Bank Capital Buffers in a Dynamic Model*

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Abstract

We estimate a dynamic structural banking model to examine the interaction between risk-weighted capital adequacy and unweighted leverage requirements, their differential impact on bank lending, and equity buffer accumulation in excess of regulatory minima. Tighter risk-weighted capital requirements reduce loan supply and lead to an endogenous fall in bank profitability, reducing bank incentives to accumulate equity buffers and, therefore, increasing the incidence of bank failure. Tighter leverage requirements, on the other hand, increase lending, preserve bank charter value and incentives to accumulate equity buffers, therefore leading to lower bank failure rates.

JEL Classification: E44, G21, G38

Key Words: Banking, Equity Buffers, Regulatory Interactions, Dynamic Models

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1 Introduction

Policy makers recognize the importance of developing quantitative models to assess both microprudential and macroprudential risks in the financial system. These tools aim to improve the identification and assessment of systemically important risks from high leverage,[1] credit growth,[2] or money market freezes.[3] Moreover, quantitative structural models can be used in real time to perform counterfactual experiments and inform policy making.

Given the need for such applied, quantitative models, we construct a dynamic structural model of bank lending behavior and capital structure choices with the following features. Banks transform short-term liabilities into long-term loans (a maturity transformation function) and premature liquidation of loans is costly, in the spirit of Diamond and Dybvig (1983), Gorton and Pennacchi (1990), Diamond and Rajan (2001), and Holmström and Tirole (1998). One key departure from Modigliani-Miller (MM) arises because banks are run by managers maximizing bank charter value, defined as the utility from consuming current and future dividends accruing to shareholders for as long as the bank remains a going concern. Another departure from MM is the existence of deposit insurance, implying that depositors do not respond to bank riskiness. Banks also operate in an incomplete markets setup in the spirit of Allen and Gale (2004) and face uninsurable background risks in funding conditions and asset quality. Banks raise equity capital only internally through retained earnings while

[1]Kiyotaki and Moore (1997) and Bernanke, Gertler and Gilchrist (1999) are seminal examples where leverage interacts with asset prices to generate amplification and persistence over the business cycle, while Gertler and Kiyotaki (2010) and Gertler and Karadi (2010) illustrate the importance of banking decisions in understanding aggregate business cycle dynamics. Adrian and Shin (2010) provide empirical evidence further stressing the importance of leveraged bank balance sheets in the monetary transmission mechanism.

[2]Bernanke and Blinder (1988) provide the macro-theoretic foundations of the bank lending channel of monetary policy transmission. Using aggregate data, Bernanke and Blinder (1992), Kashyap et al. (1993), Oliner and Rudebusch (1996) provide evidence that supports the existence of the bank-lending channel.

[3]Brunnermeier (2009) discusses the freeze of money markets during the recent recession in the U.S.

we abstract from seasoned equity issuance.[4]

In such an environment the limited liability option of bank shareholders may lead to incentives to shift risks to creditors and to the deposit insurance fund. Especially for banks whose charter value is low, excessive risk taking in good times could lead to high losses when the cycle turns, as documented in Beltratti and Stulz (2012) and Fahlenbrach and Stulz (2011).[5] Bank capital regulation exists to contain excessive risk-taking and limit potential losses to the deposit insurance fund.[6]

Using U.S. individual commercial bank data, we first establish empirical regularities similar to the ones emphasized in, for instance, Kashyap and Stein (2000) and Berger and Bouwman (2013), who also use disaggregated data to understand bank behavior. We complement their approach by building a quantitative structural model to replicate the cross-sectional and the time series evolution of bank financial statements. We consider a relatively rich balance sheet structure where illiquid loans and liquid assets are funded by short-term insured deposits, unsecured wholesale funds and equity.

To perform counterfactual experiments, we estimate the quantitative model using a Method of Simulated Moments, as in Hennessy and Whited (2005). The model replicates the wide range of cross-sectional heterogeneity in bank financial ratios through the endogenous

[4] Banks' limited access to equity markets could be due to a debt overhang problem as in Myers (1977) and Hanson, Kashyap and Stein (2011). It could also be due to adverse selection problems à la Myers and Majluf (1994) and the information sensitivity of equity issuance. That problem might be particularly acute in a situation where a bank faces an equity shortfall due to loan losses, in which case information sensitivities may prevent the bank from accessing external equity capital from private investors as discussed in Duffie (2010).

[5] Fahlenbrach and Stulz (2011) also find evidence that better alignment of incentives between bank managers and shareholders implies worse performance during the crisis, supporting the idea of risk-shifting moral hazard due to limited liability.

[6] Jimenez, Ongena, Peydro and Saurina (2014) also show that banks with less "capital in the game" are susceptible to excessive risk-taking.

response to idiosyncratic risks emanating from deposit flows and loan write-offs, as well as the motive to hedge liquidity risk arising from maturity transformation. Consistent with the data, smaller banks are estimated to face a higher cost of accessing the wholesale funding market and therefore rely more heavily on deposit funding. Small banks also have a more concave objective function associated with more severe financial frictions (Hennessy and Whited (2007)). Larger banks, on the other hand, are more highly levered due to the additional flexibility provided by easier access to wholesale funding.

Loan growth is strongly procyclical and peaks at the onset of expansions leading to an increase in leverage during the first few quarters of an expansion, consistent with Adrian and Shin (2010, 2014). However, over the course of the expansion, banks retain part of their higher earnings to replenish their equity, leading to a reduction in leverage, as in He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014). During recessions, banks curtail new lending and shrink their balance sheets, reducing reliance on wholesale funding. The model also generates strongly countercyclical bank failures induced by a deterioration in asset quality and the associated reduction in the bank charter value. Consistent with the empirical results in Berger and Bouwman (2013), banks that fail tend to have higher (lower) average leverage (equity capital) than surviving banks, regardless of size.

We interpret these findings as consistent with quantitative features of the data. We therefore use the model to analyze the effect of changing capital requirements, a major issue of policy concern. We assume that regulatory intervention takes the form of a prudential limit on bank leverage (henceforth, the leverage requirement), measured as the ratio of total assets to equity. In addition to the leverage constraint, banks face regulatory restrictions with respect to the ratio of risk-weighted assets to equity (henceforth, the capital adequacy requirement), a proxy for Tier 1 capital ratio.

Tighter capital requirements could increase bank resilience to shocks and reduce the likelihood of bank failure.[7] On the other hand, tighter capital requirements reduce financial flexibility. Lower flexibility might increase the likelihood of bank failure by either reducing bank charter value or increasing the likelihood of breaching a tighter limit, or both.[8] Therefore, setting capital requirements at an appropriate level is a balancing act, as shown by Freixas and Rochet (2008), Van den Heuvel (2007, 2008) and De Nicolo, Gamba and Lucchetta (2014).

In the model, banks respond to tighter capital adequacy requirements by accumulating more equity and lowering loan issuance consistent with the empirical findings in Aiyar et al. (2014) and Behn et al. (2015). When capital adequacy requirements get too tight, bank charter value and equity buffers relative to the regulatory minimum fall, leading to an increase in bank failures.[9] However, for a given capital adequacy requirement, a tighter leverage restriction induces banks to increase lending, in line with Miles, Yang and Marcheggiano (2012) and Admati and Hellwig (2013), while bank failures remain relatively unchanged.

What is the intuition behind the differential impact of tightening the two constraints? At the optimum, banks are indifferent between holding an extra unit of higher-yielding (yet high risk-weighted) loans or low risk-weighted (yet lower-yielding) liquid assets. A tighter capital

[7]Higher equity capital might mechanically increase an individual bank's survival probability, while higher equity capital can also alleviate other frictions, thereby increasing the likelihood of survival (see Allen, Carletti and Marquez (2011) and Mehran and Thakor (2011)).

[8]For instance, Koehn and Santomero (1980) and Besanko and Kanatas (1996).

[9]Gale (2010) uses general equilibrium arguments to question the same conventional wisdom that higher capital requirements reduce failures. We show that even in a partial equilibrium model this conventional wisdom can be questioned.

adequacy ratio induces a substitution of high risk-weighted loans with liquid assets, leading to an endogenous fall in the expected return on assets. Banks also respond to the tighter constraint by increasing equity. As a result of both effects, a tighter capital adequacy ratio lowers the expected return on equity, thereby weakening bank incentives to accumulate more equity. Therefore, banks increase equity by less than the increase in the capital requirement, making failure more likely.

On the other hand, by tightening the leverage constraint – which does not discriminate between the two types of assets – the capital adequacy constraint becomes less important. As a result, loans start dominating liquid assets, since lower risk weights matter less for bank asset choices, leading to an increase in loan supply. Tighter leverage requirements keep the expected return on equity relatively intact because the induced asset reallocation towards loans increases profitability, counteracting the increase in equity. Therefore, banks increase equity in proportion to the tighter constraint, leading to relatively unchanged failure rates, especially for large banks.

Our findings complement the recent literature emphasizing the link between asset and liability structure. In the presence of uncertain but relatively "sleepy" deposits and differential (by bank size) costs of accessing wholesale funding markets, banks lever up and invest in illiquid long-term loans and liquid assets to maximize their charter value while managing background risks (DeAngelo and Stulz (2015) and Hanson, Shleifer, Stein and Vishny (2015)).

Relative to De Nicolo et al. (2014), we estimate a structural model with a richer balance sheet structure to match several bank-related empirical moments. As a result our model features bank failures even in the presence of capital requirements, while tighter risk-weighted and leverage requirements generate a differential impact on loan supply and bank failures. In our model, wholesale funding and liquid assets coexist, with substantial cross-sectional heterogeneity arising from background risks and bank choices. Repullo and Suarez (2013) analyze capital regulation in a dynamic model where precautionary equity buffers arise from asymmetric information stemming from relationship lending and associated costly equity issuance. We differ by generating precautionary equity buffers in excess of the regulatory minimum through the presence of background idiosyncratic risks. Corbae and D'Erasmo (2011 and 2012) build a dynamic model of banking to investigate optimal capital requirements in a general equilibrium model featuring strategic interaction between a dominant big bank and a competitive fringe. We differ by emphasizing the maturity transformation role of banks and by analyzing the implications of a richer balance sheet structure.

The rest of the paper is organized as follows. Section 2 discusses the data to be replicated, and Section 3 the theoretical model. Section 4 shows the estimation results and Section 5 compares the model with the data and discusses the model's implications. Section 6 examines the effect of changing capital requirements and Section 7 concludes.

2 Data

We consider a sample of individual bank data from the Reports of Condition and Income (Call Reports) for the period 1990:Q1-2010:Q4. Following Kashyap and Stein (2000), we categorize banks in three size categories (small, medium and large) for every quarter. Small banks are those below the 95th percentile of the distribution of total assets in a given quarter, medium those between the 95th and 98th percentile, and large those above the 98th percentile. We also consider the bank failures reported by the Federal Deposit Insurance Corporation (FDIC) for the same period. Bank failure occurs when either the FDIC closes down a bank or assists in the re-organization of the bank. A more detailed description of our sample and variable definitions is given in the Data Appendix.

2.1 Cross-sectional Statistics

Table 1 shows descriptive statistics for bank balance sheet compositions at the end of 2010, sorted by bank size.[10] Deposits are the major item on the liability side of all commercial banks. Smaller banks rely more on deposits (85 percent of total assets) than the largest banks (68 percent). Larger banks tend to have more access to alternative funding sources like Fed funds, repos and other instruments in the wholesale funding market. Figure 1 confirms that these differences persist and are both economically and statistically different across bank sizes over the 1990-2010 period. We use these differences in deposit and wholesale funding reliance as a defining variation between large and small banks in the structural model.

Figure 2 shows the evolution of the asset side of the balance sheets. The biggest components are loans that represent around 60% of total assets for both small and large banks. The largest remaining asset class is liquid assets, which comprise cash, Fed funds lent, reverse

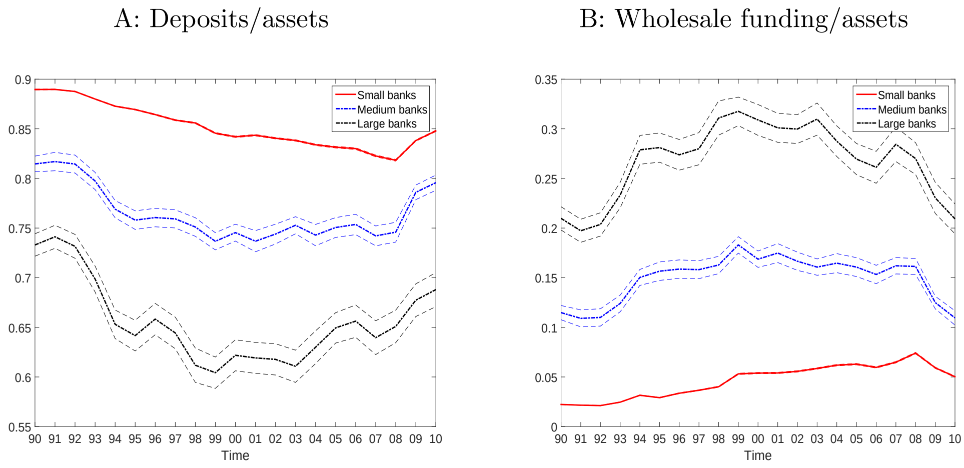
[10] There was a significant reduction in the number of banks over the sample period mainly due to regulatory changes that led to substantial consolidation in U.S. commercial banking. According to Calomiris and Ramirez (2004), branch banking restrictions and protectionism towards unit banks (i.e. one-town, one-bank) led to a plethora of small U.S. commercial banks over the last century. In the early 1990s protectionism was relaxed, especially following the Riegle-Neal Interstate Banking and Branching Efficiency Act (IBBEA) in 1994. That spurred a wave of mergers and acquisitions that reduced significantly the number of U.S. commercial banks. Calomiris and Ramirez (2004) provide some key facts and references on the subject. For some excellent reviews, see also Berger, Kashyap, and Scalise (1995), Calomiris and Karceski (2000) and Calomiris (2000). We abstract from endogeneizing mergers in our model.

Table 1: Balance sheets of U.S. commercial banks by bank size in 2010.

Size percentile	<95th	95th - 98th	>98th
Number of banks	6528	206	137
Mean assets (2010 $million)	238	2715	72000
Median assets (2010 $million)	141	2424	13600
Frac. total system as.	13%	5%	82%
Fraction of tangible asset			
Cash	9%	7%	7%
Securities	21%	21%	20%
Fed funds lent & rev. repo	2%	1%	2%
Loans to customers	62%	64%	61%
Real estate loans	45%	49%	38%
C&I loans	9%	10%	11%
Loans to individuals	4%	5%	11%
Farmer loans	4%	0%	0%
Other tangible assets	5%	7%	10%
Total deposits	85%	79%	68%
Transaction deposits	22%	10%	7%
Non-transaction deposits	63%	70%	61%
Fed funds borrowed & repo	1%	4%	6%
Other liabilities	4%	7%	16%
Tangible equity	10%	9%	10%

This table shows summary statistics and balance sheet information of U.S. commercial banks in the last quarter of 2010, by size class. Small banks are those below the 95th percentile of total assets. Medium banks are those in the 95th-98th percentile. Large banks belong to the top two percentiles.

Figure 1: Evolution of deposit and wholesale funding of U.S. commercial banks



This figure shows the evolution of liability classes as a proportion of total assets of U.S. commercial banks in the period 1990-2010 by bank size. Panel A shows the deposit to asset ratio while Panel B shows the wholsale funding to asset ratio. Deposits consist of transaction and non-transaction deposits. Wholesale fundings consists of Fed funds borrowed, repos and other liabilities. Small banks are those below the 95th percentile of total assets. Medium banks are those in the 95th-98th percentile. Large banks belong to the top two percentiles.

repos and securities. Liquid assets, as a proportion of total assets, remain higher on average for small banks throughout the sample period, consistent with Kashyap and Stein (2000).

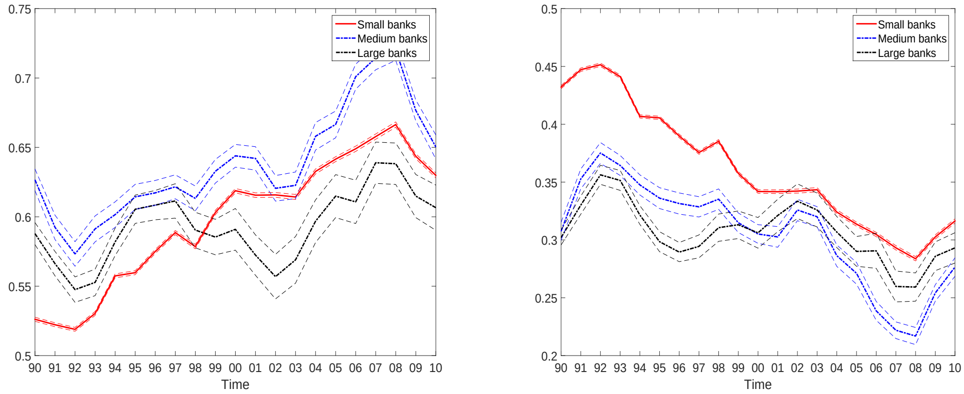
Another variable of interest is bank leverage (tangible assets divided by tangible equity),[11] shown in Figure 3. Small banks are consistently less leveraged than large banks with the exception of the recent crisis (Figure 3A).[12] Figure 3B shows the average leverage of failed and non-failed banks over the 10-year period prior to failure, where the x-axis is the time to failure in quarters. For banks that eventually fail, leverage is consistently higher prior to failure relative to non-failed banks, and increases sharply as they approach failure, consistent with the empirical findings in Berger and Bouwman (2013).

[11] Tangible equity equals total assets minus total liabilities minus intangible assets, such as goodwill.
[12] This might reflect special government programs under TARP (Troubled Assets Relief Program) mainly affecting larger banks.

Figure 2: Evolution of loan and liquid assets of U.S. commercial banks

A: Loans/assets

B: Liquid assets/(total) assets

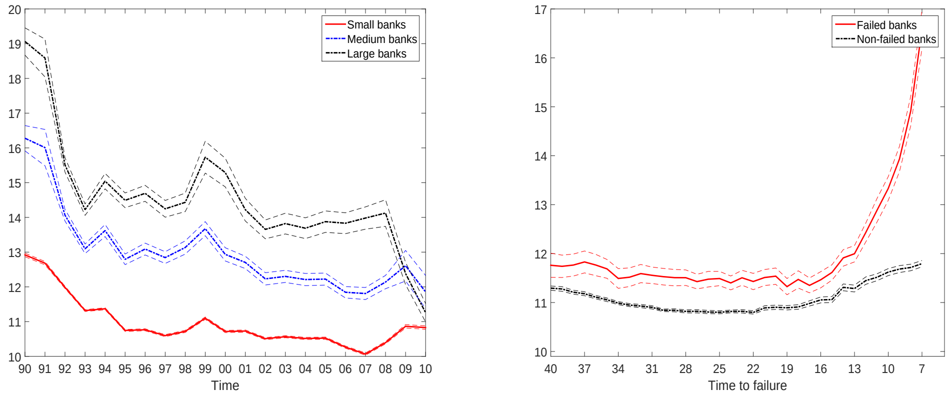


This figure shows the evolution of asset classes as a proportion of total assets of U.S. commercial banks in the period 1990-2010 by bank size. Panel A shows the loan to total asset ratio while Panel B shows the liquid asset to total asset ratio. Loans consist of real estate, commercial, industrial, farmer loans and loans to individuals. Liquid assets are cash, reverse repos, Fed funds lent and securities. Small banks are those below the 95th percentile of total assets. Medium banks are those in the 95th-98th percentile. Large banks belong to the top two percentiles.

Figure 3: Leverage by size and of failed and non-failed banks

A: Leverage by size

B: Leverage of failed and non-failed banks



Panel A shows the evolution of leverage of U.S. commercial banks in the period 1990-2010 by bank size. Small banks are those below the 95th percentile of total assets. Medium banks are those in the 95th-98th percentile. Large banks belong to the top two percentiles. Panel B shows the leverage of failed banks (FDIC regulatory-assigned bank failures) and non-failed banks during the period 1990-2010. The x-axis is the time to failure measured in quarters.

2.2 Aggregate and Idiosyncratic Uncertainty

We estimate the data generating processes of the exogenous uncertainty banks face. Banks in the model are subject to aggregate uncertainty and uninsurable idiosyncratic shocks stemming from deposit growth and loan write-offs. The idea will be to use these processes as empirically relevant exogenous inputs to the structural model.

2.2.1 Uninsurable risks

To capture uninsurable risks from deposit growth and loan write-offs, we examine the time-series statistical properties of these processes individually for each bank over a twenty-year period (84 quarters). We concentrate on the first and second moments and the persistence of these risks, conditional on an expansion or a recession state,[13] and on bank size.

Table 2 reports statistics for loan write-offs, deposit growth and bank failure rates. In unreported tests we reject the hypothesis that log deposits follow a stationary process. We therefore analyze the behavior of the growth rate in individual bank deposits and find that the persistence of real deposit growth is around zero over both states (expansions and recessions) and bank sizes (small and large). Moreover, even after conditioning on the aggregate state of the economy, individual bank heterogeneity remains pervasive, as illustrated by the large standard deviation of deposit growth rates.

On the other hand, the idiosyncratic component of the loan write-off process follows a stationary process and we observe that the persistence is higher for large (0.72) than for small

[13] We count as a recession the two quarters before the start, and the six quarters after the end, of the NBER-dated recessions. There are two reasons for doing this. First, this allows us to extend the sample given the short recessions in this period. Second, loan write-off rates in the data start picking up before the official NBER recession dates and continue well after the official recession end date.

Table 2: Time-series statistics of key variables.

Parameter (% except AR(1))	Small banks			Large banks		
	Uncon	Rec	Exp	Uncon	Rec	Exp
Loan write-offs: mean	0.10	0.13	0.08	0.31	0.37	0.22
Loan write-offs: AR(1)	0.21	0.20	0.14	0.72	0.70	0.51
Loan write-offs: s.d.	0.17	0.20	0.10	0.24	0.28	0.14
Deposit growth: mean	0.81	0.65	0.90	1.63	1.60	1.64
Deposit growth: AR(1)	-0.01	-0.01	-0.01	0.03	0.03	0.03
Deposit growth: s.d.	3.71	3.50	3.48	5.64	5.31	5.41
Deposit rate	-0.46	-0.34	-0.51	-0.55	-0.48	-0.58
Loan spread	1.83	1.72	1.87	1.84	1.68	1.89
Liquid asset spread	0.81	0.42	0.92	0.96	0.56	1.07
Bank failure rate	0.05	0.17	0.01	0.08	0.18	0.01

This table shows the estimation results for the mean, standard deviation and persistence across different variables of interest that capture bank heterogeneity. It also shows expected real rates of return on deposits as well as loan and liquid asset spreads relative to the deposit rate. Small banks are those below the 95th percentile in the distribution of total assets and large are those above the 98th percentile. Uncon is the unconditional statistic, whereas Rec and Exp denote the statistics conditional on being in a recession, or an expansion, respectively. All statistics are computed at the individual level over time and then averaged across banks at a quarterly frequency (not annualized), and deposit growth is deseasonalized as described in the data appendix.

banks (0.21). Moreover, the persistence is slightly higher in recessions than in expansions. The standard deviation of loan write-offs is also higher in recessions and is higher for larger banks.

2.2.2 Returns, loan growth rates and failures

For each bank we use the profit and loss statements from individual Call Reports to derive expected real rates of return on deposits, and liquid asset and loan spreads (relative to the deposit rate). Table 2 also shows that mean loan spreads are not very cyclical, liquid asset spreads are procyclical and bank failure rates are highly countercyclical. We also find that loan growth is procyclical: the contemporaneous correlation between average loan growth and loan write-offs (proxying for recessions) is -0.75 and statistically significant.

Table 3: Bank balance sheet in the model

Assets		*Liabilities*	
Loans L	r_L	Deposits D	r_D
Liquid assets S	r_S	Wholesale funding F	r_F
		Equity E	

This table represents the balance sheet of the banks in our model. There are illiquid loans and liquid assets on the asset side while the liability side consists of deposits, short-term wholesale market funds and equity with associated rates of return.

2.3 Summary

In the cross-section, there is a significant degree of heterogeneity. Larger banks rely less on deposits, more on wholesale funding and tend to be more leveraged. Moreover, banks that fail tend to have more leveraged balance sheets ahead of failure. Further cross-sectional heterogeneity exists within each size class with respect to the loan write-off process and deposit growth rate. In the time series, real loan growth is procyclical, whereas loan write-offs and bank failures are countercyclical. We next build a structural model to replicate quantitatively these stylized facts.

3 The Model

We consider a discrete-time infinite horizon model. Banks are identical ex ante but heterogeneous ex post because they face undiversifiable background risks. Banks invest in illiquid loans L and liquid assets S and fund their assets through insured deposits D, uninsured wholesale funding F, and equity capital E. Interest income earned on illiquid loans and liquid assets is the key driver of bank decisions. A stylized balance sheet is shown in Table 3, which also reports the real rate of return on each asset and liability class.

The continuous state variables are balance sheet variables: loans L, deposits D, and equity E; the various returns $\mathbf{r}$[14] and loan write-offs w, which are stochastic and vary with the business cycle b_t. Consistent with the maturity transformation role of banks,[15] we assume that loans are long-term, with a fraction ϑ be repaid. This generates an exogenous deleveraging process, which we calibrate to the data. Loan write-offs are assumed to be persistent over time following an AR(1) process with moments that depend on the state of business cycle, which we also calibrate to the data:

$$w_{t+1} = \mu_b + \rho_b w_t + \sigma_{b\varepsilon}\varepsilon_{t+1}, \tag{1}$$

where $\varepsilon_{t+1} \sim N(0,1)$. The business cycle follows a two-state Markov process (expansion or recession). Consistent with the data, loan write-offs have a higher mean μ_b, persistence ρ_b and shocks variance $\sigma^2_{b\varepsilon}$ in recessions than in expansions, reflecting heightened uncertainty during recessions.

Another background risk that generates ex post heterogeneity is funding risk through deposit flows. The idiosyncratic deposit growth rate follows an i.i.d. process whose mean and variance depend on the state of the business cycle b_t, consistent with the data:

$$\log\left(\frac{D_{it+1}}{D_{it}}\right) \sim N(\mu_{bD}, \sigma^2_{bD}). \tag{2}$$

[14] In bold to denote a vector of returns.

[15] We suppress the i-subscript for banks, but all bank-specific variables must be understood to have an i-subscript.

3.1 Timing

The bank enters period t with a stock of loans L_{t-1}, liquid assets S_{t-1}, deposits D_{t-1}, wholesale funding F_{t-1}, and book value of equity E_{t-1}. At that point, the aggregate and idiosyncratic shocks to loan write-offs, deposits and returns are realized and the bank decides whether to continue or fail. If the bank continues, it liquidates S_{t-1}, it repays F_{t-1}, realizes loan losses w_t, leading to pre-tax profits

$$\Pi_t = (r_{L,t} - w_t)\, L_{t-1} + r_{S,t} S_{t-1} - r_{D,t} D_{t-1} - g_F(F_{t-1}, D_{t-1}, E_{t-1}) - g_N\,(N_{t-1}, D_{t-1}) - cD_{t-1}. \tag{3}$$

where $(r_{L,t} - w_t)\, L_{t-1}$ is the interest income on loans net of write-offs, $r_{S,t}S_{t-1}$ is the return on liquid assets, $r_{D,t}D_{t-1}$ is the interest cost on deposits, g_F is the interest cost of wholesale funding and g_N is the screening cost of issuing new loans (g_F and g_N are discussed in Section 3.3), and cD_{t-1} is the non-interest expense that we assume proportional to deposits. The last term captures various operating expenses, including overhead costs and the FDIC surcharge to fund deposit insurance. Corporate taxes τ are paid on positive profits Π_t generating after-tax profits $(1-\tau)\Pi_t$, with negative profits not being taxed.

The bank chooses dividends X_t, new loans N_t, liquid assets S_t, and wholesale funds F_t, simultaneously. Equity is accumulated retained profits over time, i.e. after dividends and corporate taxes have been paid. Therefore, at the end of period t, the bank has a new equity level E_t, which equals equity at the beginning of the period net of current dividends

$(E_{t-1} - X_t)$, plus current profits Π_t, minus any tax τ on profits, if positive:

$$E_t = E_{t-1} - X_t + (1-\tau)\Pi_t \mathcal{I}_{\Pi_t>0} + \Pi_t(1 - \mathcal{I}_{\Pi_t>0}) \tag{4}$$

where $\mathcal{I}_{\Pi_t>0}$ is an indicator function that is one when profits are positive.

New loans N_t can be negative, capturing the possibility of premature liquidation taking place at an additional proportional cost. Therefore, the new stock of loans after loan repayments and write-offs becomes:

$$L_t = (1 - \vartheta - w_t)\, L_{t-1} + N_t. \tag{5}$$

In addition to investing in loans, the bank can also invest in liquid assets S_t. Funding from equity E_t and deposits D_t is complemented by short-term wholesale funding with book value F_t. At that point the balance sheet equation holds:

$$L_t + S_t = D_t + F_t + E_t. \tag{6}$$

The bank must respect two regulatory capital requirements. The first is the capital adequacy constraint, which consists of a maximum ratio of risk-weighted assets to equity, captured by parameter λ_w:

$$\frac{\omega_L L_t + \omega_S S_t}{E_t} \leq \lambda_w. \tag{7}$$

The numerator in (7) represents risk-weighted assets after new loans N_t and liquid assets S_t have been chosen, and the denominator is the new equity level E_t, i.e. after dividends and retained after-tax profits. The risk weight on loans ω_L is higher than on liquid assets ω_S.

The second regulatory capital requirement consists of a plain (unweighted) leverage ratio of total assets (loans plus liquid assets) to equity, captured by λ_u:

$$\frac{L_t + S_t}{E_t} \leq \lambda_u. \tag{8}$$

3.2 Objective and Value Functions

We assume that banks are run by managers with limited liability that maximize the present discounted value of shareholder utility from dividends X_t, and discount the future with a constant discount factor β:

$$V = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{{X_t}^{1-\gamma}}{1-\gamma} \tag{9}$$

where $\mathbb{E}_0$ denotes the conditional expectation given information at time 0. Following Hennessy and Whited (2007), the objective function is concave to capture the magnitude of financial frictions, such as bankruptcy costs or dividend taxes. This concavity also captures the idea that banks (like other firms) smooth dividends over time, as suggested by empirical evidence in Acharya, Le and Shin (2017).

A banker who has not exited in the past solves the following continuation problem that takes into account that exit is possible in the future:

$$V^C\left(L_{t-1},D_{t-1},E_{t-1};\Omega_t\right)=\max_{X_t,S_t,F_t,N_t}\left\{\frac{\left(X_t\right)^{1-\gamma}}{1-\gamma}+\right.\tag{10}$$

$$\left.\beta\mathbb{E}_t\left[V\left(L_t,D_t,S_t,F_t;\Omega_{t+1}\right)\right]\right\}$$

subject to the balance sheet constraint (6), the regulatory capital constraints (7) and (8), the evolution of the loan stock (5), profits (3), and equity evolution equation (4), where Ω_t summarizes the state of the business cycle, the rate of returns, the deposit growth and the loan write-off rate.

Limited liability implies that the banker may choose an outside option V^D and the expected value in (10) is defined as the upper envelope:

$$V\left(L_t,D_t,S_t,F_t;\Omega_{t+1}\right)=\max[V^D,V^C\left(L_t,D_t,E_t;\Omega_{t+1}\right)].\tag{11}$$

If equity is high enough, the bank continues for another period. If equity is low enough that the bank violates any of the regulatory capital constraints even with zero dividends, the bank fails. For slightly higher values of equity the bank could survive by choosing a low dividend and thereby respect both capital requirements. However, the implied utility would be so low that the banker prefers the outside option.

3.3 Wholesale funding and screening costs

To avoid a very volatile loan process, we assume adjustment costs for new loans. Issuing new loans requires banks to assess and screen their clients. This screening cost is assumed to be convex in new loans either because bank resources are stretched over more projects or because the quality of additional projects declines. We also assume that the cost function is homogeneous of degree one in deposits because the model is non-stationary in deposits.[16] Thus, the resulting cost function is:

$$g_N\left(N_t, D_t\right) = \mathcal{I}_{N_t>0}\phi_N \frac{N_t^2}{D_t} + (1 - \mathcal{I}_{N_t>0})\psi\phi_N \frac{N_t^2}{D_t} \tag{12}$$

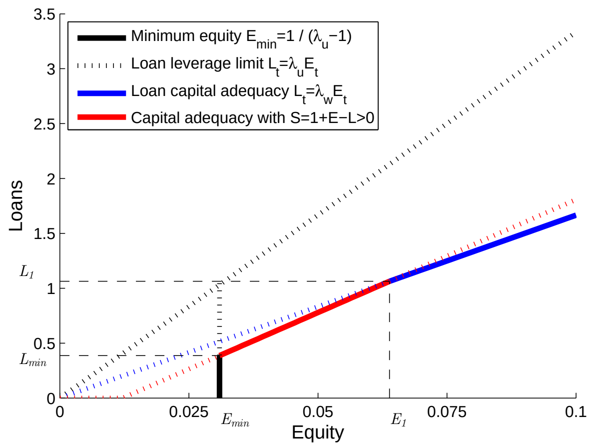
where $\mathcal{I}_{N_t>0}$ is an indicator function that is one when new loans are positive, ϕ_N determines the intensity of the cost, and $\psi > 1$ captures costly loan liquidation.

To access wholesale funding banks have to pay a risk premium in excess of the risk free rate. Ideally, the risk premium function should be endogenously derived (as, for example, Chatterjee et al. 2007). We choose to avoid introducing this additional complexity by assuming the following function that scales with deposits:

$$g_F(F_{t-1}, D_{t-1}, E_{t-1}) = r_{Dt}F_{t-1} + \phi_F \frac{F_{t-1}^2}{D_{t-1}} - \phi_E \frac{E_{t-1}^2}{D_{t-1}}. \tag{13}$$

The first term depends on the risk free rate (r_D), the second and the third term capture counterparty risk that increases with the amount borrowed and decreases with bank equity: ϕ_F determines the intensity of the cost depending of the exposure to wholesale funding, and ϕ_E the degree of cost reduction associated with bank equity holdings.

Figure 4: The two regulatory capital requirements



The figure shows how the two capital requirements can constrain loan choices as a function of equity. Normalizing deposits to one, the binding leverage constraint implies minimum equity $E_{min} = 1/(\lambda_u - 1)$. The maximum allowed loans increase linearly with equity with slope λ_u. The binding capital adequacy constraint with no liquid assets corresponds to the line with slope λ_w/ω_L starting from the origin. For low levels of loans, as liquid assets are included in the balance sheet $S = 1+E-L$, the capital adequacy constraint starts from the right of the origin and increases with slope $(\lambda_w - \omega_S)/(\omega_L - \omega_S)$. Only combinations of equity and loans below and to the right of the solid lines satisfy both constraints simultaneously.

3.4 Effect of Capital Requirements

Figure (4) shows the region of the state space where a bank remains a going concern and how the two capital requirements can constrain bank choices. The loan and equity combinations where both constraints are satisfied are to the right of the solid lines. The graph is shown for $D = 1$ (a convenient normalization) and $F = 0$. Choosing any $F > 0$ would increase the bank's balance sheet and this would increase the likelihood of violating the constraints, for a given level of equity. The two assumptions imply that total assets are given by $1 + E$. Therefore, the leverage constraint implies a minimum equity level below which a bank fails (vertical line at $E_{\min} = \frac{1}{\lambda_u - 1}$).[17]

[16] This assumption is common in the investment literature (Abel and Eberly (1994)).
[17] Assuming a different level of (exogenous) deposits would imply a parallel shift of the constraint.

For equity levels between $E_{\min}$ and E_1, the bank holds positive amounts of liquid assets to satisfy both the balance sheet and the capital adequacy constraint. As a result, the slope of the binding constraint depends on the risk weights on loans and liquid assets and becomes $\frac{\lambda_w - \omega_S}{\omega_L - \omega_S}$. In this region the capital adequacy constraint is more binding than the leverage constraint since, for any given level of loans between L_{min} and L_1, the leverage constraint is satisfied even for equity levels as low as E_{min}. Beyond a certain level of equity ($E_1 = \frac{\omega_L}{\lambda_w - \omega_L}$) the bank fully invests in loans ($S = 0$) and the slope of the binding capital adequacy constraint in this part of the state space is $E_{\min} = \frac{\lambda_w}{\omega_L}$.

Thus, both constraints affect bank decisions but their relative importance changes depending on the stock of loans and the equity level of the bank. The minimum equity level, implied by the leverage limit, is crucial for a bank with low equity, whereas the capital adequacy constraint binds more at higher levels of equity. However, even if a bank starts at an equity level where the capital adequacy constraint matters more, loan losses during bad times may deplete equity to a point where the minimum equity level becomes more relevant to the bank's decisions.

4 Estimation

In this section we first discuss the normalization needed to make the model stationary. Then we discuss the calibration choices. Lastly, we show the results from the Method of Simulated Moments estimation.

4.1 Normalization

The estimated process for deposits contains a unit root. To render the model stationary, we normalize all variables by deposits (D_t). For example, equity (E_t) is transformed into $e_t \equiv \frac{E_t}{D_t}$. For this transformation to work, all profit and cost functions have to be homogenous of degree one in deposits. Details of these transformations are shown in the solution appendix.

4.2 Calibration

The model features aggregate and idiosyncratic uncertainty. We choose the transition probabilities for the aggregate state to obtain recessions that last for eight quarters on average and expansions that last for 20 quarters on average. Idiosyncratic uncertainty depends on the aggregate state and is captured by two different variables: loan write-offs and deposit growth rates. We use the estimated moments (means and standard deviations) and the persistence parameters reported in Table 2 as exogenous inputs. Note that these are conditional on an expansion or a recession and are also conditional on bank size (small versus large). Table 2 also shows the expected real return on deposits and loan and liquid asset spreads. The fraction of loans (ϑ) that are repaid every quarter is 6% (8%) for large (small) banks and the fire sale discount is thirty percent ($\psi = 1.3$). The corporate tax rate (τ) is set to 15%.

Regarding capital requirements, the FDIC initiates an enforcement action when a bank is deemed to be undercapitalized, significantly undercapitalized, or critically undercapitalized. The extent of undercapitalization is determined by the (risk-weighted) capital adequacy requirement and the (unweighted) leverage requirement. Once a bank is deemed to belong in any of the three categories, an enforcement action (known as Prompt Corrective Action) is initiated and the bank faces restrictions on dividend payouts, and asset growth and also needs to submit a capital restoration plan. Given the breadth and complexity of possible enforcement actions, we make the simplifying assumption that a bank fails if it is deemed significantly undercapitalized. The FDIC rules and regulations (that hold over most of our sample period) define as significantly undercapitalized banks those with a risk-weighted capital ratio less than 6.0% and (inverse) leverage ratio less than 3.0%.[18] These numbers imply that their model counterparts are $\lambda_w = 16.66$ and $\lambda_u = 33.33$. The risk weights for the capital adequacy requirement are $\omega_L = 1$ for loans and $\omega_S = 0.2$ for liquid assets.

4.3 Baseline Results

There are seven parameters left to be estimated: the discount factor β, the curvature of the utility function γ, the flow cost of operating the bank c, the new loans screening cost parameter ϕ_N, the external finance premium for accessing wholesale funding ϕ_F, the reduction in cost from accessing wholesale funding when bank equity is higher ϕ_E, and the value of consumption after failure c^D. We estimate the model separately for small and large banks by the Method of Simulated Moments using 11 moment conditions. We use the standard deviations of the chosen moments in the cross-section to weight the moment conditions and minimize their squared differences from their simulated counterparts.[19]

Table 4 shows the estimated parameters and Table 5 the estimated moments and their empirical counterparts for both large and small banks. One important difference between

[18] More details can be found at https://www.fdic.gov/regulations/laws/rules/2000-4500.html#fdic2000part325103.

[19] Since there is no cross-sectional distribution for the failure rate, but it is an important variable in our model, we choose a high weight for it.

large and small banks is the cost of accessing wholesale funding; the estimated parameter ϕ_F is almost ten times lower for large banks than for small banks. Based on equation (13), the estimated parameters ϕ_F and ϕ_E (Table 4), and the estimated capital structure (Table 5), the average cost of accessing wholesale funding is 1.09% (1.17%) over the deposit rate for large (small) banks. Facing a higher marginal cost of accessing wholesale funding, small banks optimally decide to borrow less, which leads to relatively similar average costs of wholesale funding for small and large banks. Since small banks borrow less in the wholesale funding market, they depend more on deposits (Table 5).

Table 4: Estimated parameters using the Method of Simulated Moments.

Parameter	Large banks	Small banks
Wholesale funding friction ϕ_F	0.0092 (0.0023)	0.080 (0.00293)
Wholesale funding friction ϕ_E	0.07 (0.0036)	0.007 (0.0014)
Discount factor β	0.975 (0.0041)	0.986 (0.0115)
CRRA γ	1.30 (0.0042)	1.90 (0.0056)
Consumption after bank failure c^D	2e-5 (3.8e-4)	4e-5 (8.4e-4)
Operating cost c	0.011 (0.0023)	0.0096 (0.0012)
Screening cost new loans ϕ_N	0.43 (0.0037)	0.90 (0.0035)

This table shows the results of the method of simulated moments estimations of our benchmark model. We estimate the small and large banks separately. The standard errors of the estimated parameters are shown in parenthesis.

Large banks have a higher rate of time preference and a less concave objective function than small banks leading to a more volatile dividend to equity ratio. A smaller degree of concavity in the objective function of large banks is interpreted as large banks facing less severe financial frictions compared to small banks. The mean failure rate is matched mainly through the consumption after failure parameter c^D. Similarly, the mean loan to asset ratio is matched by the cost of screening new loans. The average large (small) bank pays 4.4% (5.7%) of the value of new loans as issuance costs (Equation (12) evaluated at mean new loans). The higher marginal cost for small banks leads them to have a smaller loan share in total assets.

For both large and small banks the model underpredicts mean equity holdings, slightly underpredicts the mean profit to equity ratio but matches the mean dividend to equity ratio. The operating costs of 1.1% (0.96%) for large (small) banks are reasonable and imply that profits do not become too large relative to the data. The model also matches second moments of key ratios reasonably well with the exception of the standard deviations of the loan to asset ratio and the dividend to equity ratio. The loan to asset ratio is more volatile than in the data because large banks can adjust their liquid asset holdings very quickly by changing their wholesale borrowing. Small banks, on the other hand, hardly borrow wholesale and cannot adjust their loan to asset ratio as quickly, leading to a less volatile loan to asset ratio than in the data. On the other hand, the dividend to equity ratio is too smooth for both small and large banks. While a smaller degree of concavity would lead to a more volatile dividend to equity ratio, this would come at the expense of an even lower equity to asset ratio.

5 Discussion of Results

We first present individual bank policy functions and a typical time path of a bank to enhance our intuition about the economics behind the model, and then proceed with analyzing the implications of the model for the cross-section and for aggregate fluctuations.

Table 5: Model and Data Moments.

	Large banks		Small banks	
Moments	model	data	model	data
Mean failure rate (in %)	0.092	0.084	0.051	0.050
Mean loans/assets	0.704	0.665	0.626	0.622
Mean deposits/assets	0.638	0.633	0.891	0.857
Mean equity/assets	0.065	0.072	0.067	0.099
Mean profit/equity	0.055	0.063	0.029	0.037
Mean dividends/equity	0.029	0.028	0.012	0.013
Std. loans/assets	0.100	0.076	0.050	0.082
Std. deposits/assets	0.062	0.086	0.021	0.035
Std. equity/assets	0.013	0.013	0.015	0.014
Std. profit/equity	0.035	0.048	0.024	0.024
Std. dividends/equity	0.011	0.034	0.007	0.016

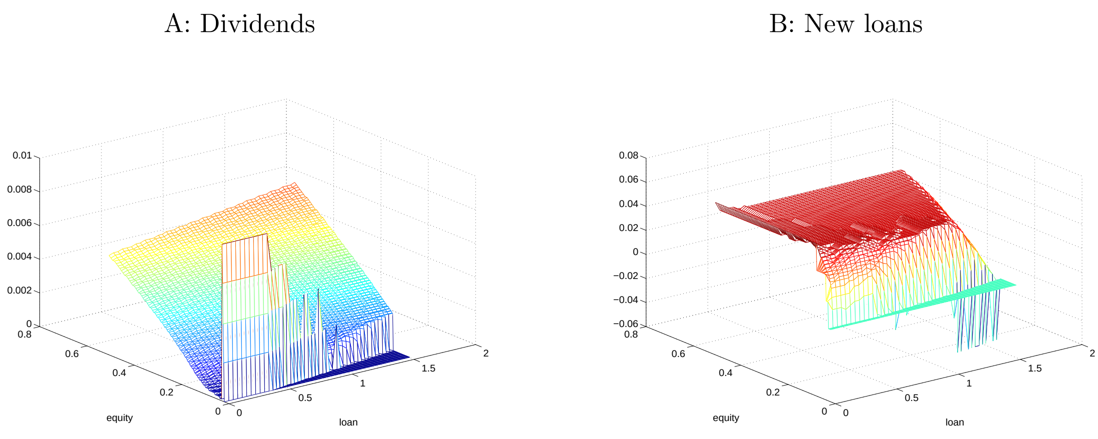
This table shows the results of the method of simulated moments estimations of our benchmark model and the corresponding data moments for small and large banks separately at a quarterly frequency. The sample is all U.S. commercial banks in the period 1990-2010. Small banks are those below the 95th percentile of total assets. Large banks belong to the top two percentiles.

5.1 Policy Functions and the Life of a Bank

Having normalized the model by deposits, we are left with two continuous state variables: (normalized) loans and (normalized) equity. Figure 5A shows the dividend policy function conditional on the low loan losses idiosyncratic state during a boom. Dividends are increasing in equity due to a wealth effect for most parts of the state space. For low levels of equity and low levels of loans, bankers exhibit risk-shifting behavior by expropriating value from other stakeholders and consuming excessive dividends. The bank moves close to the regulatory capital constraints but does not violate them. Depending on the shock realizations next period, the bank might either survive or fail. For low levels of equity and high loan levels, the constraints are violated and the bank fails, in which case dividends are zero.

Figure 5B shows new loan issuance. New loans are monotonically increasing in equity and decreasing in the stock of loans for most parts of the state space. As in the dividend

Figure 5: Policy functions with low idiosyncratic loan losses during a boom



This figure shows policy functions of the model for large banks in a boom when they experience low loan write-offs. Panel A shows normalized dividends, while Panel B shows normalized new loan issuance.

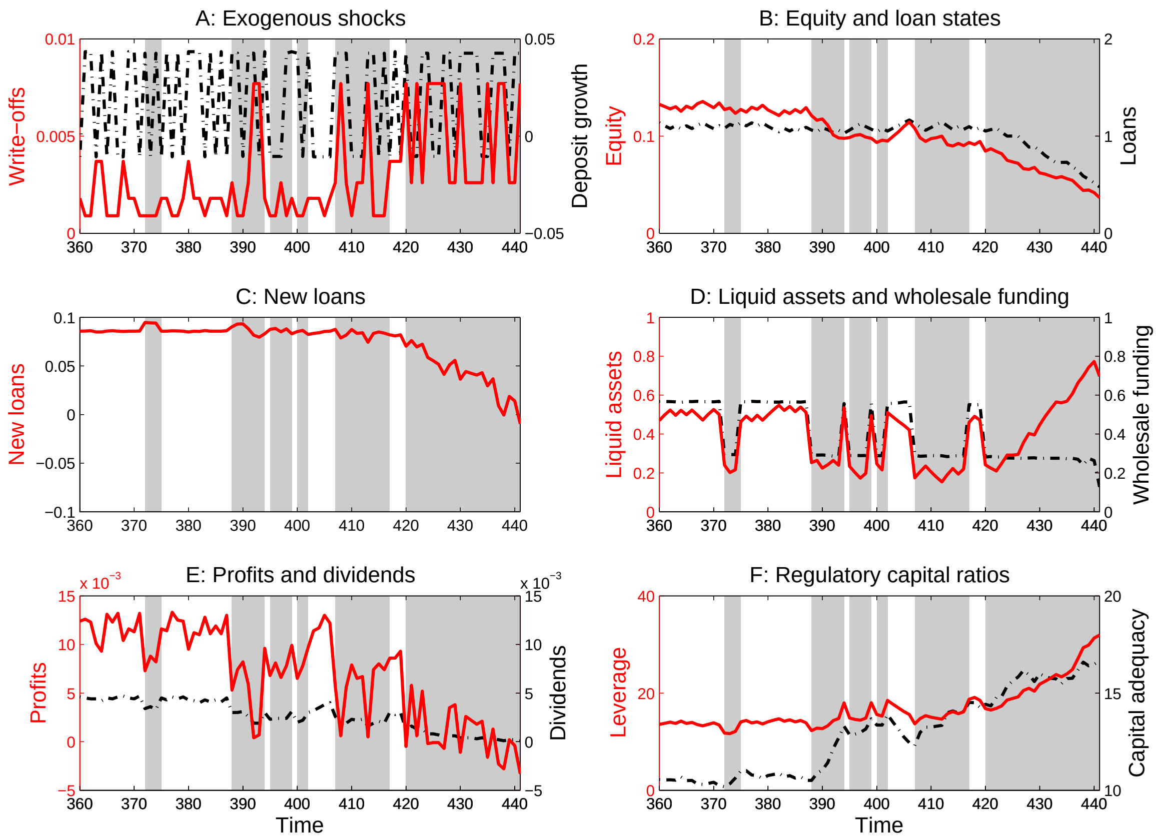
policy function, there are two distinct regions for low values of initial equity: at low levels of existing loans, the bank curtails new lending and at higher levels it starts liquidating loans.

Having solved for the policy functions, Figure 6 shows the behavior of an individual large bank that eventually fails.[20] Panel A reports the exogenous simulated loan write-off and deposit shocks. In reaction to this substantial idiosyncratic uncertainty, the bank accumulates an equity buffer above the regulatory capital requirements (Panel B). Panel C shows that loan issuance falls when write-offs are high. Liquid asset holdings and wholesale funding are procyclical (Panel D). Both profits and dividends also fall in recessions, but dividends are significantly smoother than profits (Panel E).

In the final recession starting in period 420, the bank fails. At the beginning of this recession, the bank experiences a few periods of low or negative profits which deplete equity, but the share of loans has not yet fallen significantly. In period 425 the bank has risk-

[20] The shaded areas denote model recessions.

Figure 6: Life of a bank that eventually fails



This figure shows the behavior of a large bank that eventually fails. Panel A shows the exogenous shocks and Panel B the endogenous equity and loan states. Bank choices are shown in Panels C-E. Liquid asset holdings and wholesale funding are strongly procyclical and dividends are smoother than profits. Panel F shows the evolution of regulatory capital ratios as the bank approaches failure. In the run-up to bank failure, loan write-offs (Panel A) gradually deplete equity (Panel B). The bank also engages in costly loan liquidation (Panel C), while it increases its liquid asset holdings (Panel D). Loan liquidation depletes equity further, causing the bank to hit the leverage constraint (Panel F) and eventually fail.

weighted assets of around 16 times equity, which is close to the capital adequacy constraint. But the unweighted leverage ratio is around 20, still far from its constraint.

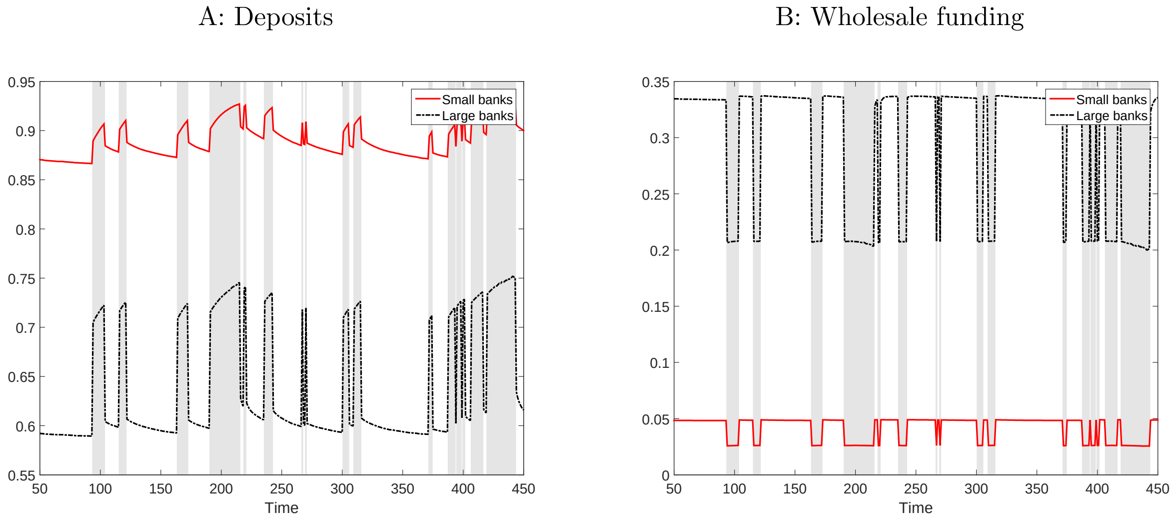
To observe the capital adequacy requirement, the bank issues less new loans and substitutes into liquid assets that carry a lower risk weight. Since loan write-offs remain elevated, equity is gradually depleted. In the run-up to failure, the bank engages in costly liquidation of loans and increases liquid assets. This behavior is driven by the capital adequacy requirement, since loans have a five times higher risk weight than liquid assets. However, costly loan liquidation depletes equity further. Thus, ultimately in period 442 the bank violates the leverage requirement and fails. This interaction between the two regulatory capital requirements is typical for failures in the model and demonstrates the importance of studying them jointly.

5.2 Time Series Behavior: Small versus Large Banks

Figures 7 to 10 provide a more detailed view of the model's time series behavior. Figure 7A (Figure 7B) compares the deposit (wholesale funds) to asset ratio for large and small banks over time. Consistent with the data, small banks rely significantly more on deposit funding, while large banks rely more on wholesale funds. Nevertheless, even for large banks, deposits remain the main funding source. During recessions, banks shrink total assets and reduce wholesale borrowing. As a result, the relative importance of deposits as a funding source increases. This cyclical pattern is consistent with Figure 1.

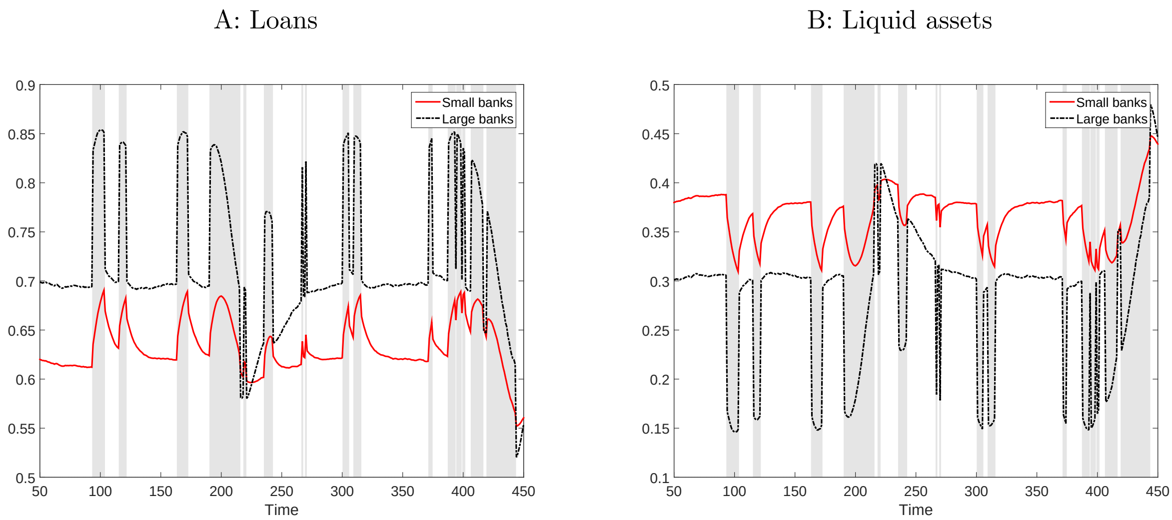
Figure 8 shows the asset side of the balance sheet. Small banks hold more liquid assets than large banks. This is consistent with the idea of precautionary liquidity buffers in

Figure 7: Evolution of the share of deposits and wholesale funding in the model



This figure shows the evolution of the deposit to asset ratio (Panel A) and the wholesale funding to asset ratio (Panel B) for small and large banks in the model. These ratios are the results of simulating 100,000 small and large banks independently for 2,000 periods of which only the last 500 periods are shown. Grey areas depict recessions. Details of the simulation can be found in the appendix.

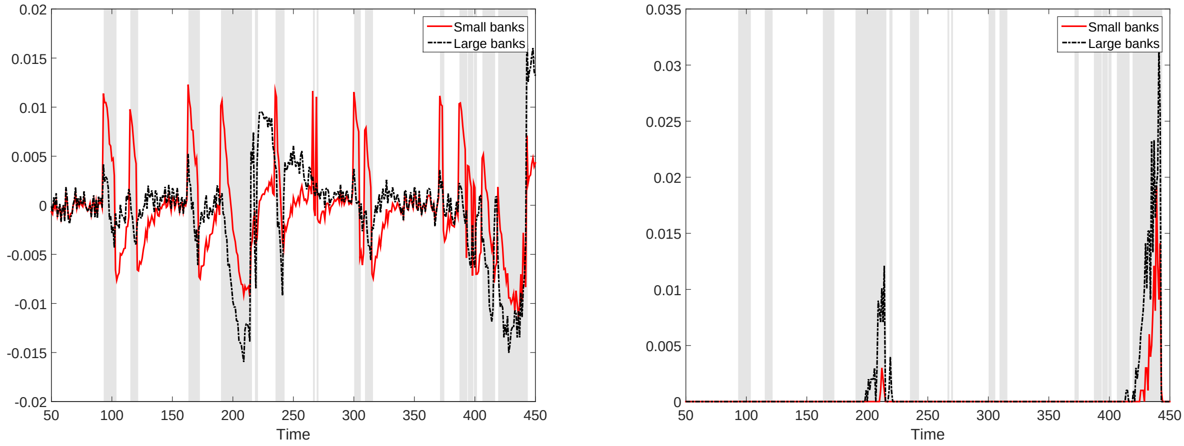
Figure 8: Evolution of the share of loans and liquid assets in the model



This figure shows the evolution of the loan to asset ratio (Panel A) and the liquid asset to total asset ratio (Panel B) for small and large banks in the model. These ratios are the results of simulating 100,000 small and large banks independently for 2,000 periods of which only the last 500 periods are shown. Grey areas depict recessions. Details of the simulation procedure can be found in the appendix.

Figure 9: Cyclical properties of loan growth and bank failures

A: Aggregate loan growth B: Bank failures



Panel A of this figure shows aggregate loan growth for small and large banks in the model. Loan growth is defined as the log difference of the outstanding stock of loans. The simulations are for 100,000 small and large banks independently for 2,000 periods of which only the last 500 periods are shown. Panel B shows the evolution of bank failure rates. Grey areas depict recessions. Details of the simulation can be found in the appendix.

Kashyap and Stein (2000), given that small banks face higher costs of accessing wholesale funding. At the onset of the recession, banks shrink their balance sheet by initially reducing liquid assets, given that loan liquidation is costly. Therefore, the share of loans initially jumps, before declining deeper into the recession. This effect is more pronounced for large banks because they rely more on wholesale funding, which can be cut back quickly. A slower reduction in loans arising from a more stable funding source (deposits) during a recession is consistent with the empirical findings in Ivashina and Scharfstein (2010) and Dagher and Kazimov (2015).

Figure 9A shows that aggregate loan growth is strongly procyclical. Figure 9B shows that failures are countercyclical. The intensity of failures increases strongly with the length of a recession. In short recessions there are only few failures, while in long recessions the failure rate rises by up to three percent.

Figure 10A shows that, consistent with the data, large banks are more leveraged than small banks on average. Since small banks have less access to the wholesale funding market, they rely more on deposit and equity funding. Thus, they hold significantly more precautionary equity. This increase in equity funding translates into a lower leverage ratio. To the extent that large banks have better access to wholesale funding than small banks, they use higher leverage to take advantage of profit opportunities, consistent with De Angelo and Stulz (2015).

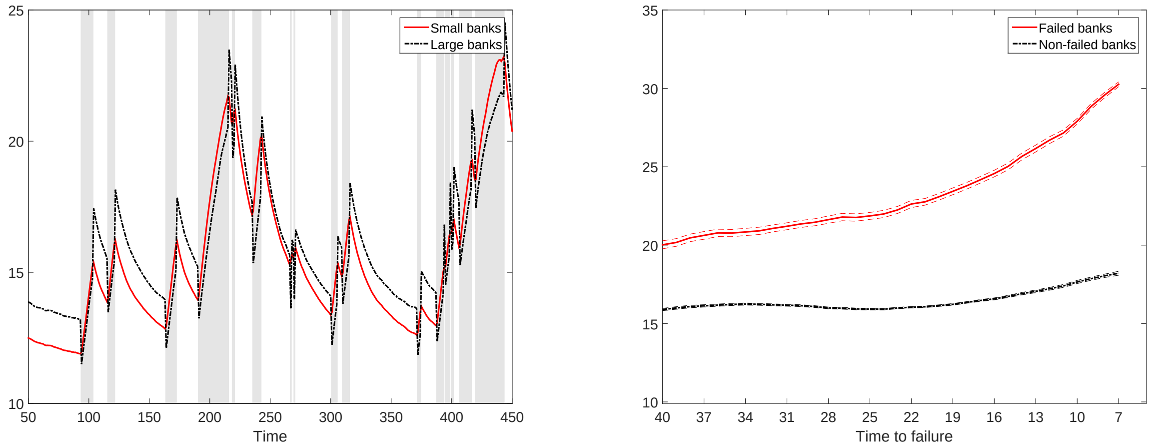
In good times, banks use retained earnings to build up equity. During recessions, equity declines and leverage increases because profits fall. Since banks want to smooth dividends, they do not lower dividend payouts as much as profits. At the onset of a recession, large banks reduce wholesale borrowing quickly leading to a rise in equity relative to total assets and a fall in leverage. Such leverage procyclicality is consistent with Adrian and Shin (2010, 2014). Deeper into the recession, loan losses eat into bank equity, making leverage countercyclical. This longer-run behavior is consistent with He and Krishnamurthy (2013) and Brunnermeier and Sannikov (2014).

Figure 10B is the model counterpart to Figure 3B; it shows the average leverage of failed and non-failed banks over a ten-year period prior to failure. The leverage of failed banks is consistently higher than that of surviving banks and increases significantly towards failure. Thus, an increase in leverage is an indicator for subsequent vulnerability, consistent with the evidence in Berger and Bouwman (2013).

Figure 10: Leverage by size and of failed and non-failed banks in the model

A: Leverage

B: Leverage of failed and non-failed banks



This figure shows the evolution of leverage ratios for small and large banks in the model in Panel A. These ratios are the results of simulating 100,000 small and large banks independently for 2,000 periods of which only the last 500 periods are shown. Grey areas depict recessions. Panel B shows the evolution of leverage of failed banks and their non-failed peer group. The x-axis measures the time-to-failure in quarters. Details of the simulation can be found in the appendix.

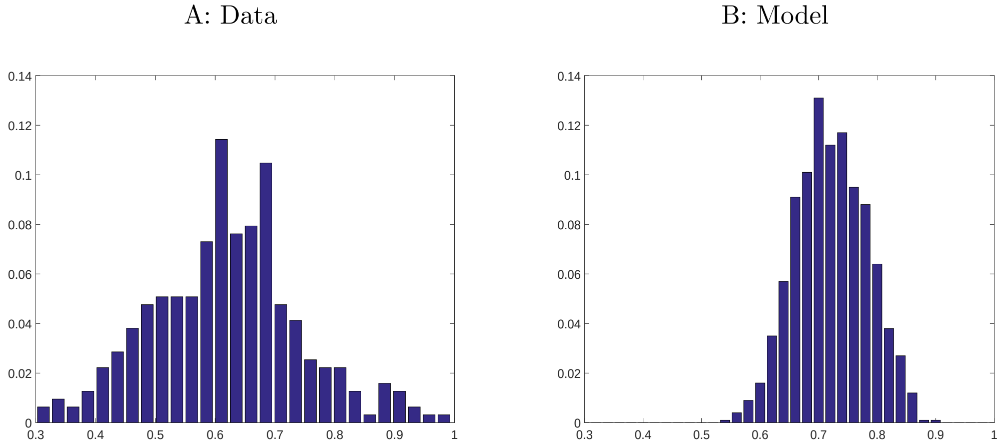
5.3 Cross-section

In this section, we compare model outcomes to their data counterparts focusing on cross-sectional heterogeneity. The results here are the outcome of simulating the model for large banks.[21] Figure 11 shows the distribution of mean loan to asset ratios across banks. The model produces significant heterogeneity despite banks being ex ante identical and facing only two sources of idiosyncratic uncertainty. Nevertheless, the model distribution is not as wide as in the data.

Figure 12 shows the distributions of mean leverage across banks. This is important since bank failures are ultimately driven by high leverage. Mean leverage in the data and the model are symmetrically distributed. As in the case of the mean loan to asset ratio, the

[21]The cross-sectional results for small banks are similar and skipped for brevity.

Figure 11: Distribution of loan to asset ratios



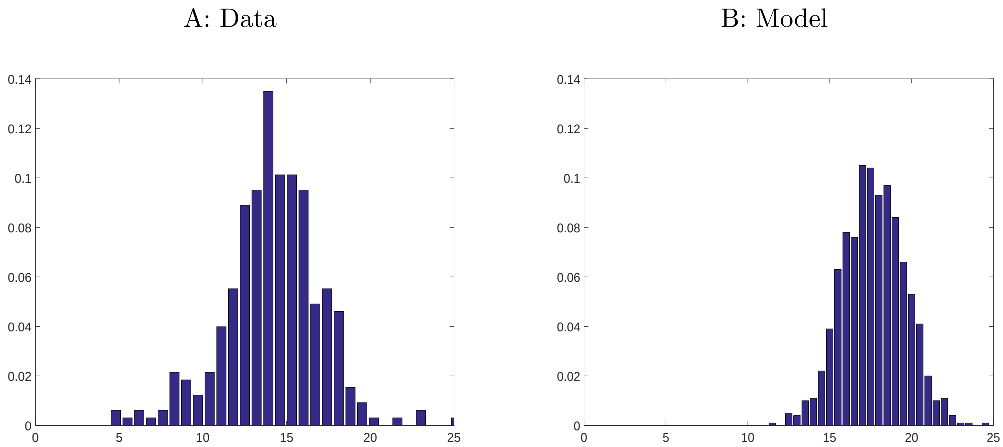
This figure shows the distribution of loan to asset ratios of large banks in the data (Panel A) and in the model (Panel B). The data are for U.S. commercial banks in the period 1990-2010. Panel B shows the results of simulating 100,000 banks for 2,000 periods of which only 80 periods are used for comparability with the data. Details can be found in the appendix.

model dispersion is not as wide as in the data.

6 Counterfactual Experiments

Part of the appeal in building a structural quantitative model lies in the ability to perform realistic counterfactual experiments. The presence of both capital adequacy and leverage constraints affects loan choices differently. Figure 13 illustrates how the feasible loan set changes as each constraint is separately tightened. The black (solid) line is the baseline situation: the vertical segment is at the minimum equity level implied by the binding leverage limit and the upward-sloping segment is the binding capital adequacy constraint. Tightening the capital adequacy constraint shifts down the upward-sloping segment, leaving the vertical segment at the minimum equity level unchanged. Since the capital adequacy parameter λ_w

Figure 12: Distribution of leverage ratios



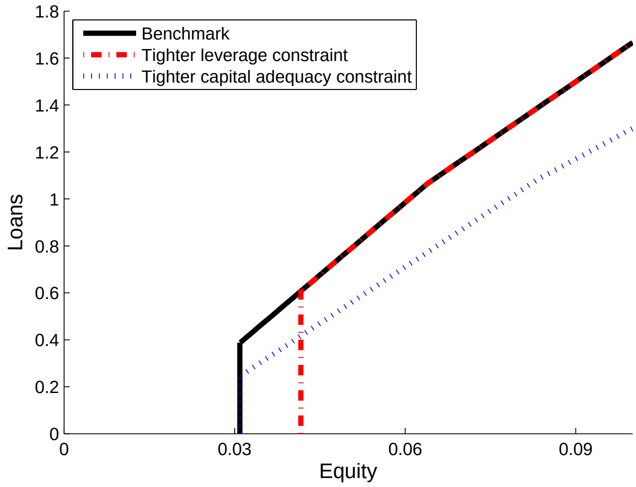
This figure shows the distribution of leverage ratios of large banks in the data (Panel A) and in the model (Panel B). The data are for U.S. commercial banks in the period 1990-2010. Panel B shows the results of simulating 100,000 banks for 2,000 periods of which only 80 periods are used for comparability with the data. Details can be found in the appendix.

also influences the slope of this constraint positively, a tighter constraint (lower value of λ_w) leads to a flattening of this constraint. Tightening the leverage limit shifts the minimum equity level to the right but leaves the upward-sloping segment unchanged.

We perform two experiments and compare the results across stochastic steady states. The first experiment analyzes the implications for different risk-weighted capital adequacy constraints (λ_w) between 13 and 20 (baseline is 16.66, which corresponds to a 6% Tier 1 capital ratio). The second experiment analyzes what happens when the unweighted leverage requirement (λ_u) changes from 25 to 41 (baseline is 33.33, which corresponds to a 3% leverage ratio under Basel III).

To better understand the effects of changing capital requirements it is useful to formally

Figure 13: Changes in the regulatory capital requirements



This figure shows the capital requirements at the beginning of a period for a bank that has exogenous deposits D=1. The capital requirements are shown for the benchmark values, a tighter capital adequacy constraint and a tighter leverage constraint. A tighter leverage constraint increases the minimum equity level, so that the vertical line shifts to the right. A tighter capital adequacy constraint shifts the constraint down and lowers its slope. See Figure 4 for a detailed derivation of the benchmark case.

define equity buffers:

$$\textit{Equity Buffer} = \min\left[\left(\frac{E}{w_L L + w_S S} - \frac{1}{\lambda_w}\right), \left(\frac{E}{L+S} - \frac{1}{\lambda_u}\right)\right]. \tag{14}$$

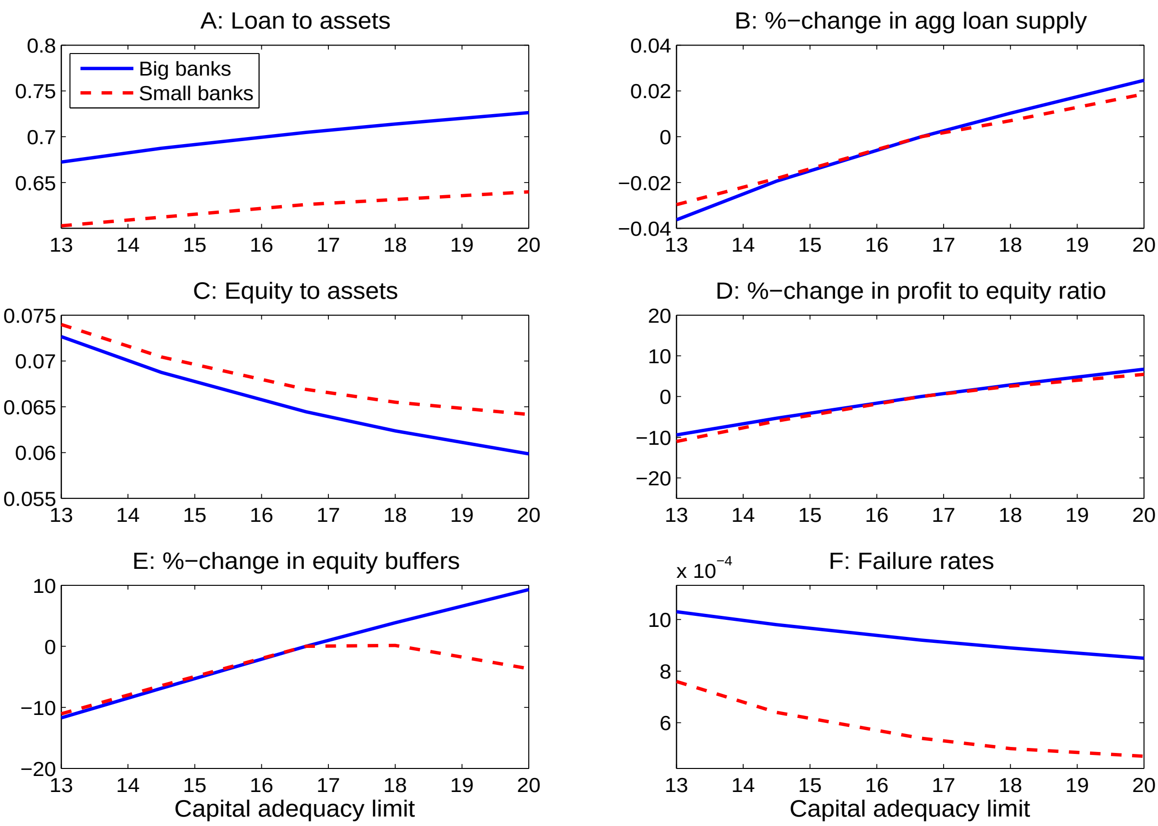
The first term in the minimum operator shows equity relative to risk-weighted assets minus the threshold amount of equity implied by the risk-weighted capital adequacy constraint. The second term shows equity relative to total assets minus the threshold amount of equity implied by the unweighted leverage constraint. The overall equity buffer is defined as the minimum of these two values.[22]

[22]For example, consider the average large bank in the model which has 6.5% equity, 70% loans and 30% liquid assets, all relative to total assets, see also Table 5. For risk weights $w_L = 100\%$ for loans and $w_S = 20\%$ for liquid assets, the equity buffer implied by the capital adequacy constraint is $\frac{0.065}{1\times0.7+0.2\times0.3} - \frac{1}{16.66} = 0.0255$. The equity buffer implied by the leverage constraint is $\frac{0.065}{0.7+0.3} - \frac{1}{33.33} = 0.035$. Since the overall equity buffer is given by the minimum, the average large bank has an equity buffer of 2.55% in the baseline model.

6.1 Changing Capital Adequacy Requirements

We solve the model for different values of the capital adequacy constraint leaving all other parameters, including the leverage limit, unchanged. The simulation uses exactly the same shock sequence in every experiment. Figure 14 shows the effect of tightening λ_w from 20 to 13 (corresponding to a minimum capital adequacy requirement increase from 5% to 7.7%) for small and large banks.

Figure 14: The effects of changing the risk-weighted capital adequacy constraint



This figure shows the effects of changing the capital adequacy limit between 13 (7.7% minimum risk-weighted equity ratio) and 20 (5% minimum risk-weighted equity ratio). Panel A shows that the loan to asset ratio falls as the constraint is tightened (λ_w is lowered). Panel B shows that this translates into a fall in the aggregate loan supply (expressed relative to the baseline (16.66) calibration). Panel C shows that the equity to asset ratio increases as the constraint is tightened; while Panel D shows that this leads to a fall in the profit to equity ratio (expressed relative to the baseline calibration). Panel E shows that the equity buffer mostly falls as the constraint is tightened, also expressed relative to the baseline calibration. Panel F shows that failure rates increase as the constraint is tightened.

As the risk-weighted capital adequacy constraint is tightened, the average loan to asset ratio of both small and large banks falls (Panel A) because banks substitute out of high-yielding, high risk-weighted loans into low-yielding, low risk-weighted liquid assets. This lowers the return on assets. Panel B shows that the decrease in the loan to asset ratio translates into a fall in aggregate loan supply. As expected a tighter capital adequacy constraint implies a higher equity to asset ratio for precautionary reasons (Panel C).

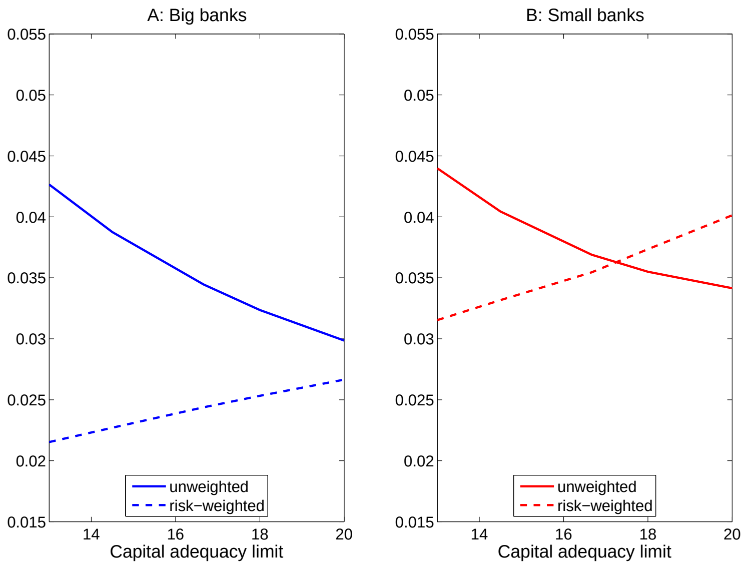
Given the fall in the return on assets and the increase in equity, the return on equity falls as the constraint tightens (Panel D). In our incomplete markets setup, bankers are relatively impatient and make their equity accumulation decisions by comparing the expected return on equity to the discount rate: the lower rate of return on equity weakens their incentive to accumulate equity. Therefore, the equity buffer falls (Panel E).[23]

For large banks, equity buffers fall monotonically as the constraint is tightened. However, for small banks, the change in the equity buffer is non-monotonic. This difference can be seen in Figure 15, Panel A (B) for large (small) banks, where we show the two components of the equity buffer. Since λ_u is kept constant and mean equity rises as the capital adequacy constraint tightens, equity relative to the unweighted leverage constraint (solid lines) increases. On the other hand, equity relative to the risk-weighted constraint (dashed line) falls because the direct effect of tightening the constraint is greater than the endogenous increase in equity. For large banks, the risk-weighted capital adequacy constraint is always tighter

[23]The intuition behind this result is similar to the intuition given in Campbell and Viceira (1999) and Gomes and Michaelides (2005) on how saving responds to higher elasticities of intertemporal substitution for different measures of risk aversion. For higher risk aversion coefficients there is a lower portfolio allocation to stocks, generating a lower expected return. Saving therefore responds differently to changing elasticities of intertemporal substitution depending on the expected rate of return and therefore the risk aversion coefficient. The same intuition applies here since the constraint affects the expected return on equity (or average profits to equity) in two ways. First, potentially lower loan supply reduces profits. Second, the higher precautionary equity implies a lower average return on equity.

than the unweighted leverage constraint, since the risk-weighted capital adequacy constraint is always below the unweighted leverage constraint. For small banks, the unweighted leverage constraint becomes more binding at around $\lambda_w = 17$ when the capital adequacy constraint becomes relatively loose. This happens because small banks hold more equity. Since the equity buffer is the minimum of the two, the equity buffer of small banks exhibits a hump, which can be seen in Panel E of Figure 14.

Figure 15: Equity buffer components for different values of the risk-weighted capital adequacy constraint



This figure shows the two components of the equity buffers (see equation 14). The dashed line shows the equity relative to the risk-weighted capital adequacy constraint, which varies between 13 and 20. The solid line shows the equity relative to the unweighted leverage constraint, which is kept constant at its baseline value of 33.33. The equity buffer is the smaller of the two values.

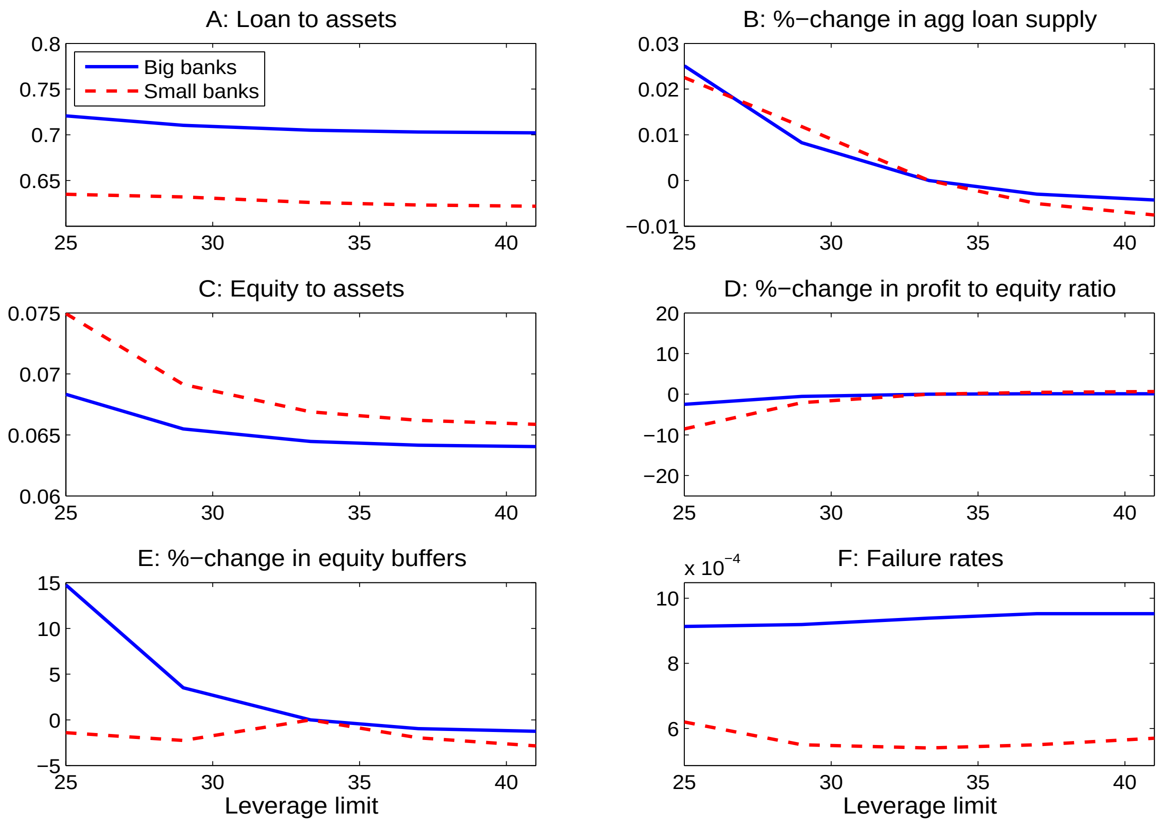
Panel F shows that the failure rates increase as the risk-weighted constraint is tightened. This happens because the equity buffer falls. The average bank moves closer to the constraint: the endogenous increase in equity is not as large as the tightening of the constraint. At high values of λ_w, the equity buffer and, as a result, failure rates of small banks flatten since at these values the unweighted leverage constraint is the tighter of the two constraints, as shown in Panel B of Figure 15.

6.2 Changing Leverage Requirements

In this section, we solve the model for different values of the leverage constraint leaving all other parameters, including the capital adequacy constraint, unchanged. Figures 16 and 17 show the effect of tightening λ_u from 41 to 25 (corresponding to a minimum requirement that increases from 2.44% to 4%).

As the leverage constraint is tightened, Panel A of Figure 16 shows that the loan to asset ratio rises mildly. This happens because the leverage constraint does not discriminate between loans and liquid assets, unlike what happens when the capital adequacy constraint is tightened (Section 6.1). The increase in the loan to asset ratio leads to an increase in the aggregate loan supply as the constraint is tightened (Panel B). Quantitatively, a one percentage point increase in the leverage constraint (lowering λ_u from 33 to 25) leads to a two percent increase in aggregate loan supply. Banks raise their equity to asset ratio in response to a tighter leverage constraint for precautionary reasons (Panel C). Because the loan to asset ratio rises, the return on assets increases. Thus, the effect on the return on equity is ambiguous. On the one hand, the increase in the return on assets raises the return on equity. On the other hand, the increase in equity holdings lowers it. Panel D shows that the net effect of a tightening of the constraint is a small decline in the profit to equity ratio for large banks. For small banks the drop in the profit to equity ratio is larger because they raise relatively more equity in response to a tighter constraint.

Figure 16: The effects of changing the unweighted leverage constraint

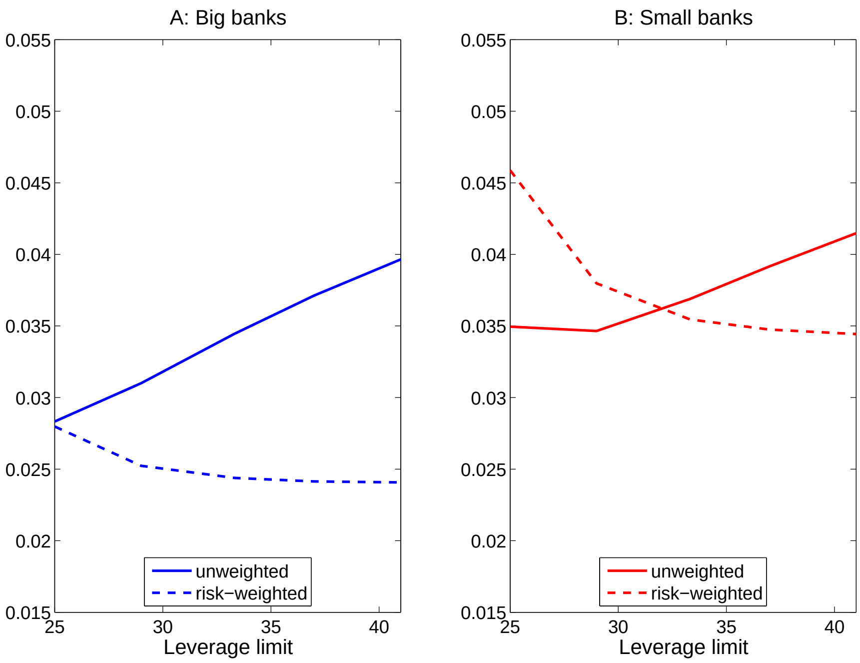


This figure shows the effects of changing the unweighted leverage limit between 25 (4% minimum equity ratio) and 41 (2.44% minimum equity ratio). Panel A shows that the loan to asset ratio rises as the constraint is tightened (λ_u is lowered). Panel B shows that this translates into an increase in the aggregate loan supply (expressed relative to the baseline (33.33) calibration. Panel C shows that the equity to asset ratio increases as the constraint is tightened; while Panel D shows that this leads to a small fall in the profit to equity ratio (expressed relative to the baseline calibration). Panel E shows that the equity buffer mostly increases as the constraint is tightened. Panel F shows that the failure rate of large banks falls as the constraint is tightened, whereas it first falls and then rises for small banks.

Consistent with the rise in equity buffers (Panel E), the failure rate falls uniformly for large banks. For small banks it falls at high values of λ_u (Panel F). But beyond a certain point of tightening the leverage constraint, the failure rate for small banks rises, which is also consistent with the behavior of equity buffers.

In contrast to the experiment in Section 6.1, the equity buffer rises for large banks as the leverage constraint tightens. This happens because the endogenous rate of return on equity falls only mildly since banks re-allocate into loans. As shown in Figure 17, the effect is stronger for large banks since the risk-weighted constraint is the tighter of the two constraints. This effect is also present for small banks but only for values of $\lambda_u > 32$: for smaller values, it is the unweighted leverage constraint that binds more.

Figure 17: Equity buffer components for different values of the unweighted leverage constraint



This figure shows the two components of the equity buffers (see equation 14). The dashed line shows equity relative to the risk-weighted capital adequacy constraint, which varies is kept at its baseline value of 16.66. The solid line shows equity brelative to the unweighted leverage constraint, which varies from 25 to 40. The equity buffer is the smaller of these two values.

Comparing the evolution of the two components of the equity buffers across the two experiments (Figures 15 and 17), we see that for large banks, the risk-weighted capital adequacy constraint is more binding than the leverage constraint since the dashed line is uniformly below the solid line. The reason for this is that large banks are more levered and hold more loans. The situation is different for small banks though. For them, the two constraints are close to being equally important in the baseline scenario. Therefore, it is always the constraint that gets tightened that becomes the more binding one. When the capital adequacy constraint is tightened, it is equity relative to the capital adequacy constraint that is smaller (Figure 15). When the leverage constraint is tightened, it is equity relative to the leverage constraint that is smaller (Figure 17).

6.3 Policy implications

The first important policy implication illustrates that the two constraints can have opposite effects on loan supply. Tightening the risk-weighted constraint leads to a contraction in loan supply, since loans carry a higher risk weight. On the other hand, tightening the unweighted constraint leads to an increase in loan supply because banks substitute out of liquid assets into loans, since both asset classes carry the same risk weight but loans offer a higher expected return.

The second important policy implication is that a tightening of the constraints does not necessarily imply a reduction in bank failures. Banks always respond to a tightening with an increase in equity holdings. However, this increase in equity is not always enough to also increase the equity buffer. The exact quantitative magnitude depends on the effect on the return on equity. Note, however even though bank failures can increase when a constraint is tightened, the fiscal costs of bank bail-outs might still decline. While we do not model bail-outs explicitly, we can use our model to assess their implications. Bail-out costs depend on failure rates and the bail-out costs conditional on failure. We have already seen that tighter regulatory capital requirements may sometimes increase the incidence of bank failures. However, bail-out costs conditional on failure decline since banks hold more equity at the time of failure.

Comparing the two capital requirements, tightening the leverage constraint is clearly the better policy in our model: it leads to an increase in loan supply and a decline in failure rates, at least for large banks. Thus, tightening the leverage requirement could complement the tightening of capital adequacy requirements helping to avoid a fall in loan supply, thereby preventing an unintended consequence of the tightening of capital adequacy requirements for the real economy.

The third important policy implication emphasizes the differential effect of the capital requirements on different sized banks. The capital adequacy constraint is always tighter than the leverage constraint for larger banks. This happens because larger banks are more highly levered, use wholesale funding markets more extensively and have a higher loan to asset ratio than smaller banks, both in the model and in the data. Thus, taking heterogeneity into account when designing regulatory policy is warranted: this heterogeneity might even justify differential regulation based on bank size.

7 Conclusion

We use individual U.S. commercial bank financial statement information to develop stylized facts about bank behavior in both the cross section and over time. We then estimate the structural parameters of a quantitative banking model that includes choices of new loans, liquid investments and failure in the presence of undiversifiable background risks (loan write-offs, interest rate spreads and deposit shocks) and regulatory capital constraints. The model replicates many features of the data and can be used to perform counterfactual experiments.

We find that tighter risk-weighted capital requirements reduce loan supply and increase bank failures because endogenous equity holdings increase by less than capital requirements. On the other hand, tighter leverage requirements increase lending because high-yielding loans start dominating low risk-weighted liquid assets, but bank failure rates remain relatively unchanged. We also find that heterogeneity matters; capital adequacy constraints affect larger banks more strongly than smaller banks. Moreover, the two capital requirements interact in a non-trivial way and should therefore be studied jointly. The model can be extended in future research to analyze the quantitative effects of other regulatory policies like prompt corrective action, liquidity requirements, and countercyclical capital buffers.

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9 Data Appendix

The analysis draws on a sample of individual bank data from U.S. Call Reports for the period 1990:Q1-2010:Q4. For every quarter, we categorize banks as small if they are below the 95th percentile of the distribution of total assets, as medium if they are between the 95th and 98th percentile and as large if they are above the 98th percentile.

Our initial dataset is a panel of 890,252 quarterly observations, corresponding to 17,226 different identification numbers of commercial banks. We drop 38,563 observations that have an FDIC identification number equal to zero and 4,313 observations due to missing values. We exclude banks with exceptional growth (e.g. due to mergers and acquisitions or winding down of bank activities) by winsorizing at the 1st and 99th percentile of the sample distribution of growth rates in customer loans and tangible assets at every quarter.[24] This removes 25,292 outlier observations and 22,647 observations due to missing values in growth rates. The final sample is a panel of 799,437 quarterly observations from 16,564 uniquely identified commercial banks.

The loan write-off ratio (the analog of w in the model) is calculated by dividing quarterly loan charge-offs by lagged gross loans (total loans plus quarterly charge-offs). Real deposit growth is calculated by taking the log difference in broad deposits, defined as the sum of transaction and non-transaction deposits. To avoid the impact of outliers when estimating the exogenous processes for loan write-offs and real deposit growth, we winsorize their sample distributions at the 1st and 99th percentile every quarter, by bank size. The autoregressive processes for loan write-offs and deposit growth are estimated at the individual bank level,

[24] Tangible assets equal total assets minus intangible assets, such as goodwill.

considering only banks with at least 35 observations in expansions and 35 observations in recessions, i.e. at least 70 observations in total. For deposit growth in particular, the autoregressive process is estimated taking into account seasonal effects at a bank level by adding quarterly dummies. The model parameters that we consider for the autoregressive processes are the averages of the estimated ones across banks by size, after winsorizing them at the 1st and 99th percentile of their estimated sample distribution.

To derive targeted moments for balance sheet and profit and loss ratios, we first winsorize them at the 1st and 99th percentile of their sample distribution every quarter by size. Moments of ratios are calculated at the individual bank level by considering only banks with at least 20 observations in expansions and equally in recessions, i.e. at least 40 observations in total. We only consider positive tangible equity in all the calculations, and profits are before tax, extraordinary items and other adjustments. For the Method of Simulated Moments estimation we use average moments across banks and for weighting purposes we use the standard deviations around these averages.

A similar approach is used for estimating the average real return on loans, liquid asset returns and deposit rates from individual bank data. For loan returns we use the ratio of quarterly interest income on loans over lagged loans. For liquid asset returns we use the ratio of quarterly interest income on Fed funds sold and reverse repo plus gains or losses on securities over lagged liquid assets. For deposit rates we use the ratio of quarterly interest expense on deposits over lagged deposits.

To calculate the fraction of loans that are repaid every quarter (the analog of ϑ in the model), we use one fourth of the ratio of loans that mature in less than 1 year divided by total loans outstanding. The resulting average estimate is 6% (8%) for large (small) banks, which assumes a uniform repayment rate over time.

We also consider all bank failures and assistance transactions that occurred during the sample period, altogether 1,292 bank-specific events.[25] From these events we are able to identify 810 failed banks in the data, given that reports often become unavailable some time prior to the effective failure date. This is particularly true for the early part of the sample, where, for example, there are no matching data for 214 and 145 failed banks in the years 1990 and 1991, respectively.

10 Solution Appendix

This section shows the model normalization and outlines the numerical computational approach.

10.1 Normalization

The deposit process contains a unit root but is i.i.d. in growth rates. To make the model stationary, we normalize by deposits. Denote the growth rate of deposits with $\Gamma_{t+1} = \frac{D_{t+1}}{D_t}$ and the normalized variables as lower case variables, for example $f_t = \frac{F_t}{D_t}$.

The risk-weighted limit (7) becomes

$$\frac{\omega_L \left(l_t + n_t\right) + \omega_S s_t}{e_t} \leq \lambda_w. \tag{15}$$

[25] Available at https://www.fdic.gov/bank/individual/failed

The equity evolution (4) becomes

$$\begin{aligned} e_t &\equiv \frac{E_t}{D_t} = \frac{E_{t-1} - X_t + (1-\tau)\Pi_t \mathcal{I}_{\Pi_t>0} + \Pi_t(1-\mathcal{I}_{\Pi_t>0})}{D_t} \\ &= (e_{t-1} - x_t)\frac{1}{\Gamma_t} + (1-\tau)\pi_t \mathcal{I}_{\Pi_t>0} + \pi_t(1-\mathcal{I}_{\Pi_t>0}). \end{aligned} \tag{16}$$

All other equations are normalized analogously.

10.2 Computational Appendix

After the normalization there are 2 continuous state variables: normalized equity e_t and normalized loans l_t. The aggregate state b_t is approximated by a two state Markov chain, and the transition probabilities are chosen to generate expansion and recessions that last, on average, 5 and 2 years, respectively. The state dependent stochastic process for bad loans follows an AR(1) process which is discretized using the procedures described by Adda and Cooper (2003). The numerical solution algorithm is as follows.

1. Assign values for all exogenous parameters.
2. Construct two grids for the two continuous state variables equity (e) and loans (l).
3. Draw a sequence for all shocks for the simulation.
4. Assign initial starting values for the seven parameters to be estimated.

   The remaining computational steps have two components: solution of the value functions and simulation.

   Solution of value function problem

5. Consumption after failure ($\bar{c}$) implies a continuation value after failure v^d.

6. A guess is made for the (normalized) value function $v(l, e; \Omega)$

7. The optimization problem is solved for all discrete states: expansion and recession, and nodes for bad loans and for all values on the grids for e and l. At each node, the bank chooses dividends x, new loans n, liquid assets (securities) s and wholesale borrowing f simultaneously to maximize the normalized value function. The details for this step are as follows.

   (a) At each node (e, l) three nested grids are made for (x, n, f), and s follows from the balance sheet constraint: $s = 1 + f + e - x - l - n$.

   (b) If the candidate (x, n, f) is feasible and obeys the capital requirements, a loop is made over all possible future states, and profits in each state are calculated. The shocks and the choices imply a certain level of profits in each state, which leads to a different level of equity and loan (l', e') in the future period. The continuation value is computed in each of these states. This is either $v(l', e'; \Omega')$ or v^d if failure is preferred and the banker pursues a career outside the bank.

   (c) If the candidate (x, n, f) violates any of the regulatory constraints, the regulator takes control of the bank, shareholders are deprived of any dividends and failure utility v^d is assigned.

   (d) Since future values of (l', e') will not, in general, lie on the grid, a two-dimensional linear interpolation routine is chosen to obtain the values $v(l', e'; \Omega')$ at this node.[26]

8. The solution to the optimization problem at each node provides an update value function $\widetilde{v}(l, e; \Omega)$.

   (a) If the maximum absolute difference between $\widetilde{v}(l, e; \Omega)$ and $v(l, e; \Omega)$ at every single node is below the tolerance level, the value function has converged;

   (b) otherwise $v(l, e; \Omega)$ at the beginning of step 7 is replaced with $\widetilde{v}(l, e; \Omega)$ and step 7 repeated.

9. After convergence, the decision rules for dividends x, new loans n, and wholesale borrowing f are saved for the simulation.

Simulation

10. The previously drawn shock sequences and the saved decision rules are used to simulate $N = 10,000$ banks for $T = 2,000$ periods.

11. Each bank starts with some specific initial value for (e_t, l_t), aggregate and idiosyncratic states. The decision rule is then used to compute new loans n_t, dividends x_t, and wholesale borrowing f_t. The shocks $t + 1$ are realized, which in turn yield profits π_{t+1}. This yields the new equity level: e_{t+1}. Similarly, loans next period are l_{t+t}.

12. A bank that fails during the simulation is replaced by a new one which starts with mean equity, mean loans and a low idiosyncratic loan loss, i.e. loan losses. Due to the very low number of failures, this choice has no influence on aggregate statistics.

[26] Linear interpolation is chosen because, being a local method, it is more stable than, for example, cubic splines.

13. After the simulation is concluded, the first $1,500$ periods are excluded and all statistics reported are calculated based on the last 500 periods.

14. The criterion function of the estimation is calculated.

    (a) The squared differences between model and data moments are calculated.

    (b) These are weighted by the efficient weighting matrix which uses the standard deviations of the empirical moments.

15. If the criterion function is too high, a new set of values is tried in step 4. For this optimization, we use a standard derivative-free simplex method.