on impact, in contrast to 30 p.p. fall in an economy without insurance. In the four years subsequent to a banking panic in the baseline economy, the average cumulative losses in output and consumption are 4.4% and 4.3%. Instead in the economy without deposit insurance, the losses are 14.7% and 15.4%, respectively.

By substituting for banks' incentives to exert proper risk management, deposit insurance increases the risk of fundamental insolvencies in the economy. The proportion of banks failing in normal times (absent panics) increases from 0.16% to 0.19%. The average public cost of funds in satisfying the deposit guarantees increases from zero to 0.26% of GDP. While these fiscal and loss-of-discipline costs might appear small in comparison to the stabilizing effects during panics, one has to take into account that panic episodes are infrequent (occur with an annual frequency of 4%). Computing the welfare of the representative household under alternative values of the deposit insurance limit, I find that the socially optimal coverage is 56% of deposits. In determining this level, the large direct and indirect losses that are avoided conditional on the realization of panics are traded off with the negative effects induced over calm periods.

Related literature. This paper connects to the literature on optimal bank regulation and to recent work incorporating financial panics in dynamic macroeconomic models. Beginning with the pioneer analysis of Van den Heuvel (2008), a strand of banking literature has worked on quantifying the effects of bank capital requirements, and in assessing its socially optimal level (see, e.g., Collard, Dellas, Diba, and Loisel, 2017; Begenau, 2020; Malherbe, 2020; Corbae and D'Erasmo, 2021; Elenev, Landvoigt, and Van Nieuwerburgh, 2021; Begenau and Landvoigt, 2022; Mendicino, Nikolov, Rubio-Ramírez, Suárez, and Supera, forthcoming; Abad, Martinez-Miera, and Suarez, 2024). In many of these papers, distortions in banks' incentives due to deposit insurance justify the need for constraining leverage via regulation.[3]

[3] The distortions due to deposit insurance, which also appear in my model, find roots in a large theoretical banking literature. Kareken and Wallace (1978) were among the first to formalize it and present capital requirements as a substitute for market discipline. See also Keeley (1990), Hellmann, Murdock, and Stiglitz (2000), and Repullo (2004).

However, all of these setups abstract from bank runs, which is a crucial feature of my model. An exception to this is Angeloni and Faia (2013), who develop a general equilibrium macro model with bank fragility to study the interaction between monetary policy and bank capital regulation.

Bryant (1980) and Diamond and Dybvig (1983) laid the foundation for a vast microeconomic literature on bank runs. A number of papers consider models in which some depositors receive interim information about the prospects of the bank (e.g., Jacklin and Bhattacharya, 1988; Chari and Jagannathan (1988)). These models explain bank runs as an equilibrium phenomenon. Rochet and Vives (2004) and Goldstein and Pauzner (2005) also consider bank run models with unique equilibria, but without information asymmetry between depositors. Using global games techniques, they analyze models in the which every agent makes withdrawal decision based on a noisy signal about the bank's asset quality (see also Allen, Carletti, Goldstein, and Leonello, 2018). Dávila and Goldstein (2023) provide a comprehensive account of theoretical papers on bank runs, together with a review of the literature that analytically characterizes optimal contracts to prevent runs.

This paper is more closely related to work that incorporates financial panics in quantitative models (see, e.g., Gertler, Kiyotaki, and Prestipino, 2020, and Rottner, 2023). Following the analysis of Uhlig (2010), a common feature of these papers is the focus on systemic runs: a bank is affected by a liquidity withdrawal only if other banks are affected by liquidity withdrawals too. That is, a depositor withdraws from her bank if she perceives all other depositors will withdraw from all their banks, and that the ensuing systemic run could collapse the entire banking system due to fire sale of liquid assets to inefficient outside investors. Similarly to these papers, I model panic episodes as the result of a sunspot and some underlying strategic complementarities that drive investors' rational withdrawal decisions. Differently from these papers, those complementarities operate at bank level (rather than at a system-wide level) and panic episodes in my model have heterogeneous implications across banks.

Finally, the effects of deposit insurance on banks' risk taking incentives in my model are related to the view of financial fragility as source of incentives for bank managers (Calomiris and Kahn, 1991; Diamond and Rajan, 2001), which implies a loss of market discipline from the insurance of bank deposits and, more generally, from making banks less exposed to runs. In line with this view and the trade-offs captured by my model, the cross-country analysis in Anginer, Demirgüç-Kunt, and Zhu (2014) shows that providing more generous deposit insurance increased bank risk in the years leading up to the global financial crisis, while offering stabilization effects during the crisis.[4]

Outline. The rest of the paper is organized as follows. Section 2 describes the model and its key equilibrium conditions. Section 3 contains the baseline calibration of the model and its results regarding banks' risk taking incentives and the response of the economy to the realization of a panic episode. In Section 4 I analyze the performance of the economy under alternative levels of the deposit insurance coverage, identifying the level that maximizes social welfare. The Appendix contains a complete list of equilibrium conditions, data sources, solution method, and several complementary materials referred throughout the main text.

2 The model

I consider an infinite-horizon economy cast in discrete time, in which dates are indexed by t. There is a single non-durable consumption good in every date used as the numeraire, and which can be transformed into physical capital used for production. At any given date the economy is populated by: (i) households; (ii) banks; (iii) a representative non-bank-dependent (physical-)capital-producing firm; (iv) a representative consumption-good producing firm; and (v) a deposit insurance agency (DIA).

Households. Each household is infinitely-lived and makes consumption-savings decisions to maximize its inter-temporal expected utility. It can invest its savings in the non-bank-dependent capital-producing firms, and hold (partially) insured demand deposits with banks. The household consists of two classes of members: workers and bankers. These agents obtain consumption insurance from the household. The workers inelastically supply one-unit of labor to the representative consumption-good producing firm and transfer their wage income to the household. The bankers manage the household's investments in banks' equity which are subject to frictions further specified below.

Banks. There are a continuum of measure one of banks. They are perfectly competitive and operate under limited liability. They borrow from households by issuing demand deposits and issue equity among bankers in order to comply with a regulatory capital requirement. Each bank manages an investment project in physical-capital production that is operational between two consecutive dates. Its project is subject to bank-idiosyncratic shocks, whose realization affects the effective-units of capital produced. Banks can exert effort in reducing

[4] Demirgüç-Kunt and Detragiache (2002), Demirgüç-Kunt and Huizinga (2004), and Gropp, Gruendl, and Guettler (2014) provide additional evidence of risk taking incentives induced by deposit insurance. See Allen, Carletti, and Leonello (2011) and Anginer and Demirgüç-Kunt (2018) for excellent reviews.

the likelihood of its project being exposed to the idiosyncratic-shocks.

Non-bank-dependent firms and consumption goods production. There is a representative non-bank-dependent (physical-)capital-producing firm that raises direct financing from households. A representative consumption-good producing firm combines non-bank-dependent physical capital, bank-dependent physical capital, and labor to produce consumption good.

Deposit insurance agency. The DIA is responsible for the resolution of failed-banks. It raises lump-sum taxes from the household to cover the losses on the insured portion of deposits of the banks that defaulted as a result of their previous period of operation. The taxes are subject to deadweight costs, explained below in greater detail.

The following subsections describe each of these agents, their optimization problems, and the definition of equilibrium in detail.

2.1 Production environment

Non-bank-dependent firms and banks produce one class of physical capital each, labeled h and b, respectively. These classes of physical capital are not perfect substitutes and, hence, can be eventually rented to the consumption-good-producing firms at different equilibrium rental rates.[5]

Non-bank-dependent production. The representative firm from the non-bank dependent sector can transform a_t^h consumption good units from the household in period t into $k_{t+1}^h = a_t^h$ units of physical capital of class h in period $t+1$. Renting this capital at $t+1$ yields a per-unit rental rate r_{t+1}^h and the recovery of $1-\delta^h$ units of consumption good, where δ^h is the depreciation rate.[6] So the gross return of this class of capital is $R_{t+1}^h = 1 + r_{t+1}^h - \delta^h$.

Bank-dependent production. A bank j can transform a_{jt}^b units of consumption good into

$$k_{jt+1}^b = \begin{cases} \omega_j \left(a_{jt}^b - \frac{l_{jt+1}}{1-\lambda} \right), & \text{with probability } 1 - m_{jt}, \\ a_{jt}^b - l_{jt+1}, & \text{with probability } m_{jt} \end{cases} \tag{1}$$

[5]The non-bank-dependent sector in my model can be interpreted as consisting of large firms with access to capital markets, and the bank-dependent sector as consisting of small-and-medium sized firms who primarily rely on bank financing. My modelling framework closely follows Abad et al. (2024). See Begenau (2020) or Davydiuk (2017) for alternative frameworks with similar interpretation.

[6]I model physical capital as fully fungible into consumption good after one period to minimize the number of state variables in the model.

units of physical capital of class b in period $t+1$. Renting this capital at $t+1$ yields a per-unit gross return $R^b_{t+1} = 1 + r^b_{t+1} - \delta^b$, where r^b_{t+1} and δ^b are the corresponding rental and depreciation rates.

In Equation (1), ω_j is a bank-idiosyncratic shock realized at $t+1$. It is identically distributed across time and across banks. $m_{jt} \in [0,1]$ is a variable that captures managerial bank-level risk choice. It is private information of the bank at date t. The term $l_{jt+1} > 0$ captures the possibility that at the beginning of period $t+1$, the bank j may have to (early-)liquidate a portion of investment, after learning whether or not it is exposed to the idiosyncratic-shocks, but before the realization of shocks and the completion of production process. The early liquidation process involves reversing the investment into consumption good, and is associated with proportional losses λ conditional on the investment being exposed to the idiosyncratic-shocks.[7]

The bank-idiosyncratic shocks ω_j are log-normally distributed, with $\mathbb{E}(\omega_j) \leq 1$. Bank j's exposure to the shock at $t+1$ is determined by its choice m_{jt}.[8] I assume that the choice of m_{jt} is associated with a cost $\mathcal{C}(m_{jt})$ per unit of investment, where the function $\mathcal{C}(m)$ satisfies $\mathcal{C}(0) = \mathcal{C}'(0) = 0$, $\mathcal{C}'(m) > 0$, and $\mathcal{C}''(m) > 0$. Under this formulation, banks' risk choice can be interpreted as their effort in exerting proper *risk management*.

The role of banks in my model is justified along the lines of Diamond and Rajan (2001). As I will show below, the fragility of banks' capital structure provides incentives for them to exert proper risk management. At the same time, the safety-net due to deposit insurance, standard limited liability distortions, and the unobservability of m_{jt} to depositors and the DIA can make sub-optimal risk management (risk-shifting) attractive to the banks.

Consumption goods production. A representative consumption-good producing firm combines non-bank-dependent physical capital K^h_t, bank-dependent physical capital K^b_t, and labor H_t to produce

$$Y_t = z_t G(K^h_t, K^b_t, H_t) \tag{2}$$

units of consumption good, where $G(\cdot)$ is a constant-returns-to-scale production function, and z_t is an aggregate productivity shock. The firm maximizes its profits $Y_t - r^h_t K^h_t - r^b_t K^b_t - W_t H_t$ taking the rental rates r^h_t and r^b_t and the wage rate W_t as given.

[7] These losses can be interpreted as due-diligence costs, or costs incurred due to lack of redeployability of assets exposed to idiosyncratic risk (see, e.g., Williamson, 1988).

[8] The formulation of banks' risk taking choices in probabilistic terms is similar in spirit to Martinez-Miera and Repullo (2017).

2.2 Households

In each period t, the households obtains utility from the consumption of non-durable goods. They inelastically supply one unit of labor to the representative consumption-good producing firm, remunerated with a wage W_t; receive net dividend payments Ξ_t from bankers as further specified below; and pay lump-sum taxes T_t to the DIA. Households save in the form of demand deposits at banks and invest in claims on physical capital issued by the non-bank-dependent sector.

Bank deposits held by households are insured by the DIA up to a limit $\bar{D}$. In practice, this means that even in the event of a bank failure, the household is guaranteed to recover deposits in the failing bank up to $\bar{D}$ (including any accrued interest). Deposits in excess of the insured limit are subject to default risk. In particular, if a banks fails the DIA repossess its assets in order to first recoup what it owes to satisfy the deposit guarantees, and any residual proceeds are distributed among (partially) insured depositors on a pro-rata basis.

The problem of the household involves choosing consumption C_t, bank deposits D_t, and investment in claims issued by the non-bank-dependent sector A_t^h, so as to maximize its expected discounted lifetime utility

$$\mathbb{E}_t \sum_{\tau=0}^{\infty} \beta^{\tau} U(C_{t+\tau}), \tag{3}$$

where β is the subjective discount rate, and $U(\cdot)$ is a standard concave, twice continuously differentiable function. In each period the household is subject to the following budget constraint

$$C_t + D_t + A_t^h \;=\; W_t + \min\{\bar{D}, R_{t-1}^d D_{t-1}\} + \max\{\tilde{R}_t^d D_{t-1} - \bar{D}, 0\} + R_t^h A_{t-1}^h + \Xi_t - T_t, \tag{4}$$

where the second term on the right hand side are the (safe) gross returns $\min\{\bar{D}, R_{t-1}^d D_{t-1}\}$ in period t of the deposits held at banks up to the insured limit $\bar{D}$, and the third term are the (potentially risky) gross returns $\max\{\tilde{R}_t^d D_{t-1} - \bar{D}, 0\}$ in period t of any deposits held at banks above the insured limit. I am interested in a symmetric equilibrium, hence I assume that at date t the household invests its deposits symmetrically in all the (symmetric) banks in the economy.

In addition to the inter-temporal decisions in the above problem, households also face an intra-temporal choice regarding early versus late withdrawal of their deposits. Abstracting from idiosyncratic intra-period liquidity needs that might justify early withdrawals as in the literature (e.g., Diamond and Dybvig, 1983), my analysis focuses on the vulnerability to self-fulfilling runs that the demandability of deposits generates. Particularly, in between any two consecutive dates, coordination problems may trigger (some) households to withdraw their deposits from some banks (specifically, those suffering realizations of ω_j for which a run has the power to turn the bank insolvent). Further details on households' *run* incentives on specific banks are described in Section 2.4.

2.3 Bankers

Bankers manage their household's investment in bank equity. Let $V_t(n_t^b)$ be the value of being a banker managing net worth n_t^b in period t. The banker can vary that net worth by b_t at a pecuniary cost $\Upsilon(b_t^+)$ given by an increasing and convex function with $\Upsilon(0) = \Upsilon'(0) = 0$ and $b_t^+ \equiv \max\{b_t, 0\}$. So, reflecting (unmodeled) frictions in the equity raising process, equity issuance ($b_t > 0$) is costly while discretionary dividends ($b_t \in [-n_t^b, 0)$) are not.

The banker can invest the resulting funds, $n_t^b + b_t$, in equity of any of the banks operating between t and $t+1$, taking as given the distribution of equity returns R_{t+1}^e. Out of the gross returns earned at $t+1$, an exogenous fraction $1-\theta$ is paid out to the household and the rest is retained under the management of the banker. The optimization problem of a banker can be recursively stated as follows

$$V_t(n_t^b) = \max_{b_t \geq -n_t^b} \left\{ -b_t - \Upsilon(b_t^+) + \mathbb{E}_t \left[\Lambda_{t+1}(1-\theta) R_{t+1}^e \right] (n_t^b + b_t) + \mathbb{E}_t \left[\Lambda_{t+1} V_{t+1}(n_{t+1}^b) \right] \right\} \quad (5)$$

with

$$n_{t+1}^b = \theta R_{t+1}^e (n_t^b + b_t), \quad (6)$$

where the first two terms in (5) account for newly raised equity (or discretionary dividends if $b_t < 0$) and its issuance costs; the third term reflects the expected discounted value of the exogenously distributed part of the returns generated at $t+1$ by the investment in bank equity in period t; and the fourth term is the expected discounted value of the net worth retained under banker's management at $t+1$. Equation (6) is the law of motion of that net worth. As the household is the final receiver of all the payoffs from the wealth that bankers manage, future payments and values are discounted with the stochastic discount factor $\Lambda_{t+1} = \beta U'(C_{t+1})/U'(C_t)$. I am interested in a symmetric equilibrium, hence I assume that each banker invests symmetrically in all the (symmetric) banks in the economy.

2.4 Banks

Banks are constant-returns-to-scale intermediaries that operate between any two consecutive periods. They maximize the net present value of the equity that bankers invest in them. In period t, a bank j combines this equity e_{jt} with (partially) insured deposits d_{jt} issued to the household in order to finance investment a^b_{jt} in a physical capital project. Hence, the balance sheet identity of bank j imposes that

$$a^b_{jt} = e_{jt} + d_{jt}. \tag{7}$$

In addition to capital structure decisions, the bank chooses its risk management effort, m_{jt}, which determines the probability that its funded investment is exposed to the bank-idiosyncratic shocks at $t+1$. Importantly, all items on the bank's balance sheet are publicly observable at date t, but its choice of risk management effort is not.

As under the various versions of the Basel Accord after 1988, I assume that banks are subject to a minimum regulatory capital requirement of the form

$$e_{jt} \geq \gamma a^b_{jt}, \tag{8}$$

which imposes that at least a fraction γ of the bank's assets have to be financed with equity capital.[9]

At any date t, all banks in the economy face identical constraints, receive a symmetric infusion of equity from bankers, as well as symmetric investment of deposits from households. Since all banks are ex-ante identical, I focus on a symmetric equilibrium in which banks make identical decisions at t.

Sunspot process and panic runs. At the beginning of $t+1$, before the realization of the shocks and the completion of production, a fraction ζ of banks' depositors – dubbed *alert* depositors – learn the identity of banks which are exposed to the idiosyncratic shocks and can withdraw their deposits. That is, the alert depositors at this stage can distinguish between banks whose risk management effort at t either succeeds ($s_j = 1$) or fails ($s_j = 0$) in insulating itself from the (yet-to-be-realized) shocks ω_j. The non-alert depositors are called *sleepy* and remain uninformed and passive at this stage.[10]

[9] Consistent with the assumption that banks' risk management effort is not observable to depositors and the DIA, this requirement is not contingent on m_{jt}.

[10] The distinction between *sleepy* and *alert* depositors has been made in the previous literature by, e.g., Jacklin and Bhattacharya (1988); Hanson, Shleifer, Stein, and Vishny (2015); Jiang, Matvos, Piskorski, and

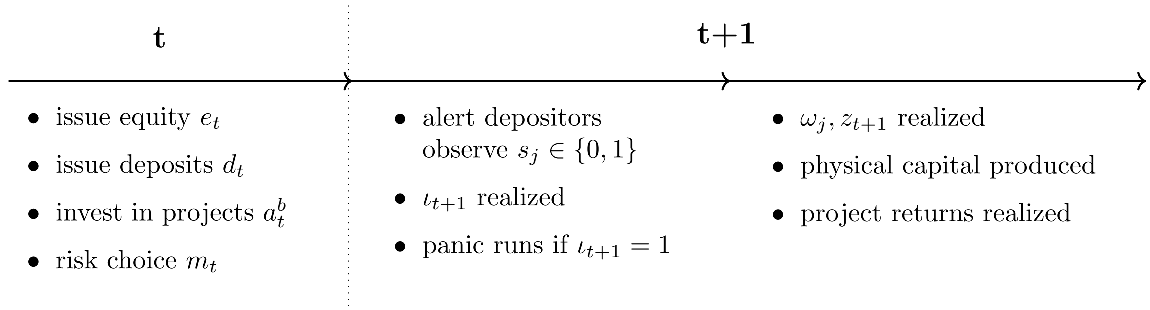

Figure 1. Timing

During this stage, coordination problems can trigger panic runs. In particular, a (partially -insured) alert depositor runs on a bank if, given their (rational) beliefs about the behavior of other alert depositors, they attribute a sufficiently high probability to the possibility that the bank becomes insolvent. To simplify the analysis, I assume that under the parameterizations explored in the analysis, this sufficiently large probability of insolvency requires all other alert depositors to withdraw their deposits, forcing the bank to early-liquidate investments.[11] As in the literature, the incentives for alert depositors who expect the bank to go bankrupt to run are driven by first-mover-advantages associated with a sequential service constraint (see Diamond and Dybvig, 1983). In this situation two equilibria can exist: a "normal" equilibrium in which there are no early liquidations and only the fundamentally insolvent banks (if any) eventually fail, and a "panic" equilibrium in which alert depositors run on all the vulnerable banks (those with $s_j = 0$).[12]

An aggregate sunspot process determines the coordination of alert depositors in the panic equilibrium in i.i.d. manner over time but perfectly correlated across vulnerable banks. Specifically, let ι_t be a binary sunspot variable that takes on a value of 1 with an exogenous probability ε and a value of 0 with probability $1-\varepsilon$. When $\iota_{t+1} = 1$, alert depositors coordinate to (partially) withdraw their deposits from the vulnerable banks. Figure 1 summarizes the timing of events. Below, I elaborate further on alert depositors' run-incentives.

Fundamental failures. Let π^{ι}_{st+1} denote the terminal net worth at $t+1$ of a bank

Seru (2020); Drechsler, Savov, Schnabl, and Wang (2023). In a recent study on the 2023 panic runs in the US surrounding the collapse of Silicon Valley Bank, Jiang, Matvos, Piskorski, and Seru (2024) highlight the role of *sleepy vs. alert* depositors in determining the consequences of panics.

[11]The precise probability threshold above which this assumption holds will be provided in the quantitative part of the analysis.

[12]This feature resulting from the information environment in my model is consistent with the findings in Blickle, Brunnermeier, and Luck (2024), who highlight depositors' inability in perfectly differentiating between banks during episodes of panic runs. In particular, they study run on the German banking system in 1931 and find no difference in total deposit outflows between failing and surviving banks.

conditional on its exposure to the idiosyncratic shocks and the realization of the aggregate sunspot shock. Then, when $\iota_{t+1} = 0$,

$$\pi^0_{0t+1}(\omega_j) = \omega_j R^b_{t+1} a^b_t - R^d_t d_t - \mathcal{C}(m_t) a^b_t, \tag{9}$$
$$\pi^0_{1t+1} = R^b_{t+1} a^b_t - R^d_t d_t - \mathcal{C}(m_t) a^b_t. \tag{10}$$

A bank is fundamentally insolvent if its portfolio returns at $t+1$ are insufficient to pay the promised repayment in full, i.e., its terminal net worth is negative. To simplify the exposition, I assume that parameter values are such that in equilibrium $\pi^0_{1t+1} > 0$, so that a bank not exposed to the idiosyncratic shocks never fails in the normal equilibrium.[13] As for a bank exposed to the shocks at $t+1$, Equation (9) can be used to define a threshold value for ω_j, $\bar{\omega}^{\iota}_{t+1}$, below which the bank's net worth is negative and it is therefore insolvent

$$\bar{\omega}^0_{t+1} = \frac{R^d_t d_t + \mathcal{C}(m_t) a^b_t}{R^b_{t+1} a^b_t}. \tag{11}$$

Thus, the probability with which a vulnerable bank ($s_j = 0$) becomes insolvent if it does not suffer a run is $F(\bar{\omega}^0_{t+1})$, where F denotes the cumulative distribution function of the bank-idiosyncratic shocks.

By the law of large numbers, for any arbitrary risk management effort m_t exerted at date t, a fraction $\mathcal{M}_{t+1} = m_t$ of banks have $s_j = 1$ and are immune to the idiosyncratic shocks ω_j at date $t+1$. Then, the aggregate proportion of banks that fail due to weak fundamentals is

$$\mathcal{D}^0_{t+1} = (1 - \mathcal{M}_{t+1}) F(\bar{\omega}^0_{t+1}). \tag{12}$$

Probability of self-fulfilling failures. Following Dávila and Goldstein (2023), I assume that when the sunspot is realized ($\iota_{t+1} = 1$), the proportion ζ of alert depositors consider withdrawing the uninsured portion of their deposits at all their banks. Then, using the notation introduced in (1), and denoting $x_t \equiv \min\left\{\frac{\overline{D}}{R^d_t D_t}, 1\right\}$ the insured share of deposits, the investment to be liquidated by any bank that is subject to runs is

$$l_{t+1} = \zeta(1 - x_t) R^d_t d_t. \tag{13}$$

Taking into account the liquidation costs λ introduced in Equation (1), the terminal net

[13] I will guess and verify that this assumption holds for every combination of parameters used in the quantitative analysis.

worth of a bank conditional on $s_{jt+1} = 0$ and $\iota_{t+1} = 1$ is

$$\begin{aligned}\pi^1_{0t+1}(\omega_j) &= \omega_j R^b_{t+1}\left(a^b_t - \frac{l_{t+1}}{1-\lambda}\right) - [(1-\zeta)(1-x_t)+x_t]R^d_t d_t - \mathcal{C}(m_t)a^b_t \\ &= \omega_j R^b_{t+1}\left(a^b_t - \frac{\zeta(1-x_t)R^d_t d_t}{1-\lambda}\right) - [(1-\zeta)(1-x_t)+x_t]R^d_t d_t - \mathcal{C}(m_t)a^b_t. \qquad (14)\end{aligned}$$

Equation (14) can be used to define the threshold value for ω_j below which the exposed banks experiencing a panic run turn insolvent

$$\bar{\omega}^1_{t+1} = \frac{[(1-\zeta)(1-x_t)+x_t]R^d_t d_t + \mathcal{C}(m_t)a^b_t}{R^b_{t+1}\left(a^b_t - \frac{\zeta(1-x_t)R^d_t d_t}{1-\lambda}\right)}, \qquad (15)$$

which is lower than $\bar{\omega}^0_{t+1}$ and strictly so unless deposits are fully insured ($x_t = 1$). Thus, the probability with which a vulnerable bank ($s_j = 0$) ends up defaulting if it suffers a run ($\iota_{t+1} = 1$) is $F(\bar{\omega}^1_{t+1})$, which, unless $x_t = 1$, is strictly larger than the probability with which it would default in the absence of a run, $F(\bar{\omega}^0_{t+1})$.

Finally, guaranteeing that banks with $s_j = 1$ are not vulnerable to runs requires that their terminal net worth in case they were experiencing a run is non-negative:

$$R^b_{t+1}\left(a^b_t - l_{t+1}\right) - [(1-\zeta)(1-x_t)+x_t]R^d_t d_t - \mathcal{C}(m_t)a^b_t \geq 0, \qquad (16)$$

and a sufficient condition for this is having $\bar{\omega}^1_{t+1} \geq 1$ (since $\lambda > 0$), which I guess and verify to be true under the parameter values considered in the analysis below. Given the immunity of $s_j = 1$ banks to the sunspot, we eventually have $\pi^1_{1t+1} = \pi^0_{1t+1}$, with the expression for π^0_{1t+1} given by (10).

Then, the aggregate proportion of banks that fail when a sunspot is realized is

$$\mathcal{D}^1_{t+1} = (1-\mathcal{M}_{t+1})F(\bar{\omega}^1_{t+1}), \qquad (17)$$

and, the proportion of bank failures due to self-fulfilling losses when the aggregate sunspot shock realizes is

$$\mathcal{D}^1_{t+1} - \mathcal{D}^0_{t+1} = (1-\mathcal{M}_{t+1})\left[F(\bar{\omega}^1_{t+1}) - F(\bar{\omega}^0_{t+1})\right]. \qquad (18)$$

A higher deposit insurance limit $\bar{D}$ increases the share of insured deposits, x_t, which reduces the investment that needs to be liquidated conditional on runs (as seen in (13)). Other things equal, this reduces the proportion of banks $F(\bar{\omega}^1_{t+1})$ subject to panic-induced failures.

2.5 Deposit insurance agency

The deposit insurance agency (DIA) supervises the liquidation process of failed-bank assets, which is subject to proportional repossession costs μ.[14] The funds recovered are first used to meet its own obligations towards satisfying the deposit guarantees. The residual funds (if any) are distributed among holders of uninsured deposits on a pro-rata basis. The DIA's slack in satisfying the deposit guarantee (if any) is met by raising lump sum taxes from households to ex-post balance its budget. The DIA has to balance its budget period-by-period. I denote the losses to the DIA at time t as Ψ_t. Following Dávila and Walther (2020), the total lump sum tax T_t imposed on the households to balance the agency's budget is

$$T_t \;=\; \Psi_t + \tau(\Psi_t), \tag{19}$$

where $\tau(\cdot)$ is a weakly increasing and convex function that satisfies $\tau(0) = 0$ and $\lim_{\Psi\to\infty} \tau(\Psi) = \infty$. A detailed expression for Ψ is provided in the Appendix A.

2.6 The problem of the bank

Banks maximize the net present value of the equity that bankers invest in them. Prior to the analysis of the banks' decision problem, it is useful to first discuss the solution to bankers' optimization problem in (5)-(6).

Following Abad et al. (2024), I guess and verify that a banker's value function is an affine function of her net-worth. It involves a linear term $v_t n_t^b$ that implies a constant marginal shadow value v_t of the net worth under the banker's management in period t, and an intercept v_t^0 which accounts for the extra value of the option to raise additional funds from the household (at a convex cost). The marginal shadow value of each unit of n_t^b satisfies

$$v_t = \mathbb{E}_t \left[\Lambda_{t+1}(1 - \theta + \theta v_{t+1}) R^e_{t+1}\right]. \tag{20}$$

Equation (20) defines the bankers' stochastic discount factor as $\Lambda^b_{t+1} = \Lambda_{t+1}(1 - \theta + \theta v_{t+1})$,

[14]The model follows Bernanke, Gertler, and Gilchrist (1999) in adopting a "costly state verification" setup, by which the DIA / banks' depositors must incur a cost that is proportional to the assets of the bank in order to observe the realization of the idiosyncratic shocks ω.

where Λ_{t+1} is the stochastic discount factor of the household on whose behalf the banker manages investments in bank equity, and the term $(1-\theta+\theta v_{t+1})$ accounts for the marginal value $v_{t+1} \geq 1$ of the net worth that bankers can retain under their management at $t+1$. Whenever $v_{t+1} > 1$, retained equity returns have extra value to bankers as they avoid incurring the equity issuance costs captured by the function $\Upsilon(\cdot)$. The remaining details of the banker's problem are provided in Appendix A.

Banks' optimization problem. Banks operate under limited liability, which means that the equity payoffs generated by a bank at time $t+1$ are given by the positive part of the difference between the returns from its assets and the repayments due to its depositors, net of the risk management effort costs. If the returns from the assets are greater than the repayments, the difference is paid back to the bank's equity holders. Otherwise, the bank's equity is written down to zero and its assets are repossessed by the DIA. Using the notation introduced above, the problem of the bank can be compactly written as

$$\mathbb{E}_t \left\{ \Lambda^b_{t+1} \left[m_t \max\{\pi^{\iota}_{1t+1}, 0\} + (1-m_t) \max\{\pi^{\iota}_{0t+1}, 0\} \right] \right\} - v_t e_t, \tag{21}$$

subject to the balance sheet constraint, and the minimum capital requirement. The bank's objective function in (21) reflects that the equity e_t is valued at its equilibrium opportunity cost v_t. Additionally, the presence of v_{t+1} in Λ^b_{t+1} reflects that, other things being equal, equity returns generated by the bank when v_{t+1} is relatively high are more valuable to the banker than those generated when v_{t+1} is relatively low. This produces what Abad et al. (2024) call a scarce-bank-equity-preservation effect, which reduces banks' risk taking incentives (relative to static formulations of banks' systemic risk-taking).

The first order condition with respect to the choice of risk management effort is

$$\mathbb{E}_t \left\{ \Lambda^b_{t+1} \left[\pi^{\iota}_{1t+1} - \max\{\pi^{\iota}_{0t+1}, 0\} \right] \right\} = \mathbb{E}_t \left\{ \Lambda^b_{t+1} \left[m_t \mathcal{C}'(m_t) a^b_t - (1-m_t) \frac{\partial \max\{\pi^{\iota}_{0t+1}, 0\}}{\partial m_t} \right] \right\}, \tag{22}$$

where the term on the left hand side reflects the expected discounted increase in payoffs generated from a marginal increase in risk management effort, and the term of the right hand reflects the expected discounted increase in effort costs.

Equation (22) sheds light on the main drivers of banks' risk choices. On the one hand, a marginal increase in risk management effort reduces the likelihood of being exposed to the idiosyncratic shocks. Conditional on being in normal times – absent panic runs but including normal expansions and recessions – this yields a higher expected amount of physical capital (and therefore asset returns), since $\mathbb{E}(\omega_j) \leq 1$. Conditional on the realization of sunspot, this also increases the bank's probability of avoiding early liquidation of investments to satisfy deposit withdrawals. To the extent that aggregate bank equity is scarcer and therefore more valuable conditional on panic runs, the term Λ^b_{t+1} further introduces an incentive for the bank to generate higher equity returns in this state. On the other hand, lower effort allows saving on risk management costs and, exposure to idiosyncratic shocks allows the bank to enjoy higher upside risk.

The main (direct) effect of higher deposit insurance is the increase in $\max\{\pi^1_{0t+1}, 0\}$, i.e., the expected payoffs conditional on both the realization of aggregate sunspot ($\iota = 1$) and being exposed to the bank-idiosyncratic shocks ($s_j = 1$). This reduces the bank's incentives in exerting risk management effort. Importantly, the forward-looking force captured by Λ^b_{t+1} amplifies the reduction in incentives, since the gains from being a surviving bank are lower when bank-runs cause lower net worth losses in the aggregate.

2.7 Equilibrium

A competitive equilibrium is given by some price functions determining prices in each state of the economy as well as the policy functions of the households, the banks, the representative non-bank-dependent firm, and the representative consumption-good producing firm, such that, given a sequence of shocks, the sequence of each of the agents' decisions solve their corresponding optimization problems, the sequence of prices clears all markets, and the sequence of endogenous state variables satisfies their corresponding laws of motion. A formal definition of the competitive equilibrium, together with the complete set of optimality and market clearing conditions, is provided in Appendix A.

3 Quantitative analysis

This section introduces the functional forms chosen for the numerical analysis, and presents the baseline parameterization. It then discusses the quantitative fit of the model by looking at its business-cycle properties, and explores the endogenous responses in the baseline economy to the realization of a sunspot shock. All data used in the quantitative analysis is publicly available. To account for the non-linearities associated with the possibility of panic runs, I rely on a global numerical solution method. Details of the solution method are in Appendix B.

3.1 Functional forms and shock processes

In the quantitative analysis below, the functional form chosen for the utility function of the household is

$$U(C_t) = \frac{C_t^{1-\nu} - 1}{1-\nu}, \tag{23}$$

with constant risk-aversion parameter ν. The production function of the consumption-good producing firm is Cobb-Douglas with

$$G(K_t^h, K_t^b, H_t) = \mathcal{K}(K_t^h, K_t^b)^\alpha H_t^{1-\alpha}, \tag{24}$$

where $\alpha \in (0,1)$ and $\mathcal{K}(K_t^h, K_t^b)$ is a physical capital composite

$$\mathcal{K}(K_t^h, K_t^b) = [\phi(K_t^h)^\rho + (1-\phi)(K_t^b)^\rho]^{\frac{1}{\rho}}, \tag{25}$$

with $\phi \in (0,1)$ and $\rho > 0$, that features a constant elasticity of substitution $1/(1-\rho)$ between the physical capital produced by non-bank dependent firms K^h and that produced by bank dependent firms K^b. The cost of risk management effort is specified as

$$\mathcal{C}(m_t) = \frac{\kappa}{2}(m_t)^2, \tag{26}$$

with $\kappa > 0$, which satisfies the properties stated in the model section. Following Dávila and Goldstein (2023), the marginal cost of public funds is specified as

$$\tau(\Psi_t) = \frac{\tau_1}{\tau_2}\left(e^{\tau_2 \Psi_t} - 1\right), \tag{27}$$

for which the parameter $\tau_1 = \tau'(0)$ represents the marginal cost of public funds for a small intervention and the parameter $\tau_2 = \tau''(\Psi)/\tau'(\Psi)$ modulates how quickly the cost of public funds increases with Ψ. The cost of raising new equity is specified as

$$\Upsilon(b_t^+) = \frac{\upsilon}{2}\left(b_t^+\right)^2, \tag{28}$$

with $\upsilon > 0$, which satisfies the properties stated in the model section. The aggregate productivity shock obeys the following first-order process

$$\log(z_t) = \rho_z \log(z_{t-1}) + \sigma_z \epsilon_t, \tag{29}$$

with $\rho_z \in (0,1), \sigma_z > 0$, and where ϵ_t is normally distributed with mean zero and variance one. The bank-idiosyncratic shocks are log-normally distributed

$$\log(\omega) \sim \mathcal{N}\left(\frac{-\sigma_\omega - \psi}{2}, \sigma_\omega^2\right), \tag{30}$$

with $\sigma_\omega > 0$ and $\psi > 0$.

3.2 Mapping the model to the data

The model is calibrated to quarterly US data from 1984 Q1 to 2006 Q4. The calibrated parameters – 21 overall – can be divided into two groups. The first group consists of twelve parameters, mainly related to household preferences, production sector, and the social costs of bank failures. They are chosen to either directly match with their data counterpart, or set to commonly agreed values in the business-cycle literature and related macro-banking papers. The remaining nine parameters in the second group are mainly those governing the behaviour of the banking sector, and hence are specific to my model. They are jointly set to match model implied moments to several data targets. Given that my policy functions are non-linear, I obtain model implied moments by simulating my economy for one hundred thousand periods[15]

Table 1 and Table 2 respectively list the values assigned to all first and second group parameters in the baseline calibration, and summarize their corresponding sources or data targets. Table 3 provides the values of moments targeted in the data and compares them to their model generated counterparts. In what follows, I discuss the rationale for my choices in the calibration exercise.

Pre-set parameters. The subjective discount rate β is set to a standard 0.995, delivering an annual risk-free rate around 2%. The household's risk-aversion parameter ν is set to 2, which is a value traditionally used in macroeconomics. The output share α of the physical capital composite $\mathcal{K}$ is set to a standard 0.33 and the depreciation rate δ of physical capital is set to a standard 0.025, delivering an annual rate around 10%. I take the persistence parameter ρ_z of the aggregate productivity process from the business-cycle literature that uses a value of 0.95.

The minimum capital requirement γ is set to 8%, consistent with the general requirement

[15]As I am excluding the financial crisis from the sample, the sunspot variable is set to zero in these simulations.

Table 1
Pre-set parameters

	Parameter	Value	Source
β	Impatience	0.99	Standard
ν	Risk Aversion	2	Standard
α	Output elasticity of capital	0.33	Standard
δ	Depreciation rate of capital	0.025	Standard
ρ_z	Persistence of TFP shock	0.95	Standard
γ	Capital requirement	0.08	BCBS (2004)
ε	Sunspot Probability	1%	Jamilov et al. (2024)
ζ	Fraction of alert depositors	5%	Iyer and Puri (2012)
λ	Early liquidation costs	0.45	BCBS (2004)
μ	Bank default costs	0.30	Bennett and Unal (2015)
τ_1	Marginal cost of small intervention	0.13	Kleven and Kreiner (2006)
ψ	Risk taking losses	0.006	Begenau (2020)

under Basel II (BCBS, 2004; part 2.I, paragraph 40) as well as its Basel I predecessor. The probability of observing a sunspot ε is set at 1%, implying an average frequency of banking panics of once every 25 years, which is in line with the evidence reported in Jamilov et al. (2024) and coincides with the target for the frequency of banking panics set by Gertler et al. (2020). The proportion of alert depositors ζ is set to 5%, in line with the evidence in Iyer and Puri (2012) based on depositor-level data, and coincides with the value chosen for the proportion of *early depositors* in Dávila and Goldstein (2023).[16]

The value of the early-liquidation loss parameter λ is set to 0.45, consistent with the loss-given-default (LGD) parameter of 45% that the foundation approach of Basel II (BCBS, 2004 paragraph 287) fixed for senior corporate loans without specific collateral. The value of bankruptcy parameter μ is set equal to 0.3, consistent with the 30% average discounted total resolution cost per unit of assets estimated by Bennett and Unal (2015) using FDIC data from failed banks in the period 1986-2007.[17] Following Dávila and Goldstein (2023), the marginal cost of public funds for a small intervention, captured by τ_1, is set equal to 0.13 consistent with the estimate in Kleven and Kreiner (2006). Finally following Begenau (2020), the compensation for exerting effort in proper risk management of an investment project, governed by the parameter ψ, is set such that $1 - \mathbb{E}(\omega_j) = 0.32\%$ per quarter.[18]

[16]See also Kelly and Gráda (2000) who document withdrawals by a similar fraction of depositors during the bank run on Emigrants Industrial Savings Bank that occurred in 1854.

[17]See also Granja, Matvos, and Seru (2017), who estimate a recovery rate on bank assets after failure of 72%.

[18]In particular, Begenau (2020) obtains this spread by computing the average pretax excess return on the aggregate loan portfolio of banks relative to a maturity and credit-matched replicating portfolio based on investment-grade corporate bonds from Vanguard.

Table 2
Calibrated parameters

	Parameter	Value	Target
$\overline{D}$	Deposit insurance limit	5.2	Share of insured deposits
θ	Earnings retention rate	0.96	Return on bank equity
υ	Marginal cost, equity issuance	135	Bank equity issuance
κ	Marginal cost, risk management effort	0.008	Volatility, return on equity
ϕ	Non-bank-dependent share in capital	0.51	Bank/non-bank ratio
ρ	Substitution parameter capital composite	0.49	Volatility, share of insured deposits
τ_2	Slope of tax function	48	Marginal cost of public funds
σ_ω	Standard deviation of idiosyncratic shocks	0.031	Bank failure rate
σ_z	Standard deviation of TFP shocks	0.3%	Standard deviation of output

Calibrated parameters. The second group of parameters are calibrated so as to simultaneously match the targets listed in Table 3. Each parameter can be mainly associated with one target, as a indicated in the last column of Table 2.

The limit on deposit insurance $\bar{D}$ is set to match an average share of insured deposits of about 67% at US banks in the period 1984-2006. The bankers' wealth retention rate θ is set to 0.956 to match the about 13% average real return on average equity. The marginal cost of equity issuance υ is set to 142. It targets U.S. banks' average annual real equity issuance of about 5.36% of pre-existing equity.

The share of non-bank-dependent physical capital in the physical capital aggregator, ϕ, is fixed to match the about 86% bank to non-bank financing ratio in the economy, which is obtained following the same procedure as in De Fiore and Uhlig (2011).[19] The value of the elasticity of substitution parameter in the physical capital aggregator, ρ, and the marginal cost of risk management effort, κ, are jointly set to match (i) volatility of return on bank equity; (ii) volatility of the share of insured deposits. The parameter τ_2, governing how quickly the cost of public funds increases with taxes, is set to 48, to match an average marginal cost of public funds of 0.15 as in Dávila and Goldstein (2023). The standard deviation of bank-idiosyncratic shocks σ_ω is set to match the average annualized bank default rates in U.S. of around 0.76%. Finally, the standard deviation of the aggregate productivity shocks σ_z is set to match the volatility of real GDP.

[19] In particular, I identify such a ratio with the ratio of corporate loans to corporate securities, which is calculated using the liability and equity items in balance sheet of non-financial corporate businesses reported in the US Flow of Funds Accounts (Table B.103). Securities are the sum of commercial paper, municipal securities and corporate bonds. Loans are the sum of bank loans, mortgages and other loans and advances.

Table 3
Calibration targets and model fit

Target	Description	Data	Model
$\mathbb{E}(x)$	Share of insured deposits (%)	66.8	66.6
$\mathbb{E}(A^b/A^h)$	Bank/non-bank ratio (%)	85.9	86.2
$\mathbb{E}(R^e)$	Return on bank equity (%)	12.98	13.06
$\mathbb{E}(b/N^b)$	Bank equity issuance (%)	5.36	5.44
$\mathbb{E}(\mathcal{D}^0)$	Bank failure rate (%)	0.76	0.76
$\mathbb{E}(\tau(\cdot))$	Marginal cost of public funds	0.15	0.15
$\text{std}(R^e)$	Volatility, return on equity (p.p.)	1.22	0.59
$\text{std}(x)$	Volatility insured shared of deposits (p.p.)	0.97	0.71
$\text{std}(Y)$	Volatility output (p.p.)	0.98	1.03

Notes: Return on bank equity, equity issuance, and bank failure rates are reported in annualized percentage points. The standard deviations (std) of return on equity, insured share of deposits, and output are reported in quarterly percentage points.

3.2.1 Business-cycle properties

In this subsection, I discuss the quantitative performance of the model by looking at its business-cycle properties.

Banks' choice of risk management effort is an important source of endogenous risk-taking in my model. As it is private information of the bank, there is no direct counterpart in the data to draw comparisons. Nonetheless, to study the business-cycle behaviour of banks' risk-taking, I rely on an empirical proxy based on the "Senior loan officer opinion survey on bank lending practices" (SLO) published by the Federal Reserve Board.[20,21] The two panels of Figure 2 provide an account of the dynamics of banks' risk taking over the business-cycle in the data (left panel) and in the model (right panel). The left vertical axis in the data panel reports log deviation of real GDP from its (HP-filtered) trend. The right vertical axis reports a standardized measure of the net share of banks that tighten their lending standards – normalized around 0 and ranging between $[-1, 1]$ – published each quarter by the Fed Board. Data corresponds to the period between 1990 Q2 - 2006 Q4. The left and right vertical axes in the model panel respectively report % deviation of output and banks' risk management effort from their respective means.

[20] The survey is administered by senior staff at the Federal Reserve Banks with knowledge of bank lending practices. As stated on the Board's website, "the purpose of the survey is to provide qualitative and limited quantitative information on bank credit availability and loan demand, as well as on evolving developments and lending practices in the U.S. loan markets."

[21] See Maddaloni and Peydró (2011), who study the effect of monetary policy on lending standards. They provide evidence attributing softening in standards to banks' risk-shifting.

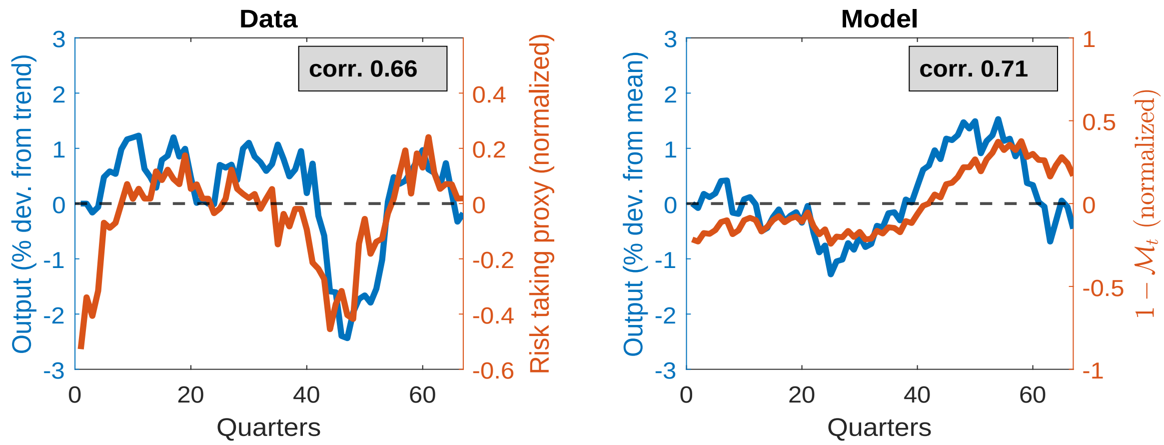

Figure 2. Risk taking in the data and the model

Notes: The empirical proxy for risk taking is the time series of the fraction of banks tightening their lending standards that is published in the "Senior loan officer opinion survey on bank lending practices" by the Federal Reserve Board. Data corresponds to 1990 Q2 - 2006 Q4. The right panel reports a model simulated time series for an equal time span (67 quarters).

While the empirical proxy does not allow for a quantitative comparison of magnitudes, the model captures the strong procyclicality in banks' incentives for risk taking. This means that banks relax lending standards during booms and tighten them during a recession, consistent with the findings on banks' risk taking behavior in Martinez-Miera and Suarez (2014).

Table 4
Business-cycle correlations
(untargeted)

Variable	Data	Model
Deposits	0.40	0.81
Insured share of deposits	-0.57	-0.81
Equity	0.16	0.81
Equity issuance	-0.11	-0.15
Return on equity	0.29	0.35
Bank/non-bank ratio	0.42	0.69

Notes: The data are the ratio of HP-filtered cycle component of the logged variable to the HP-filtered trend of GDP.

Table 4 summarizes the business-cycle correlations of the model's banking sector and compares them to the data. The model generates realistic business-cycle correlations of banks' capital structure, the return on equity they generate, and their share of financing the production of physical capital in the economy. Without being a calibration target, the

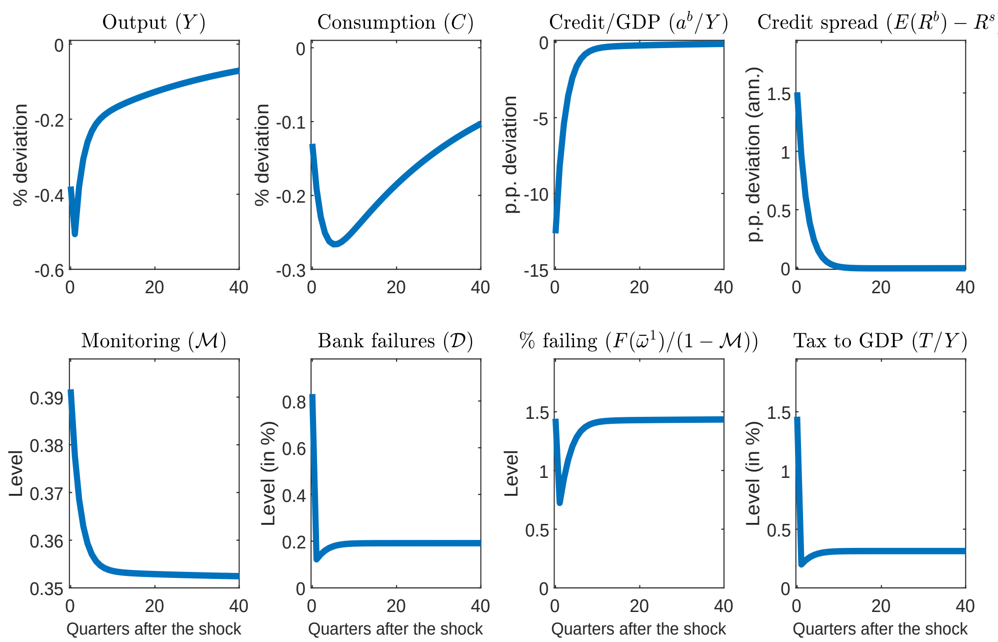

Figure 3. Endogenous responses to panic runs in the baseline economy

Vertical axes: deviations from the risk-adjusted steady state (units as indicated). Horizontal axes: quarters since the realization of the shock. The realization of the sunspot shock is set to zero for a sufficiently large number of quarters before $t = 0$, set to one at $t = 0$, and again to zero for the remaining number of displayed quarters.

model captures well the countercyclicality of the share of insured bank deposits, as well as banks' equity issuance.

3.3 Banking panics in the baseline economy

Figure 3 shows the response of key aggregate variables to the realization of a sunspot shock in the baseline economy. For illustrating the effects of panic runs, I suppose that the economy is initially in a risk-adjusted steady state.[22] At $t = 0$, the aggregate sunspot shock is realized (i.e., $\iota_0 = 1$) and then not again during the subsequent periods (i.e., $\iota_t = 0$ for $t \geq 1$). Upon the arrival of the sunspot, alert depositors coordinate to run on the vulnerable banks (those exposed to the idiosyncratic shocks), forcing early-liquidation of their investments. In the baseline economy, 0.8% banks fail during a panic, compared to 0.19% during normal times. The panics cause, on impact, a loss of about 14% of bank-dependent assets, a fall in output of 0.4%, and bank equity losses of about 11%. The depletion in net worth under bankers'

[22]This strategy to isolate the effects of sunspot-induced runs closely follows Gertler et al. (2020).

management provokes a reduction in bank credit (bank dependent investment), which largely explains the fall in output also in the second quarter (with the fall at $t = 1$ exceeding that at $t = 0$).

The net worth under bankers' management and, thus, bank equity, bank credit, and output gradually recover from $t = 1$ onwards. The fall in consumption is very significant and persistent, exceeding the fall in output because of the wealth destruction effect of the shock. The household also suffers the taxes needed to cover the deposit insurance costs as well as the consequences of the credit crunch (including, below normal wage income throughout the recovery path). Until banks fully recover their pre-crisis equity levels, the economy features reduced leverage (a low credit to GDP ratio) and a low bank to non-bank ratio.

4 The effects of deposit insurance

Having quantified the implications of a systemic sunspot panic episode in the baseline economy, I now perform counterfactual exercises. I analyze the effects of setting the deposit insurance limit $\bar{D}$ at different levels. In Figure 4, after solving for the equilibrium under each of the values of $\bar{D}$ in a grid varying from zero to a level that implies full deposit insurance (i.e., $x = 1$), I depict the stochastic steady state (SSS) levels of the same key variables previously described in Figure 3.[23]

The left bottom panel of the figure shows the strong negative effect of deposit insurance on banks' risk management effort (m_t). While with no insurance roughly 53% of banks are exposed to idiosyncratic shocks in the SSS ($1 - \mathcal{M}$), with 50% insurance coverage the proportion of exposed banks rises to 63%, and with full coverage to about 69%. The decline in risk management effort is accompanied by increasing risk of fundamental insolvencies. The aggregate proportion of banks failing in normal times (absent panics) increases from 0.16% with no insurance, to 0.21% under full insurance coverage. The associated deadweight costs of bank failures and increase in taxes needed to cover deposit insurance costs largely explains the decline in consumption. At the same time, the economy features increased leverage (a high credit to GDP ratio) and a higher bank to non-bank financing ratio from increasing deposit insurance coverage. This explains the increase in output and can be largely attributed to the decline in banks' funding costs (as deposits become cheaper).

[23] I refer to stochastic steady state as the state attained after sufficiently many periods without the realization of a sunspot shock.

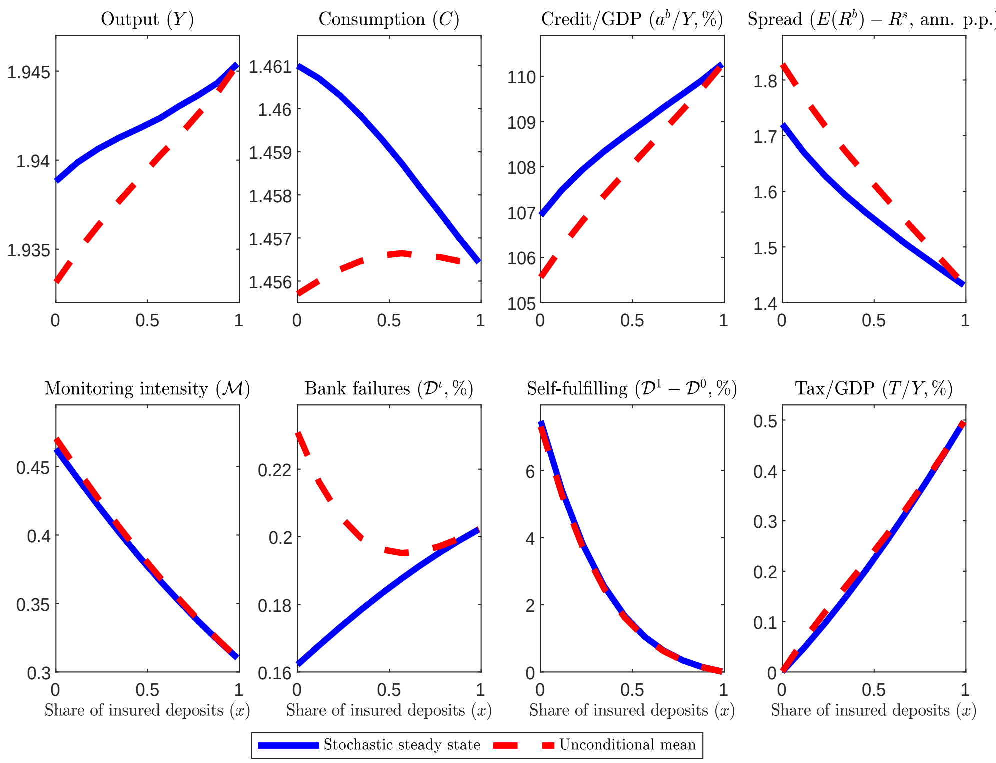

Figure 4. Effects of deposit insurance on selected equilibrium variables

Vertical axes: stochastic steady state values (solid blue lines) and unconditional mean values (dashed red lines); in levels, unless indicated otherwise. Horizontal axes: different values of the insured share of deposits x implied under various limits of deposit insurance $\bar{D}$.

The effects of deposit insurance on the unconditional means are depicted in dotted red lines. In stark contrast to the effects in the SSS, unconditional mean of bank failures is U-shaped in the level of deposit insurance. The reason is as follows. With no deposit insurance, conditional on a sunspot, the aggregate proportion of banks failing is about 7%. With even 50% insurance coverage, this falls to almost 1%. The large declines in panic-induced failures explains the sharp initial decline in the unconditional mean of bank failures from increasing deposit insurance. With further raises in the coverage, the increasing risk of fundamental insolvencies eventually dominates. Notably, the unconditional mean of consumption is hump-shaped in the level of deposit insurance coverage.

Figure 5 sheds light on the reasons for the divergence between the impact of rises of insured share of deposits x on unconditional mean consumption and on SSS consumption. It shows the responses of key aggregate variables to the realization of a sunspot shock under different coverage levels of deposit insurance. The effects of increasing insurance on the severity of panic episodes are seen to be large. In the baseline economy (with a 67% share of insured

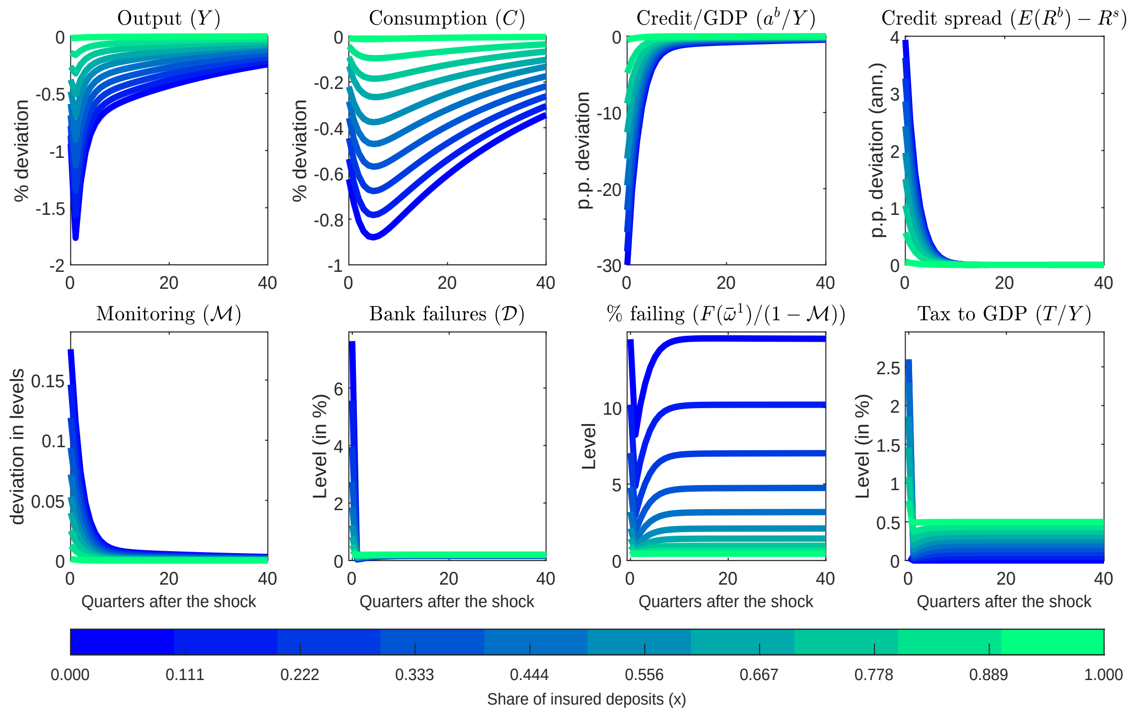

Figure 5. Effects of deposit insurance on endogenous responses to panic runs

Vertical axes: deviations from respective stochastic steady state (units as indicated). Horizontal axes: quarters since the realization of the shock. The realization of the sunspot shock is set to zero for a sufficiently large number of quarters before $t = 0$, set to one at $t = 0$, and again to zero for the remaining number of displayed quarters.

deposits), credit-to-GDP declines by 12 percentage points (p.p.) on impact, in contrast to 30 p.p. fall in an economy without insurance. In the four years subsequent to a banking panic in the baseline economy, the average cumulative losses in output and consumption are 4.4% and 4.3%. Instead in the economy without deposit insurance, the losses are 14.7% and 15.4%, respectively.

Welfare-maximizing deposit insurance coverage. Figure 6 shows the impact of deposit insurance coverage on social welfare, which I define as the unconditional mean value of the lifetime utility of the representative household and report in certainty-equivalent permanent consumption terms.[24] The welfare-maximizing level of deposit insurance coverage is around 60%, which is slightly lower than the level in baseline calibration (=67%).

In terms of unconditional mean values, the optimal deposit insurance generates, relative

[24] For each depicted x (more precisely for each $\bar{D}$ corresponding to depicted x), I solve for equilibrium and simulate 500 paths of 10000 periods, computing household's lifetime utility W using (3). After obtaining $\mathbb{E}(W)$ by averaging W across the 500 paths, I compute the associated certainty-equivalent permanent consumption as $U^{-1}((1-\beta)\mathbb{E}(W))$.

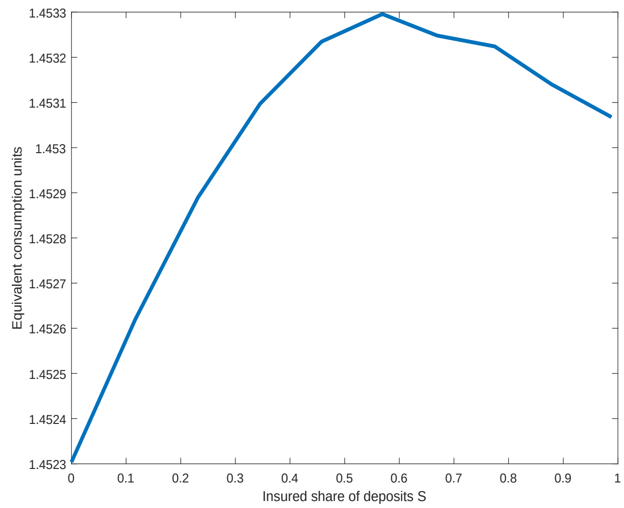

Figure 6. Effect of the deposit insurance coverage on social welfare

Vertical axis: welfare of the representative household expressed in terms of certainty-equivalent permanent consumption units. Horizontal axis: different values of the insured share of deposits x implied under various limits of deposit insurance $\bar{D}$. Social welfare is computed over 500 simulated paths, each comprised of 10000 periods, for each different value of x.

to no deposit insurance, social value equivalent to 7 bps of consumption. To put the size of this gain into perspective, one has to take into account that panic episodes are infrequent (occur with an annual frequency of 4%) and that the large direct and indirect losses that are avoided conditional on the realization of panics are traded off with the negative effects induced over calm periods.

5 Conclusions

I have developed a quantitative dynamic general equilibrium model with banks to study the effects of deposit insurance. The model incorporates the possibility of both fundamental-based and panic-based bank failures, and features endogenous and exogenous sources of risk. Starting with a baseline calibration intended to capture key balance sheet and income statement moments from banks, I have run counterfactual exercises exploring the effects of setting deposit insurance coverage at different levels.

I find a U-shaped relationship between the level of deposit insurance coverage and the risk of bank failure. This finding is the result of a large decline in panic-induced failures from increasing the level of coverage when starting from low levels, which is eventually dominated by increasing risk of fundamental insolvencies from a weakening of banks' risk management incentives. The welfare-maximizing level of deposit insurance coverage for the U.S. in 2008 – roughly 60% of aggregate deposits insured by U.S. FDIC – aligns closely with the level observed in the data. This level weighs less severe deadweight costs and macroeconomic losses during the infrequent episodes of bank panics against higher deadweight costs due to fundamental bank insolvencies in normal times.

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Appendices

A Model Details

This Appendix describes the details of the equilibrium.

A.1 Producers

Total physical capital at $t+1$ is given by

$$K_{t+1} = \left[\phi \left(K^h_{t+1}\right)^\rho + (1-\phi)\left(K^b_{t+1}\right)^\rho\right]^{\frac{1}{\rho}}. \tag{A.1}$$

The consumption-good producer combines physical capital and labor to produce the final output (GDP)

$$Y_{t+1} = z_{t+1} K^\alpha_{t+1} H^{1-\alpha}_{t+1}. \tag{A.2}$$

The consumption-good producer's first order conditions for physical capital and labor yield

$$R^h_{t+1} = \phi\alpha \left(K^h_{t+1}\right)^{\rho-1} \frac{Y_{t+1}}{K^\rho_{t+1}} + 1 - \delta^h, \tag{A.3}$$

$$R^b_{t+1} = (1-\phi)\alpha \left(K^b_{t+1}\right)^{\rho-1} \frac{Y_{t+1}}{K^\rho_{t+1}} + 1 - \delta^b, \tag{A.4}$$

$$W_{t+1} = z_{t+1}(1-\alpha)\left(\frac{K_{t+1}}{H_{t+1}}\right)^\alpha. \tag{A.5}$$

A.2 Household

The first order conditions for bank deposits and investments in physical capital are as follows:

$$\mathbb{E}_t\left[\Lambda_{t+1}\tilde{R}^d_{t+1}\right] = 1, \tag{A.6}$$

$$\mathbb{E}_t\left[\Lambda_{t+1}R^h_{t+1}\right] = 1, \tag{A.7}$$

where the stochastic discount factor of the household can be defined as

$$\Lambda_{t+1} \equiv \beta\left(\frac{C_{t+1}}{C_t}\right)^{-\nu},$$

and the realized returns on deposits are

$$\tilde{R}^d_{t+1} = R^d_t - \Omega_{t+1},$$

where Ω_{t+1} are the losses per unit of deposits defined below. The household's insured share of deposits are defined as $x_t \equiv \min\{\frac{\bar{D}}{R^d_t D_t}, 1\}$, and their budget constraint is given by

$$C_t + D_t + A^h_t \ = \ W_t + \min\{\bar{D}, R^d_{t-1} D_{t-1}\} + \max\{\tilde{R}^d_t D_{t-1} - \bar{D}, 0\} + R^h_t A^h_{t-1} + \Xi_t - T_t. \quad \text{(A.8)}$$

A.3 Bankers

Plugging the law of motion of banker's net worth given by (6) into (5) yields the following compact version of a banker's value function:

$$V_t(n^b_t) = \max_{b_t \geq -n^b_t} \left\{ -b_t - \Upsilon(b^+_t) + \mathbb{E}_t \left[\Lambda_{t+1}(1-\theta) R^e_{t+1} \right] (n^b_t + b_t) + \mathbb{E}_t \left[\Lambda_{t+1} V_{t+1}(\theta R^e_{t+1}(n^b_t + b_t)) \right] \right\}. \quad \text{(A.9)}$$

Following Abad et al. (2024), I guess and verify that this value function is affine, namely, can be expressed as

$$V_t(n^b_t) = v_t n^b_t + v^0_t.$$

Under this conjectured expression for $V_t(n^b_t)$, (A.9) can be written as

$$\begin{aligned} v_t n^b_t + v^0_t &= \max_{b_t \geq -n^b_t} \left\{ -b_t - \Upsilon(b^+_t) + \mathbb{E}_t \left[\Lambda^b_{t+1} R^e_{t+1} \right] (n^b_t + b_t) + \mathbb{E}_t \left[\Lambda_{t+1} v^0_{t+1} \right] \right\} \\ &= \mathbb{E}_t \left[\Lambda^b_{t+1} R^e_{t+1} \right] n^b_t + \max_{b_t \geq -n^b_t} \left\{ -b_t - \Upsilon(b^+_t) + \mathbb{E}_t \left[\Lambda^b_{t+1} R^e_{t+1} \right] b_t + \mathbb{E}_t \left[\Lambda_{t+1} v^0_{t+1} \right] \right\}, \end{aligned} \quad \text{(A.10)}$$

with $\Lambda^b_{t+1} = \Lambda_{t+1}(1 - \theta + \theta v_{t+1})$. The first term in the right side of (A.10) is linear in n^b_t and the second is independent of n^b_t unless the lower bound for the choice of b_t is binding in any period. That is, if the banker faces a situation in which paying out the whole net worth is strictly preferred to any other choice. This is the case if $\mathbb{E}_t[\Lambda^b_{t+1} R^e_{t+1}] \leq 1$ so that choosing $b_t = -n^b_t < 0$ is optimal and the RHS of (A.10) simplifies to $n^b_t + \mathbb{E}_t \Lambda_{t+1} v^0_{t+1}$, which is consistent with the conjectured affine form of the value function under $v_t = 1$ and $v^0_t = \mathbb{E}_t \Lambda_{t+1} v^0_{t+1}$. Now in the case that $\mathbb{E}_t[\Lambda^b_{t+1} R^e_{t+1}] > 1$, it is optimal for the banker to choose $b_t > 0$ that satisfies the first order condition

$$-1 - \Upsilon'(b_t^+) + \mathbb{E}_t(\Lambda_{t+1}^b R_{t+1}^e) = 0,$$

which does not depend on n_t^b. So the validity of (A.10) gets confirmed with

$$\begin{aligned} v_t &= \mathbb{E}_t[\Lambda_{t+1}(1-\theta+\theta v_{t+1})R_{t+1}^e], \\ v_t^0 &= \max_{b_t\in\mathbb{R}} \left\{-b_t - \Upsilon(b_t^+) + v_t b_t + \mathbb{E}_t\Lambda_{t+1}v_{t+1}^0\right\}. \end{aligned} \tag{A.11}$$

Therefore, the marginal value of a unit of banker's net worth satisfies (20), and her optimal policy for equity-issuance / discretionary-dividends is

$$b_t = \begin{cases} \text{any } b \in [-n_t^b, 0], & \text{if } \ v_t = 1, \\ (\Upsilon')^{-1}(v_t - 1), & \text{if } \ v_t > 1, \end{cases} \tag{A.12}$$

The net worth of bankers n_{t+1}^b evolves according to the following law of motion

$$n_{t+1}^b = \theta R_{t+1}^e(n_t^b + b_t). \tag{A.13}$$

A.4 Banks

The problem of a bank is compactly written as

$$\mathbb{E}_t\left\{\Lambda_{t+1}^b\left[m_t\pi_{1t+1}^\iota + (1-m_t)\int_{\bar{\omega}_{t+1}^\iota}^\infty \pi_{0t+1}^\iota(\omega_j)dF(\omega_j)\right]\right\} - v_t e_t, \tag{A.14}$$

subject to the balance sheet constraint

$$a_t^b = e_t + d_t, \tag{A.15}$$

and the regulatory capital requirement

$$e_t \geq \gamma a_t^b, \tag{A.16}$$

where as described in the text

$$\pi^0_{0t+1}(\omega_j) = \omega_j R^b_{t+1} a^b_t - R^d_t d_t - \mathcal{C}(m_t) a^b_t, \tag{A.17}$$

$$\pi^0_{1t+1} = \pi^1_{1t+1} = R^b_{t+1} a^b_t - R^d_t d_t - \mathcal{C}(m_t) a^b_t, \tag{A.18}$$

$$\pi^1_{0t+1}(\omega_j) = \omega_j R^b_{t+1} \left(a^b_t - \frac{\zeta(1-x_t) R^d_t d_t}{1-\lambda} \right) - [(1-\zeta)(1-x_t) + x_t] R^d_t d_t - \mathcal{C}(m_t) a^b_t, \tag{A.19}$$

$$\bar{\omega}^0_{t+1} = \frac{R^d_t d_t + \mathcal{C}(m_t) a^b_t}{R^b_{t+1} a^b_t}, \tag{A.20}$$

$$\bar{\omega}^1_{t+1} = \frac{[(1-\zeta)(1-x_t) + x_t] R^d_t d_t + \mathcal{C}(m_t) a^b_t}{R^b_{t+1} \left(a^b_t - \frac{\zeta(1-x_t) R^d_t d_t}{1-\lambda} \right)}. \tag{A.21}$$

Combining the first order conditions with respect to the choices of d_t and e_t yields

$$v_t = \xi^{CR}_t + \mathbb{E}_t \left\{ \Lambda^b_{t+1} \left[m_t R^d_t + (1-m_t) R^d_t (1 - F(\bar{\omega}^\iota_{t+1})) \right] \right\}, \tag{A.22}$$

where ξ^{CR}_t is the Lagrange multiplier associated with the regulatory capital requirement (A.16). Equation (A.22) states that, in equilibrium, the marginal cost of an additional unit of equity v_t has to be equal to the marginal benefit of relaxing the regulatory requirement constraint (A.16) plus the marginal cost of substituting that unit of equity with one unit of deposits. This condition implies that the capital requirement constraint will be binding ($\xi^{CR}_t > 0$) as long as

$$v_t > \mathbb{E}_t \left\{ \Lambda^b_{t+1} \left[m_t R^d_t + (1-m_t) R^d_t (1 - F(\bar{\omega}^\iota_{t+1})) \right] \right\},$$

that is, as long as the shadow price of bankers' equity at t exceeds the effective cost of deposit funding to bank shareholders (as given by the discounted value of the marginal repayments and costs incurred per unit of deposits if the bank does not fail). Under binding capital requirement (which I guess and verify), the first order condition with respect to investments in (physical-)capital-producing projects is

$$\begin{aligned} &\mathbb{E}_t \left\{ \Lambda^b_{t+1} \left[m_t (R^b_{t+1} - \mathcal{C}(m_t)) + (1-m_t) \left(\int_{\bar{\omega}^\iota_{t+1}}^{\infty} (\omega_j R^b_{t+1} - \mathcal{C}(m_t)) dF(\omega_j) \right) \right] \right\} \\ &\quad = (1-\gamma) \mathbb{E}_t \left\{ \Lambda^b_{t+1} \left[m_t R^d_t + (1-m_t) R^d_t (1 - F(\bar{\omega}^\iota_{t+1})) \right] \right\} + \gamma v_t, \end{aligned} \tag{A.23}$$

which states that, in equilibrium, bankers' marginal benefit of an additional unit of investment has to be equal to the effective weighted average cost of the funds needed to finance that investment.

As described in the text, the first order condition with respect to the choice of risk management effort is

$$\mathbb{E}_t\left\{\Lambda^b_{t+1}\left[\pi^\iota_{1t+1}-\int_{\bar{\omega}^\iota_{t+1}}^{\infty}\pi^\iota_{0t+1}(\omega_j)dF(\omega_j)\right]\right\}=\mathbb{E}_t\left\{\Lambda^b_{t+1}\mathcal{C}'(m_t)a^b_t\left[m_t-(1-m_t)(1-F(\bar{\omega}^\iota_{t+1}))\right]\right\}. \tag{A.24}$$

The aggregate proportion of banks that fail is given by

$$\mathcal{D}^\iota_{t+1}=(1-\mathcal{M}_{t+1})F(\bar{\omega}^\iota_{t+1}). \tag{A.25}$$

A.5 Deposit insurance agency

As described in the text, the deposit insurance agency (DIA) supervises the liquidation process of failed-bank assets, subject to proportional repossession costs μ. Let Σ^ι_{t+1} denote the total losses incurred in repossessing assets of banks operating between t and $t+1$, given by:

$$\Sigma^0_{t+1}=(1-\mathcal{M}_t)\left\{[R^d_tD_t+\mathcal{C}(m_t)A^b_t]F(\bar{\omega}^0_{t+1})-(1-\mu)R^b_{t+1}A^b_t\int_0^{\bar{\omega}^0_{t+1}}\omega_jdF(\omega_j)\right\}, \tag{A.26}$$

$$\begin{aligned}\Sigma^1_{t+1}=(1-\mathcal{M}_t)\Big\{&\left[((1-\zeta)(1-x_t)+x_t)R^d_tD_t+\mathcal{C}(m_t)A^b_t\right]F(\bar{\omega}^1_{t+1})\\&-(1-\mu)R^b_{t+1}\left(A^b_t-\frac{\zeta(1-x_t)R^d_tD_t}{1-\lambda}\right)\int_0^{\bar{\omega}^1_{t+1}}\omega_jdF(\omega_j)\Big\},\end{aligned} \tag{A.27}$$

where $x_t\equiv\min\left\{\frac{\overline{D}}{R^d_tD_t},1\right\}$ are the household's insured share of deposits. As noted in the text, the recovered funds are first used by the DIA to meet its own obligations.[25] Then, the DIA incurs a shortfall if it does not manage to recoup sufficient funds from liquidating the assets of a failing bank, which is the case if the realization of idiosyncratic shocks is below

$$\bar{\bar{\omega}}^0_{t+1}=\min\left\{\frac{x_tR^d_tD_t+\mathcal{C}(m_t)A^b_t}{(1-\mu)R^b_{t+1}A^b_t},\bar{\omega}^0_{t+1}\right\},$$

$$\bar{\bar{\omega}}^1_{t+1}=\min\left\{\frac{x_tR^d_tD_t+\mathcal{C}(m_t)A^b_t}{(1-\mu)R^b_{t+1}\left(A^b_t-\frac{\zeta(1-x_t)R^d_tD_t}{1-\lambda}\right)},\bar{\omega}^1_{t+1}\right\}.$$

[25] I assume for simplicity that the risk management effort costs of failing banks are borne by the DIA. This assumption is consistent with real world regulations wherein uninsured depositors' obligations are senior to banks' other liabilities.

Using the notation introduced in text, the DIA's total shortfall in period $t+1$ is then

$$\Psi^0_{t+1} = (1-\mathcal{M}_t)\left\{[x_t R^d_t D_t + \mathcal{C}(m_t)A^b_t]F(\bar{\bar{\omega}}^0_{t+1}) - (1-\mu)R^b_{t+1}A^b_t \int_0^{\bar{\bar{\omega}}^0_{t+1}} \omega_j dF(\omega_j)\right\}, \tag{A.28}$$

$$\Psi^1_{t+1} = (1-\mathcal{M}_t)\Bigg\{\left[x_t R^d_t D_t + \mathcal{C}(m_t)A^b_t\right] F(\bar{\bar{\omega}}^1_{t+1}) - (1-\mu)R^b_{t+1}\left(A^b_t - \frac{\zeta(1-x_t)R^d_t D_t}{1-\lambda}\right)\int_0^{\bar{\bar{\omega}}^1_{t+1}} \omega_j dF(\omega_j)\Bigg\}. \tag{A.29}$$

The DIA's slack is met by raising lump sum taxes from households to ex-post balance its budget:

$$T^\iota_t = \Psi^\iota_t + \tau(\Psi^\iota_t), \tag{A.30}$$

where the functional form of $\tau(\cdot)$ is given in (27).

Finally, residual funds from the subset $\omega_j \in [\bar{\bar{\omega}}^\iota_{t+1}, \bar{\omega}^\iota_{t+1}]$ of failing banks are distributed among holders of uninsured deposits on a pro-rata basis. Therefore, total losses incurred by depositors from investing in banks operating between t and $t+1$ are

$$\Omega^\iota_{t+1} D_t = \Sigma^\iota_{t+1} - \Psi^\iota_{t+1}. \tag{A.31}$$

A.6 Market clearing and aggregation

The physical capital of class h rented by the representative consumption-good producer must equal the stock of physical capital produced by the representative non-bank-dependent (NBD) firm

$$K^h_{t+1} = A^h_t, \tag{A.32}$$

which reflects the linear production technology of NBD firm ($k^h_{t+1} = a^h_t$), and that the claims on physical capital of class h held by the households must equal the claims issued by the NBD firm $A^h_t = a^h_t$. The physical capital of class b rented by the representative consumption-good producer must equal the stock of physical capital produced by banks

$$K^b_{t+1} = a^b_t - \iota_{t+1} \cdot \int_0^{\bar{\omega}^1_{t+1}} \frac{\zeta(1-x_t)R^d_t d_t}{1-\lambda} dF(\omega_j), \tag{A.33}$$

which reflects that in the event of a sunspot ($\iota_{t+1} = 1$), a fraction $F(\bar{\omega}^1_{t+1})$ of the banks early-liquidate investments. Labor hired by the representative consumption-good producing firm must equal the unit of labor inelastically supplied by the household

$$H_t = 1. \tag{A.34}$$

The clearing of the market for bank deposits requires

$$D_t = d_t. \tag{A.35}$$

The equity issued by banks must equal the net worth invested by bankers'

$$e_t = n_t^b + b_t. \tag{A.36}$$

The law of motion of aggregate net worth of bankers is given as

$$N_{t+1}^b = \theta R_{t+1}^e (N_t^b + b_{t+1}), \tag{A.37}$$

which reflects the retention of a fraction θ of gross returns earned by a banker at t, and the fact that aggregate net worth equals individual net worth $N_t^b = n_t^b$. The total net payments that bankers make to the household are

$$\Xi_{t+1} = (1-\theta) R_{t+1}^e e_t - b_{t+1} - \Upsilon(b_{t+1}^+). \tag{A.38}$$

The household's net worth N_{t+1}^h evolves according to the following law of motion

$$N_{t+1}^h = W_{t+1} + \tilde{R}_{t+1}^d D_t + R_{t+1}^h K_{t+1}^h + \Xi_{t+1} - T_{t+1}. \tag{A.39}$$

A.7 Equilibrium

In equilibrium, the state of the economy at any date t can be summarized by two state variables collected in the vector $\mathbf{N} = \{N^h, N^b\}$: the aggregate net worth of the representative household N_t^h, and aggregate wealth under bankers' management at the start of the period N_t^b. Formally:

Definition 1 *A competitive equilibrium is given by the policy functions of the representative household* $\left(C(\mathbf{N}), D(\mathbf{N}), A^h(\mathbf{N})\right)$ *, the representative banker* $(b(\mathbf{N}))$ *, the representative bank* $\left(a^b(\mathbf{N}), d(\mathbf{N}), e(\mathbf{N}), m(\mathbf{N})\right)$ *, and the representative consumption-good producing firm* $\left(K^h(\mathbf{N}), K^b(\mathbf{N}), H(\mathbf{N})\right)$ *, a tuple of equilibrium prices* $\left(v(\mathbf{N}), R^d(\mathbf{N}), r^h(\mathbf{N}), r^b(\mathbf{N}), W(\mathbf{N})\right)$ *, and a sequence of lump-sum taxes* T_t*, all defined over some relevant support for* $\mathbf{N}$*, such* *that for any sequence of realizations of the aggregate productivity shocks* $\{z_t\}_{t=0,1,\ldots}$, *and the aggregate sunspot shocks* $\{\iota_t\}_{t=0,1,\ldots}$:

1. *The sequence of consumption and saving decisions* $\{C_t, D_t, A_t^h\}_{t=0,1,\ldots}$ *implied by* $(C(\mathbf{N}), D(\mathbf{N}), A^h(\mathbf{N}))$ *solve the problem of the representative household, i.e., equations* (A.6) *to* (A.8).

2. *The sequences of dividend payments* $\{b_t^-\}_{t=0,1,\ldots}$ *and equity issuance* $\{b_t^+\}_{t=0,1,\ldots}$ *implied by* $(b(\mathbf{N}))$ *solve the problem of the representative banker, i.e., equation* (A.12).

3. *The sequence of capital structure decisions* $\{a_t^b, e_t, d_t\}_{t=0,1,\ldots}$ *and risk management effort* $\{m_t\}_{t=0,1,\ldots}$ *implied by* $\left(a^b(\mathbf{N}), d(\mathbf{N}), e(\mathbf{N}), m(\mathbf{N})\right)$ *solve the problem of the representative bank, i.e., equations* (A.15), (A.16), (A.23), *and* (A.24).

4. *The sequence of input choices* $\{K_t^h, K_t^b, H_t\}_{t=0,1,\ldots}$ *implied by* $\left(K^h(\mathbf{N}), K^b(\mathbf{N}), H(\mathbf{N})\right)$ *solves the problem of the representative consumption-good producing firm, i.e., equations* (A.3) *to* (A.5).

5. *The sequence of prices* $\{v_t, R_t^d, r_t^h, r_t^b, W_t\}_{t=0,1,\ldots}$ *implied by* $(v(\mathbf{N}), R^d(\mathbf{N}), r^h(\mathbf{N}), r^b(\mathbf{N}), W(\mathbf{N}))$ *clear the bank equity market, the bank deposits market, the physical capital markets, and the labor market, i.e., equations* (A.32) *to* (A.36).

6. *The sequence of taxes* $\{T_t\}_{t=0,1,\ldots}$ *satisfy the deposit insurance agency's budget constraint, i.e., equation* (A.30).

7. *The sequence of endogenous state variables* $\{N_{t+1}^h, N_{t+1}^b\}_{t=0,1,\ldots}$ *evolve according to their respective laws of motion, i.e., equations* (A.37) *and* (A.39).

B Solution Method

The model is solved using global solution methods. In particular, the method used is policy function iteration (Coleman, 1990), also known as time iteration (Judd, 1998). Functions are approximated using piecewise linear interpolation, as advocated in Richter, Throckmorton, and Walker (2014). A sketch of the numerical solution procedure is as follows:

1. Discretize the state variables by creating an evenly spaced grid, covering the relevant range of values each of them can take. The aggregate productivity shocks are discretized using the method described in Rouwenhorst (1995).

2. Select the set of policy functions. In this case, the variables chosen are $R^d(\mathbf{N}), A^h(\mathbf{N})$, $m(\mathbf{N})$, and $v(\mathbf{N})$.

3. Specify an initial guess for the policy functions at each point i of the state space (note that the size of the state space equals the product of all the state variable grid sizes) and use them as candidate policy functions. In particular, the initial guess is chosen to be equal to the deterministic steady state value of the selected variables.

4. For each point i of the state space, plug the candidate policy functions into the equilibrium equations and calculate the value of the endogenous state variables at $t+1$.

5. Using the value of the endogenous state variables at $t+1$, use linear interpolation to obtain the value of the policy variables at $t+1$ for each possible realization of the exogenous state variables.

6. Using the value of the endogenous state variables and the policy variables at $t+1$, obtain the value at $t+1$ of the remaining variables necessary to calculate time t expectations, for each possible realization of the aggregate shocks.

7. Use a numerical root-finder to solve for the zeros of the residual equations, subject to each of the remaining equilibrium conditions. Numerical integration is needed at this step to compute expectations in the equilibrium equations. The result is a set of policy values in each point i of the state space that satisfies the equilibrium system of equations up to a specified tolerance level, which characterizes the updated policy function for the next step.

8. If the distance between the candidate policy function and the updated policy values obtained in the previous step is less than the convergence criterion for all i, then the policies have converged to their equilibrium values. Otherwise, use the updated policy functions as the new candidate and go back to step 5.