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SIGURD GALAASEN
AND HAAKON
SOLHEIM

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Sigurd Mølster Galaasen[†] and Haakon Solheim[‡]

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Abstract

This paper investigates the effect of broad-based versus sectoral capital requirements using a dynamic model of bank behaviour. We study the problem facing banks when determining their dividend policy and portfolio of long-term loans to the retail and corporate sector. The return on lending is uncertain, and capital requirements may be reduced when loan losses are high, in order to stabilise lending. We find that when shifting capital between sectors is difficult or very costly, targeted regulation, such as a sectoral buffer (SCCyB), can lead to more stable lending during a crisis than a broad-based CCyB, at a lower cost. This depends on the ability of the policymaker to foresee the type of crisis. A targeted requirement is ex-post an inefficient policy if crises occur in sectors where the buffer requirement is inactive, as the targeted policy cannot effectively stabilise credit. However, the consequences of policy "mistakes" depend on the degree of sectoral segmentation in the banking market. Banks that provide credit to both the retail and the corporate sector will endogenously reallocate capital to the constrained sector in a crisis, irrespective of the kind of regulatory buffer that is implemented, thereby dampening the consequences of such inefficient policy.

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[†] *Sigurd Mølster Galaasen*: Norges Bank, Norges Bank Research, sigurd-molster.galaasen@norges-bank.no

[‡] *Haakon Solheim*: Norges Bank, Financial Stability, haakon.solheim@norges-bank.no

1 Introduction

Negative shocks to bank assets can have a significant impact on banks' solvency and lending in bad times. In the aftermath of the 2007-2008 financial crisis, regulatory reforms have led to a significant tightening of capital requirements. The goal is to increase banks' resilience to adverse shocks and to stabilise credit. However, how to set the level and structure of capital requirements is still disputed.

As a simplification, the regulatory design problem can be narrowed down to a choice between two different types of requirements. The first type of requirement is fixed over time. Banks in breach of this requirement will take measures (i.e. increase the equity/assets ratio) to fulfil the requirement. The second type of requirement varies with the economic cycle, as exemplified by the Basel III countercyclical capital buffer (CCyB). This requirement can be reduced in a severe downturn, thereby mitigating the need for recapitalisation.

Several countries have now implemented a CCyB. It has, however, been argued that the CCyB is a blunt tool. Many countries experience that financial imbalances in periods tend to be more pronounced in one sector than in the system as a whole (BCBS (2018), Chap. 3). Using a broad-based CCyB to address sector-specific imbalances creates unfortunate unintended consequences by constraining lending to other, non-booming sectors. In response, more targeted regulation has recently been proposed, such as a sectoral buffer (SCCyB).

Policymakers with full information, who can operate unconstrained, may simply set the SCCyB to replicate the CCyB. In this setting, the outcome under a sectoral buffer regime would be at least as good as with a broad-based buffer, since policymakers have more instruments at hand. In practice however, sectoral fine-tuning under uncertainty and imperfect information about underlying risk and vulnerabilities in the economy increases the risk of policy mistakes. Furthermore, regulators may operate under policy frictions, constraining their flexibility in when and how to set the buffer. So while sectoral buffers lead to better outcomes in a first-best setting, the actual outcome in a frictional world is unclear.

In this paper, we use a structural bank model to shed light on the transmission mechanism of various regulatory designs. The model is calibrated to be consistent with observed stylised facts of the Norwegian banking sector based on aggregated balance sheet and income statement data from seven of the largest Norwegian banking groups. Using our calibrated model as a laboratory, we compare bank responses to sectoral and broad-based buffers under different policy rules and with different assumptions about the foresight of policymakers.

Sectoral buffers have so far only been implemented in Switzerland (Basten and Koch (2017), Auer and Ongena (2016)). In Scandinavia, risk weights on household lending have been tightened in recent years, but this is seen as a permanent, structural change rather than time-varying regulation. Some countries, like Belgium, have for a period changed the risk weights on mortgage lending (Ferrari et al. (2017)).

Norway has implemented a CCyB, and the experience so far has been that when banks face higher risk-weighted capital requirements they make a trade-off between sectors and reduce the relative amount of high risk-weight lending (Solheim (2017)). The expectation is that if a sectoral buffer is implemented, banks may still make this trade-off. For example, even if the capital buffer is only applied to household loans, the big difference in risk weights between the household and non-financial corporate sector may make banks tighten lending to non-financial enterprises.

Auer and Ongena (2016) investigate the effects of sectoral capital buffers in Switzerland. They find that banks respond to a sectoral capital buffer by reducing lending to households. However, some borrowers who cannot get a mortgage instead apply for loans from a corporate branch. In this model, banks do not make an internal trade-off between private and corporate customers, but customers move from private to corporate lending when lending requirements in the private market become more expensive. This might indicate that the structure of the banking sector is important in understanding the possible transmission mechanism of a sectoral buffer.

Our model is based on Galaasen and Johansen (2016), who study the problem of a single bank supplying loans to both the retail and the corporate market, assuming that cycles are perfectly synchronised across sectors. We extend their approach along two dimensions, by (i) comparing the universal bank system to a two-sector bank system, in which banks either lend to the retail or to the corporate sector, and (ii) allowing for asymmetric sectoral cycles.

In the model, a bank chooses a portfolio of long-term loans and short-term securities, financed by internal (equity) and external (debt) funds. Bank loans are risky, and both the demand for loans and the return depend on the state of the business cycle, which follows an exogenous Markov process. At each point in time, the bank has to satisfy a regulatory capital requirement. Capital moves slowly over time through retained earnings, whereas loans can be adjusted immediately, subject to a quadratic loan liquidation cost. If the bank does not find it optimal to operate, it liquidates its assets and exits the market facing limited liability.

The forward-looking, profit-maximising bank can adjust its capital ratio by either changing the level of assets or the level of equity. However, we assume equity can only be raised through retained earnings, reflecting the behaviour of banks in crisis times. Deleveraging is subject to adjustment costs. Recapitalisation may therefore be slow and costly. The potential cost of a crisis, causing large losses to bank equity, is constrained credit availability for non-financial customers. Moreover, since asset adjustments come at a cost, a bank facing the need for sharp credit adjustments may choose to exit the market.

Another aspect of the model is the sectoral differentiation. Different types of assets tend to involve different risks. A natural differentiation is between retail loans (low risk, substantial collateral) and commercial and industrial (c&i) loans (more risky collateral, higher default risk). The impact of a capital requirement tends to vary across these asset types, and the aggregate implications of different requirements depend on how the banking sector makes sectoral trade-offs. Our benchmark model environment considers a universal bank which lends to both sectors. It makes an internal trade-off to ensure that the marginal return on investments will be the same in both sectors. To capture the importance of this trade-off and its impact on the consequences of capital regulation, we compare the universal bank environment with a sectoral bank environment. In the latter environment, there are two banks, each operating in either the retail or the corporate sector. The banks are not able to make sectoral trade-offs to satisfy capital requirements. An alternative interpretation of these two banking environments is that in the former, bank capital can freely and instantaneously move across sectors (since this is done within a single bank). In the latter, the process of moving capital across sectors is prohibitively costly. In this sense, the two environments capture the two extremes of how capital flows between sectors.[1]

Our model environment allows for a rich description of a bank's optimisation problem at the micro level. However, to embed this into a broader macro structure, allowing for feedback mechanisms between the bank and the rest of the economy, is beyond the scope of this paper. Further, even in this relatively simple framework, with strong prior assumptions, the effect of capital requirements is complex. Results will depend on a number of assumptions that are difficult to calibrate based on historical experience

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[1] Even in a banking market with sector-specific banks, capital owners may reallocate capital across banks. However, one would expect that this adjustment is subject to frictions that slow down the speed of adjustment, in particular during crisis times.

and that might change over time, like banks' expectations of the probability of a crisis and the expected long-term return in a negative scenario. Last, the optimal set of capital requirements will depend on the expectations and the utility function of the policymaker. Hence, the policy implications of this paper will be conditional on a strict set of assumptions.

However, a model framework of this kind does provide a setting to better understand the forces that in the end determine how capital requirements actually affect bank behaviour. It also provides a possible laboratory to explore how policy might work under counterfactual conditions. While there is a broad literature on capital requirements, some of which has relevance for sectoral capital buffers (see BCBS (2018) for an overview), there is limited research on how banking behaviour and institutional features affect the way capital requirements work in practice.

The paper proceeds as follows. The model environment is described in Section 2. Section 3.1 shows how the universal bank adjusts its portfolio when subject to heterogeneous buffer requirements across sectors. In Section 3.2, we study the impact of capital regulation across universal and sector-specific banking markets. In Section 3.1 and 3.2, sectoral cycles are entirely symmetric. In Section 3.3 we allow for asymmetric cycles, i.e. sector-specific booms and busts and ask when a sectoral buffer is preferable to a broad-based buffer.

2 Model

This section lays out the economic environment. The model is a modified single bank version of Corbae and D'Erasmo (2014) augmented with sectoral lending and closely related to De Nicolo et al. (2014) and Elizalde and Repullo (2007).

Time is discrete and infinite ($t = 0, 1, 2...$). In a partial equilibrium setting, a single bank with market power maximises the discounted value of future dividends by optimising over a portfolio of long-term loans and short-term securities, financed by internal (equity) and external (debt) funds. At the beginning of each period t, the bank chooses how many loans to extend to sector s (L_{st}) and how many securities (A_t) to hold. The amount of external funding (d) is given exogenously, and equity (e_t) is predetermined. When choosing loan supply, the bank takes into account that higher supply leads to a lower interest rate (r^L_{st}). At the end of the period, profits are realised. Bank loans are risky and the bank faces uncertainty about the fraction of defaulting loans ($1 - p_{st}$). After profits are realised, the bank chooses whether to exit or stay in the market by comparing its charter value with the liquidation value of its balance sheet. Due to the presence of fixed operating costs, the model features non-trivial exit decisions at strictly positive equity levels. If the bank exits, it liquidates its assets and pays back creditors, facing limited liability. The bank's external funding cost r^d is independent of the bank's likelihood of bankruptcy, hence creditors do not take the bank's failure risk into account.[2] If the bank stays, it chooses how much to pay out as dividends and how much to retain as equity for period $t+1$. A key friction in the model is that new equity issuance is prohibitively costly. Equity thus moves slowly over time, through retained earnings. Another key friction is that bank shareholders discount future dividends at a higher rate than the safe return on securities, implying that, absent any risk of failure, the bank would prefer debt over equity.

We want to study how capital regulation affects bank behaviour. Regulation is implemented by requiring the bank to hold a level of equity at least as large as a fraction φ of the risk-weighted value of its assets. The requirement is implemented as a hard constraint, implying that violation of the requirement induces liquidation of the bank.

2.1 Environment

The bank's objective is to maximise the expected discounted stream of dividends:

$$\mathbb{E}_t \sum_{i=t+1}^{\infty} \beta^{i-t} \mathcal{D}_i. \tag{1}$$

Each period t is divided into two sub-periods. At the beginning of the period, before any choices are made, the bank's balance sheet is given by:

$$e_t = a_t + \sum_S \ell_{st} - d, \tag{2}$$

which states that equity e_t equals net wealth, which consists of securities a_t and loan stocks ℓ_{st} carried over from the previous period net of debt d.

The bank then chooses how much to invest in period t loans and securities (L_{st}, A_t)

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[2] In the model, there is only one type of bank debt, whereas in the data, bank debt consists of both insured/secured and unsecured debt. Our model assumption that r^d is independent of the bank's probability of bankruptcy is consistent with data to the extent that unsecured creditors believe that the bank is too big to fail.

subject to the resource constraint:

$$a_t - A_t = \sum_s \left[(L_{st} - \ell_{st}) + \Psi(L_{st}, \ell_{st}) \right], \tag{3}$$

and regulatory capital requirement:

$$\varphi(z_t) H(\{L_s\}_{\mathcal{S}}, A_t) \leq e_t, \tag{4}$$

where $\varphi(z_t)$ is the (possibly) time-varying risk-weighted requirement and $H(L, A)$ denotes the function mapping assets to risk-weighted assets. Whenever loan growth is negative, the bank pays an adjustment cost:

$$\Psi_s(L_{st}, \ell_{st}) = \mathbb{I}(L_{st} < \ell_{st}) \psi_s [L_s - \ell_{st}]^2 \ , \forall s \in \mathcal{S}. \tag{5}$$

The bank faces one source of uncertainty. Loan demand and default frequency are subject to the macro shock z. The end of the period is initiated with the realisation of this shock. The new aggregate state z_{t+1} determines the share of performing loans as well as the period $t + 1$ loan demand.

We assume that the bank under consideration sets its loan supply taking into account a reduced form response by other credit suppliers. Let the loan supply of other credit suppliers be given by $L^o_{st} = M_s(z_t, L_{st})$, where M_s denotes the reduced form response function. The loan interest rate is determined by aggregate loan supply $L^A_{st} = L^o_{st} + L_{st}$ and the state of the economy, through the inverse demand function:

$$r^L_{st} = f_s^{-1}(L^A_{st}, z_t), \tag{6}$$

which is downward sloping in aggregate loan supply and upward sloping in the state of the economy z. The performing loans share is given by:

$$p_{st} = P_s(r^L_{st}, z_t, z_{t+1}), \tag{7}$$

which depends on the loan rate and the state of the macro shock.

Loans mature at an exogenous rate m_s each period and a fraction $(1 - p_{st})$ of the loan portfolio is in default. Given the beginning-of-period choices and the shock realisations, the end-of-period cash flow is given by:

$$C_t = \sum_{\mathcal{S}} [p_{st}(m_s + r^L_{st}) - c_s] L_{st} + r^a A_t - r^d d - \kappa, \tag{8}$$

where the first term captures the cash flow from performing loans net of proportional lending cost c_s, (r^a, r^d) the interest rate on securities and debt and κ the fixed cost. The bank now decides on its dividend policy, $\mathcal{D}_t$. The cash flow is distributed to equity holders or retained. Moreover, the bank has access to a short-term liquidity market in which it can borrow liquidity at cost r^b. Let $B_t < 0$ denote retained earnings and $B_t > 0$ denote short-run borrowing. Then, dividends are determined as:

$$\mathcal{D}_t = C_t + B_t - tax_t, \tag{9}$$

where tax_t denotes the tax payment. The bank pays a 27 percent tax on positive profits, where profits are defined as:

$$\pi_t = \sum_{S} \left[\left(p_{st} r^L_{st} - (1 - p_{st}) \lambda_s(z_{t+1}) - c_s \right) L_{st} - \Psi_s(L_{st}, \ell_{st}) \right] + r^a A_t - r^d d - \kappa - r^b B_t, \tag{10}$$

where $\lambda_s(z_{t+1})$ denotes loss given default, which depends on the state z_{t+1}, and r^b the cost of short-term borrowing.

The bank is constrained in its dividend policy by $\mathcal{D}_t \geq 0$, which is equivalent to ruling out new equity issuance, as dividends are constrained below at zero. If the bank wants to stay in the market despite contemporaneous negative cash flow, it has to access the short-term liquidity market ($B_t > 0$) so as not to violate the non-negativity constraint on dividends. In contrast, if cash flow is positive, the bank may not want to pay out fully as dividends, but instead retain earnings ($B_t < 0$) to raise the next period's initial securities a_{t+1}, as shown below. Short-term borrowing requires collateral in the form of securities:

$$(1 + r^b) B_t \leq A_t \,, \tag{11}$$

with $r^b = 0$ if $B_t \leq 0$. Constraint (11) also reflects the assumption that loans on the balance sheet cannot be used as collateral for short-term borrowing.

Each period, a fraction m_s of loans exogenously matures and non-performing loans are written down by a fraction $\lambda_s(z_{t+1})$. Therefore, beginning-of-period $t + 1$ heritage loans are given by:

$$\ell_{st+1} = [1 - m_s]p_{st}L_{st} + (1 - p_{st})(1 - \lambda_s(z_{t+1}))L_{st}\,, \forall s \in \mathcal{S} \tag{12}$$

Also, at the beginning of period $t+1$, before any choice is made, the short-term liquidity market clears, i.e. B_{t+1} is repaid. Thus, beginning-of-next-period securities a_{t+1} is given by:

$$a_{t+1} = A_t - (1 + r^b)B_t \geq 0. \tag{13}$$

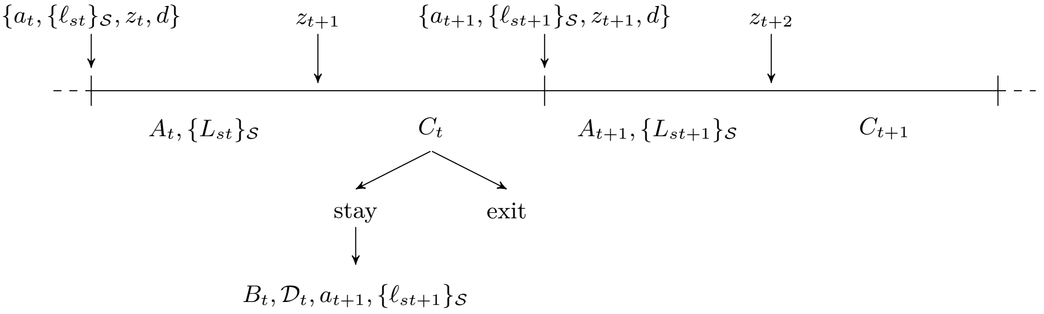
As discussed above, retained earnings ($B_t < 0$) raise a_{t+1} and thus net wealth at the beginning of the next period, which can be invested in either loans or securities.

The bank may choose to exit the market at the end of the period, in which case assets are liquidated and creditors repaid. Note that the bank has to pay liquidation costs on its loan stock. Since the bank faces limited liability, the value of exit is thus given by:

$$\max\left\{0\,, \sum_{\mathcal{S}}((m_s+r^L_{st})p_{st}-c_s)L_{st}+\ell_{st+1}-\Psi_s(0,\ell_{st+1})+(1+r^a)A_t-(1+r^d)d-\kappa\right\}. \tag{14}$$

Figure 1 summarises the timing.

Figure 1: Timing



2.2 Bank's dynamic programming problem

Due to the recursive nature of the bank's problem, we can drop time subscripts. The value of the bank at the beginning of the period is given by:

$$
\begin{aligned}
& V(a,\{\ell_s\}_{\mathcal{S}},z,d) = \max_{A,\{L_s\}_{\mathcal{S}}} \beta\,\mathbb{E}_{z'|z} W(A,\{L_s\}_{\mathcal{S}},z',d) \;\; s.t. \\
& e = a + \sum_{\mathcal{S}} \ell_s - d \\
& a - A = \sum_{s} \left[(L_s - \ell_s) + \Psi(L_s,\ell_s)\right] \\
& \varphi(z) H(\{L_s\}_{\mathcal{S}},A) \le e \\
& r_s^L = f_s^{-1}(L_s^A, z) \;, \forall s \in \mathcal{S}.
\end{aligned}
\tag{15}
$$

The end-of-period value is given by:

$$
W\left(A,\{L_s\}_{\mathcal{S}},z',d\right) = \max_{x\in\{0,1\}} \left\{ W^{x=0}(A,\{L_s\}_{\mathcal{S}},z',d)\,, W^{x=1}(A,\{L_s\}_{\mathcal{S}},z',d) \right\} , \tag{16}
$$

with the exit value $W^{x=1}$ given by equation 14. The continuation value is given by:

$$
\begin{aligned}
& W^{x=0}(A,\{L_s\}_{\mathcal{S}},z',d) = \max_{B\le\frac{A}{1+r^b}} \left\{\mathcal{D} + V(a',\{\ell_s'\}_{\mathcal{S}},z',d)\right\} \;\; s.t. \\
& C = \sum_{\mathcal{S}} [p_s(m_s + r_s^L) - c_s] L_s + r^a A - r^d d - \kappa \\
& \mathcal{D} = C + B - tax \\
& a' = A - (1+r^b)B \ge 0 \\
& \ell_s' = [1-m_s] p_s L_s + (1-p_s)[1-\lambda_s(z')] L_s, \quad \forall s \in \mathcal{S}.
\end{aligned}
\tag{17}
$$

2.3 Calibration

The model period is set to one year and we allow for two sectors, $s \in \mathcal{S} = \{retail, c\&i\}$, where *retail* denotes the retail sector and *c&i* denotes the corporate sector. Our parameter calibration is taken directly from Galaasen and Johansen (2016). For completeness, we include a detailed description of the calibration in the Appendix. The calibrated bank lends to both sectors and makes an internal trade-off to ensure that marginal return in both sectors will be the same. However, it is not obvious that a banking structure should be universal – banks can choose to specialise in corporate or retail lending. In its most extreme form, there will be no trade-off between the sectors.

As an alternative to the universal bank, we also simulate a banking sector with sector-specific banks. This environment will be similar to the environment described in Section 2.1, but there will be two banks and only one sector in each bank. One bank will lend to a high risk-weight, high-risk customer base (c&i), and one bank will lend to low risk-weight, low-risk customer base (retail). For each of these one-sector banks we recalibrate the debt level and fixed cost such that the (i) loans to total assets ratio and (ii) fixed cost to loans ratio are the same as for the universal bank.

3 Quantitative exercises

We now use the above model to study quantitatively the impact of various capital requirement regimes and banking structures. At each point in time, the economy is in a given state, labelled good, neutral, crisis or recovery state, referring to the state of the aggregate shock $z_t \in \{z_g, z_n, z_c, z_r\}$. Our primary focus throughout our quantitative exercises is on the lending behaviour of banks prior to, and in the aftermath of, the economy entering a crisis (i.e. the transition from normal times (z_g or z_n) to crisis times (z_c)). In all states of the world, the bank is subject to a fixed minimum capital requirement of 14.0 percent of risk-weighted assets, and we experiment with different buffer requirements above this minimum during normal times. Once in the crisis state, the buffer is removed. Throughout, we impose heterogeneous risk weights. Consistent with current regulation, the risk weight on retail and c&i loans is 50 percent and 100 percent, respectively.

Before proceeding, we note that in this stylised framework there remain a number of exogenous factors that affect how policy works. One such factor is the banks' perceived probability of default. The forward-looking, rational-expectation bank in our model has an incentive to hold capital to protect its charter value against the event of a default. This incentive is stronger the more heavy left-tailed its stochastic asset returns are. This is in turn influenced by our exogenous assumptions about the likelihood and severity of the crisis. With a sufficiently high probability of large negative shocks, the incentive is potentially so strong that the bank is willing to hold a voluntary capital buffer above regulatory requirements. This means that the effect of an increase in the buffer requirement will typically be lower the more our rational bank protects its charter value from the impact of large negative shocks.

Moreover, when expected returns decline during a crisis, the bank wants to increase the interest margin by cutting loan supply. A sufficiently large decline in expected returns on loans will lead to a sharp drop in bank lending, with or without a CCyB. If banks hold a pre-crisis buffer, they will simply get rid of excess capital by increasing dividends during a crisis.[3] This implies that in high risk sectors, a countercyclical buffer might have *no effect on supply in a crisis* (this will of course depend on the level of capital without a countercyclical buffer).[4]

So, the more likely and severe a crisis is, the more banks will self-insure, making the CCyB less relevant. In fact, somewhat counter-intuitively, a buffer is most effective as a means to stabilise loan supply when expected losses and probability of bank default are low. While such effects might be interesting in themselves, they complicate the comparison of different buffer policies. It also makes it difficult to predict the actual effects of buffer policies.

We now proceed as follows. In Section 3.1 the goal is to compare broad-based capital buffers (i.e. applying to both retail and c&i loans) with a regime with sectoral buffers (applying to either retail or c&i loans). In the sectoral buffer regimes, we adjust the level of the buffer such that the bank holds the same unweighted leverage ratio as in the broad-based regime in normal times.

In section 3.2, we compare different structures of the banking system and the implications for capital regulation. We compare a system with a universal bank (supplying loans to both retail and c&i sector) with a system comprising two sector-specific banks (i.e. one retail bank and one c&i bank) with no interaction between the two sectors.

In Section 3.1 and 3.2, we assume sectoral cycles are entirely symmetric. In Section 3.3 we allow for asymmetric cycles, i.e. sector-specific booms and busts and ask when a sectoral buffer is preferable to a broad-based buffer.

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[3] At this point some might argue that, in a crisis, banks will not be allowed by the FSA to pay dividends. However, by definition the countercyclical buffer is a buffer that is removed completely (unlike other capital buffers that can be draw upon, but only under conditions). We therefore believe it is appropriate that banks can pay dividends as long as capital is above the actual requirement.

[4] Note that this result will depend on the *structural level of the capital requirement*. The lower the capital requirement in total during the crisis, the higher the level of bank lending. If one could reduce the structural level of capital, at some point banks would begin to lend. For a given level of structural requirement during a crisis, however, given the calibration and simulation presented above, it does not matter how high the CCyB is *before* the crisis. In this case, if one wants to reduce credit volatility a solution may be to increase the cyclical share of the total requirement–not increase the cyclical part on top of a fixed structural requirement. This would give the policy maker more lee-way to adjust the capital requirement over the cycle.

3.1 Composition of requirement–sector-specific buffers vs. broad-based buffer in a universal banking system

Sectoral buffers shift the relative cost of financing different types of credit. In this section we compare two regulatory designs. In the *buffer-both* regime, both loan types are subject to a 2.5 percent buffer prior to a crisis. In contrast, in the *buffer-retail* and the *buffer-c&i* regimes, only retail loans in the former and only c&i loans in the latter regime are subject to a buffer requirement. We impose this asymmetric buffer requirement when $z_t = z_n$. In the good state, all loans are subject to the 2.5 percent buffer requirement. We calibrate ϕ_{retail} such that the average leverage ratio in $z_t = z_n$ is equal to the corresponding moment in the *buffer-both* regime. We follow the same procedure when calibrating $\phi_{\text{c\&}i}$ in the *buffer-c&i* regime. The calibrations give $\phi_{retail} = 4.5\%$ and $\phi_{\text{c\&}i} = 5.0\%$.

Figure 2 displays total loans (panel i) and relative loans (panel ii) dynamics when the bank transitions into a crisis from z_n. First, we focus on the pre-crisis impact of the various regulatory regimes, reflected in period 0 allocations. From panel (ii) we see that the SCCyB has the expected impact on relative loan shares, inducing a reallocation of loans towards the type not subject to a buffer. In addition to influencing relative lending, the SCCyB also has implications for the total level of lending, and the direction depends on the buffer regime. Total loans increase under a c&i-buffer regime, whereas they decrease under the retail-buffer regime. The reason is that the elasticity of loan supply with respect to capital requirements is higher for retail loans than for c&i loans.[5]

The heterogeneous pre-crisis impact and the different capital requirements for different loans also have implications for crisis outcomes. With increased pre-crisis lending under the c&i-buffer regime, the bank holds a more risky portfolio of assets for a given leverage ratio. This generates higher equity losses going into a crisis, and thus a relatively more pronounced contraction in lending.

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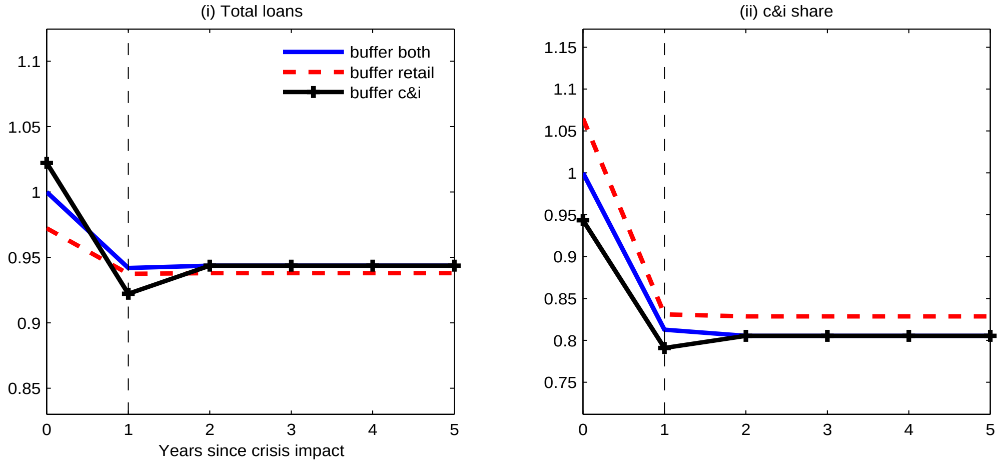
[5] The reason for higher loan supply elasticity with respect to capital requirements in the retail sector is that the interest rate in this sector is calibrated to be less responsive to supply changes than in the c&i sector.

Figure 2: Loan dynamics $z_n \to z_c$



Notes: The chart shows the evolution of lending in the transition from neutral state to crisis for the three capital requirement regimes: Buffer on both sectors, buffer on retail only and buffer on c&i only. Period 0 reflects simulated bank lending in a z_n-steady state, i.e. simulation $z_t = z_n$ for many periods. The aggregate state moves to z_c in period 1 and remains there for five periods. Panel (i) shows the evolution of total loans. Panel (ii) shows the evolution of c&i loans compared with total loans. In both panels we normalise all series with period 0 value in the *buffer-both* regime.

3.2 Sector-specific buffers and banking systems

Our model shows that when responding to regulation, a bank that can make internal adjustments across sectors is more flexible. We illustrate this by comparing the response to sectoral capital buffers in different banking systems. In the *universal* banking system, the bank supplies loans to both sectors, as in Section 3.1. We contrast this to a *sector* system, in which we consider two banks, one supplying retail loans and the other c&i loans. The key distinction between the two systems is that in the latter there will be no spill-over effects between sectors from regulation. An alternative interpretation of these two banking systems is that in the former, bank capital can freely and instantaneously move across sectors (since this is done within a single bank). In the latter, the process of moving capital across sectors is prohibitively costly.[6]

First we investigate the effects of an SCCyB on retail lending (Figure 3). As before, we focus on the evolution of lending when the bank transitions into a crisis from z_n. We

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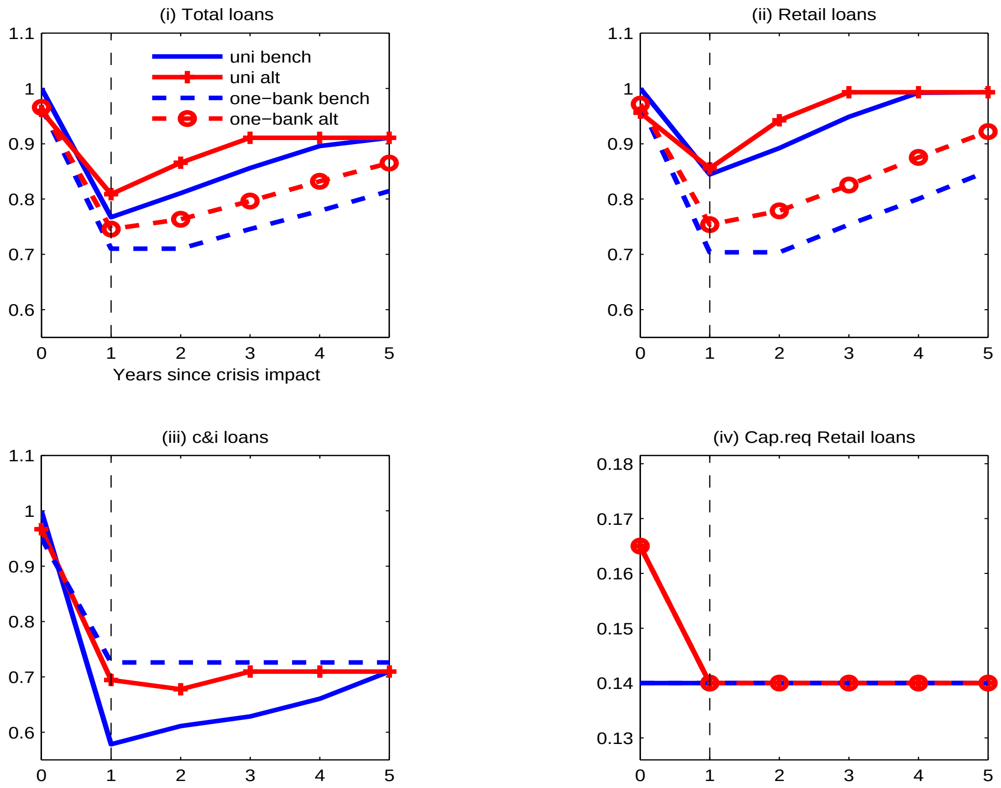
[6] One could argue that even in a banking market with sector-specific banks, capital owners may reallocate capital across banks. However, one would expect that this adjustment is subject to frictions that slow down the speed of adjustment, in particular during crisis times.

consider two capital requirement regimes: *benchmark*, with no buffer requirement when $z_t = z_n$, and *alternative*, where the bank is required to hold a buffer of 2.5 percent in $z_t = z_n$ imposed on retail loans only.

Figure 3: Loan dynamics $z_n \rightarrow z_c$ – Buffer on retail loans



Notes: The chart shows the evolution of lending in the transition from neutral state to crisis. *uni bench* refers to the universal bank under the no-buffer regime, and *uni alt* the universal bank under the regime with a buffer of 2.5 percent in $z_t = z_n$ imposed on retail loans. *one-bank bench* refers to the sectoral banks under the no-buffer regime, and *one-bank alt* refers to the sectoral banks under the regime with a buffer of 2.5 percent in $z_t = z_n$ imposed on retail loans. Period 0 reflects simulated bank lending in a z_n-steady state, i.e. simulation $z_t = z_n$ for many periods. The aggregate state moves to z_c in period 1 and remains there for five periods. Panel (*i*): total loans. For the *sector* model, total loans is the sum of retail and c&i bank lending. Panel (*ii*): retail loans. Panel (*iii*): c&i loans. Panel (*iv*): capital requirement retail loans. In panels (i)-(iii) we normalise with period 0 loan supply in the *uni bench* regime.

We find that spillovers between sectors–if possible–are important for the relative performance of alternative capital requirements. The reason is that when the bank contracts lending in response to equity losses, it makes a risk-return trade-off in both sectors, taking into account the fact that risk weights are heterogeneous. The latter enables the universal bank to alter its risk-weighted asset by changing the relative share of lending to the two sectors, while specialised banks cannot. We observe that relative to a *sector* system, retail (c&i) loans fall less (more) in the *universal* system upon crisis impact. In the short run, the universal bank finds it optimal to adjust its loan portfolio towards retail loans to satisfy the capital requirement. The fact that c&i loans have a higher risk weight than retail loans implies that the total contraction in lending is smaller in a *universal* banking system.

Furthermore, note that for the c&i bank, which is subject to the same capital requirement as in normal times, loan supply drops immediately and stays constant throughout the crisis. This lending drop reflects the assumption that the return on c&i loans falls sharply in a crisis, hence it is optimal to reduce loan supply.[7] For the universal bank, there is excess deleveraging (reduction beyond what is driven by a drop in return on lending) caused by the spillover discussed above.

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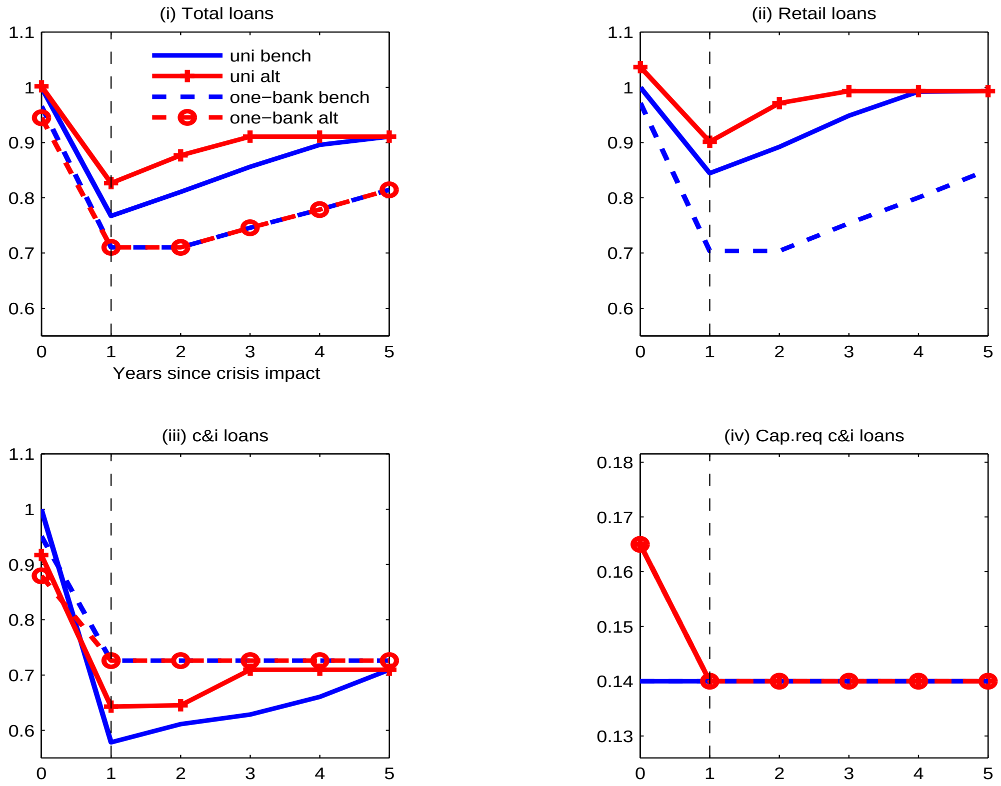
[7] Note that we assume that the return on loans is state-dependent, but independent of loan vintages, i.e. when the loan was granted has no bearing on expected loss probability. If loss probability in bad times for new loans granted after the initial crisis is lower than for loans granted before the crisis, the return on new loans would increase. Moreover, Becker et al. (2018) finds that banks' ability to sort customers based on default risk increases during bad times, which would further increase profitability on new loans.

Figure 4: Loan dynamics $z_n \to z_c$ – Buffer on c&i loans

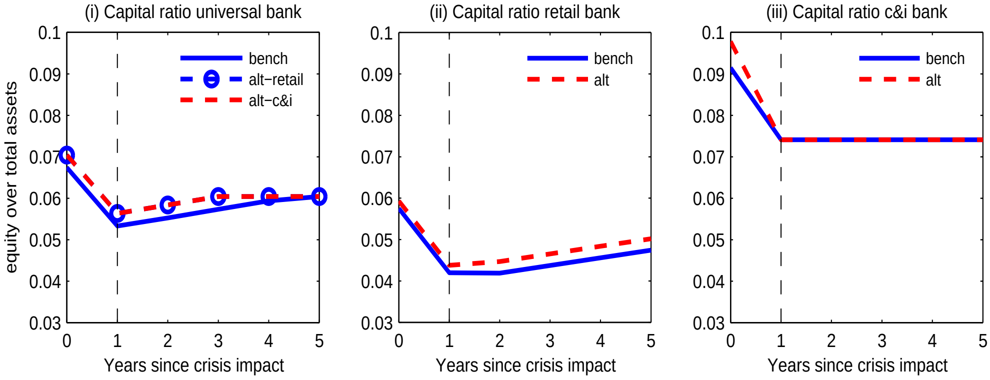


Notes: The chart shows the evolution of lending in the transition from neutral state to crisis. *uni bench* refers to the universal bank under the no-buffer regime, and *uni alt* the universal bank under the regime with a buffer of 2.5 percent in $z_t = z_n$ imposed on c&i loans. *one-bank bench* refers to the sectoral banks under the no-buffer regime, and *one-bank alt* refers to the sectoral banks under the regime with a buffer of 2.5 percent in $z_t = z_n$ imposed on c&i loans. Period 0 reflects simulated bank lending in a z_n-steady state, i.e. simulation $z_t = z_n$ for many periods. The aggregate state moves to z_c in period 1 and remains there for 5 periods. Panel (*i*): total loans. For the *sector* model, total loans is the sum of retail and c&i bank lending. Panel (*ii*): retail loans. Panel (*iii*): c&i loans. Panel (*iv*): capital requirement c&i loans. In panels (i)-(iii) we normalise with period 0 loan supply in the *uni bench* regime.

Next we redo the above exercise, but now the SCCyB in $z_t = z_n$ is imposed on c&i loans only (Figure 4). Given our calibration, the SCCyB on c&i loans has a minimal effect when imposed in a *sector* system. However, for the universal bank, there is still a considerable dampening effect on total credit volatility in a crisis. Again this reflects that the universal bank makes internal trade-offs between the two sectors in order to satisfy the capital requirement. When the requirement is relaxed in a crisis, there is less need to make this trade-off. As a result retail lending is higher with an SCCyB on c&i-loans than with no buffer (Figure 4, panel (ii)).

These results indicate that for a bank that can adjust lending between different sectors, more capital will dampen the negative impact of a crisis independent of which sector the requirement was imposed. For a bank that only lends to one sector, its initial level of capital might be irrelevant for crisis lending.

Figure 5: capital dynamics $z_n \rightarrow z_c$



Notes: The chart shows the evolution in capital ratios in the transition from neutral state to crisis. Panel(i): Capital ratios for the universal bank in the *bench* scenario (no buffer in $z_t = z_n$), and in the *alt* scenarios with a buffer of 2.5 percent on either retail loans (alt-retail) or c&i loans (alt-c&i). Panel (ii): Capital ratios for the retail bank in the *bench* (no buffer) and *alt* scenario (buffer of 2.5 percent on retail loans). Panel (iii): Capital ratios for the corporate bank in the *bench* (no buffer) and *alt* scenario (buffer of 2.5 percent on c&i loans).

Last, we want to illustrate the evolution of capital ratios prior to and during a crisis, under various capital requirement regimes and banking structures (Figure 5). The capital ratio is defined as equity over total assets. In all scenarios, the extra buffer on retail or c&i loans induces the bank to increase its capital ratios. As expected, the percentage change is less for the universal bank than for the c&i bank, since the universal bank can reduce the burden by switching into retail loans. Note that the retail bank does not increase its capital ratio by very much. This reflects the fact that the retail bank holds a voluntary capital buffer before the crisis (when in $z_t = z_n$) in the *benchmark* scenario.

3.3 Sector-specific buffers and economic cycles–perfect and imperfect foresight

When is a sectoral buffer preferable to a broad-based buffer? We study the impact of sectoral buffers when we allow the economy to enter sector-specific booms and busts.

To facilitate this, we need to augment the z-process. In the benchmark process used in Section 3.1 and 3.2, the cycles are perfectly synchronised across sectors. Now we augment the process by allowing shocks to be sector-specific (e.g. one sector is in the good state, the other in the neutral). The augmented z-transition matrix is reported in table 1

Table 1: Augmented z-transition matrix

$F(z, z')$	(z^{ci}_g, z^{re}_g)	(z^{ci}_n, z^{re}_g)	(z^{ci}_g, z^{re}_n)	(z^{ci}_n, z^{re}_n)	(z^{ci}_c, z^{re}_c)	(z^{ci}_n, z^{re}_c)	(z^{ci}_c, z^{re}_n)	(z^{ci}_r, z^{re}_r)
(z^{ci}_g, z^{re}_g)	0.75	0.07	0.07	0.07	0.04	0	0	0
(z^{ci}_n, z^{re}_g)	0.07	0.74	0.07	0.07	0.01	0.04	0	0
(z^{ci}_g, z^{re}_n)	0.07	0.07	0.74	0.07	0.01	0	0.04	0
(z^{ci}_n, z^{re}_n)	0.07	0.07	0.07	0.75	0.04	0	0	0
(z^{ci}_c, z^{re}_c)	0	0	0	0	0.71	0	0	0.29
(z^{ci}_n, z^{re}_c)	0	0	0	0	0	0.71	0	0.29
(z^{ci}_c, z^{re}_n)	0	0	0	0	0	0	0.71	0.29
(z^{ci}_r, z^{re}_r)	0.07	0.07	0.07	0	0.04	0	0	0.75

Note: z^{ci}_s refers to the state $s \in \{g, n, c, r\}$ of the c&i sector. z^{re}_s refers to the state $s \in \{g, n, c, r\}$ of the retail sector. Rows refer to current period state (t), columns refer to next period state (t+1)

A key assumption is that in a sector-specific boom, it is much more likely that a crisis occurs in the booming sector than in both sectors. Hence, cycles are neither completely synchronised nor independent. If boom-bust cycles were independent across sectors, an SCCyB would always be preferred. However, a boom in one sector can be followed by a (for the policymaker) unexpected crisis in both sectors, in which case a broad-based buffer would have been preferred. To highlight this trade-off, the SCCyB in our policy rule does not impose any buffer on the non-booming sector, despite there being a small chance of a crisis occurring in this sector as well.

We compare four alternative regulatory rules: (I) the *no-buffer* rule with a fixed structural requirement of 14 percent (i.e. no buffer), (II) the *sector-buffer* regime with an SCCyB of 2.5 percent on loans in the booming sector (the sector s in the good state z^s_g). We contrast these with a *broad-buffer* regime, where both sectors are subject to a buffer whenever at least one sector is booming (rule III and IV). The policy rules (III) and (IV) differ with the size of the buffer. In regime (III), the CCyB is 2.5 percent. Compared with an SCCyB, this regime imposes both homogeneous buffers and a tighter average capital requirement. To isolate the first effect, rule (IV) implements an alternative regime for the broad CCyB, in which we calibrate the CCyB such that banks' pre-crisis unweighted capital ratio (equity over total assets) is the same as with the SCCyB rule (implying a CCyB below 2.5 percent).

3.3.1 Sectoral buffer on retail loans

We first focus on the effects of the four capital requirement rules for the case of a boom in the retail sector. Figure 6 shows the results for the *universal* system, and Figure 7 for the *sector* system. In both figures, the left-hand panels compare rules (I-II) with the broad buffer of 2.5 percent (rule III), while the right-hand panels compare (I-II) with the calibrated broad-based buffer (rule IV). The two upper panels show the change in lending in a period where a retail boom is followed by a retail-crisis, while the two bottom panels show the change in a period where a retail boom is followed by a broad-based crisis.

In Figure 6, for the universal bank, we compare the *no-buffer* rule with the buffer rules. We find that loan contraction during a crisis is dampened whenever the policymaker can remove a capital buffer. However, this comes at a cost, as the level of pre-crisis lending is lower when buffers are imposed. This cost is much larger with a broad-based CCyB than with a SCCyB (lending is about 3 percent lower with a CCyB).

In a pure retail crisis, the effect on crisis lending seems relatively independent of which of the three buffer rules we impose (the level of crisis lending is equal under all buffer regimes). In a broad-based crisis, however, the SCCyB becomes an ex-post less efficient policy, resulting in a bigger credit drop upon crisis impact compared to the broad-based CCyB, see Figure 6 panel (iii). Although the magnitudes are small relative to the *no-buffer* rule, the SCCyB induces a lending drop of 11 percent, compared to 4 percent with the CCyB. This is partly because the pre-crisis loan level is higher with an SCCyB since the average capital requirement is lower. Once the broad-based CCyB is calibrated to give the same pre-crisis unweighted capital ratio as the SCCyB, the difference is smaller (7 percent vs. 11 percent).[8] In other words, if booms are uncorrelated, but busts are correlated across sectors, the SCCyB rule becomes less efficient. One implication of this is that the activation of an SCCyB should take into account the potential sectoral correlation of crises.

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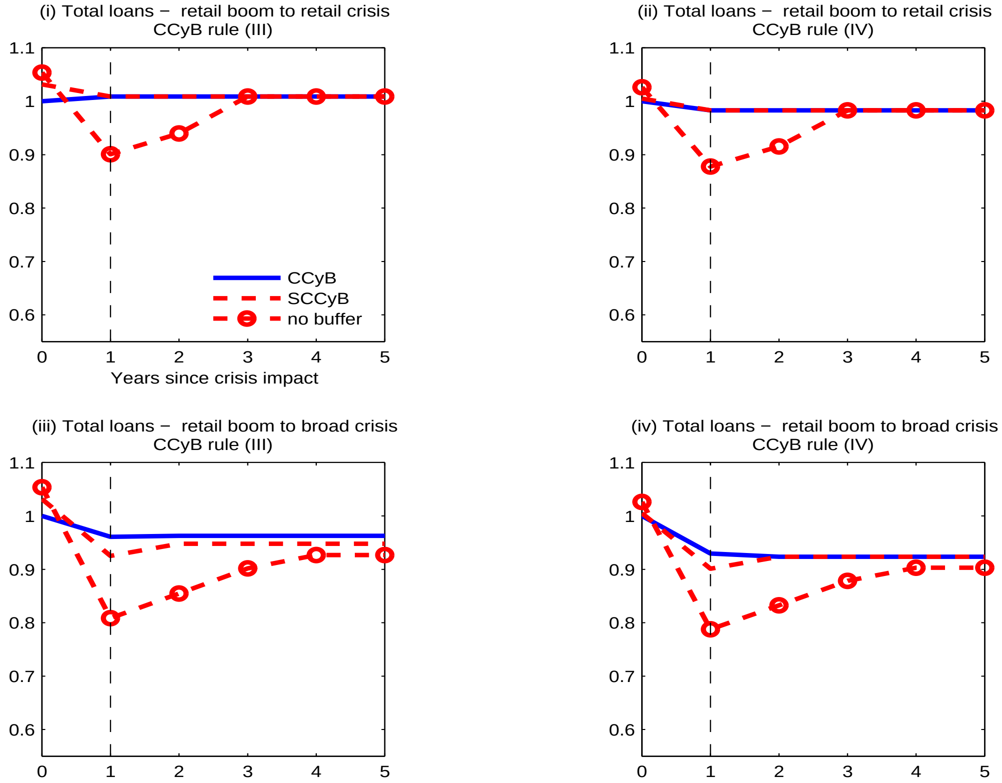
[8] The remainder can be attributed to the pre-crisis sectoral portfolio adjustment the bank makes when facing a retail buffer towards more risky c&i loans.

Figure 6: Universal bank: Retail boom to crisis



Notes: The chart shows the evolution of lending in the *universal* system in the transition from retail boom to crisis. In the top panels (i) and (ii), the crisis is retail-specific. In the bottom panels, the crisis is in both the retail and the c&i sector. We compare a *no buffer* (rule I) and a *sector buffer* SCCyB of 2.5 percent on retail loans (rule II) with two regimes for the *broad-buffer* CCyB (rule III and IV). In the left-hand panels (i) and (iii), the CCyB is 2.5 percent (rule III). In the right-hand panels (ii) and (iv), the CCyB is calibrated such that the pre-crisis unweighted capital ratio is at the same level as in the SCCyB rule. In all panels, the series are normalised with the period 0 value in the CCyB regime.

In Figure 7, we compare the *no-buffer* rule with the buffer rules for the sector-specific banks. Also here we find that loan contraction in a crisis is much larger with the *no-buffer* rule. However, the pre-crisis lending level does not decrease when imposing a buffer. This somewhat surprising effect comes from the fact that when capital requirements are constant at 14 percent, the retail bank holds an endogenous buffer of 1.6 percent to insure against negative shocks.[9]

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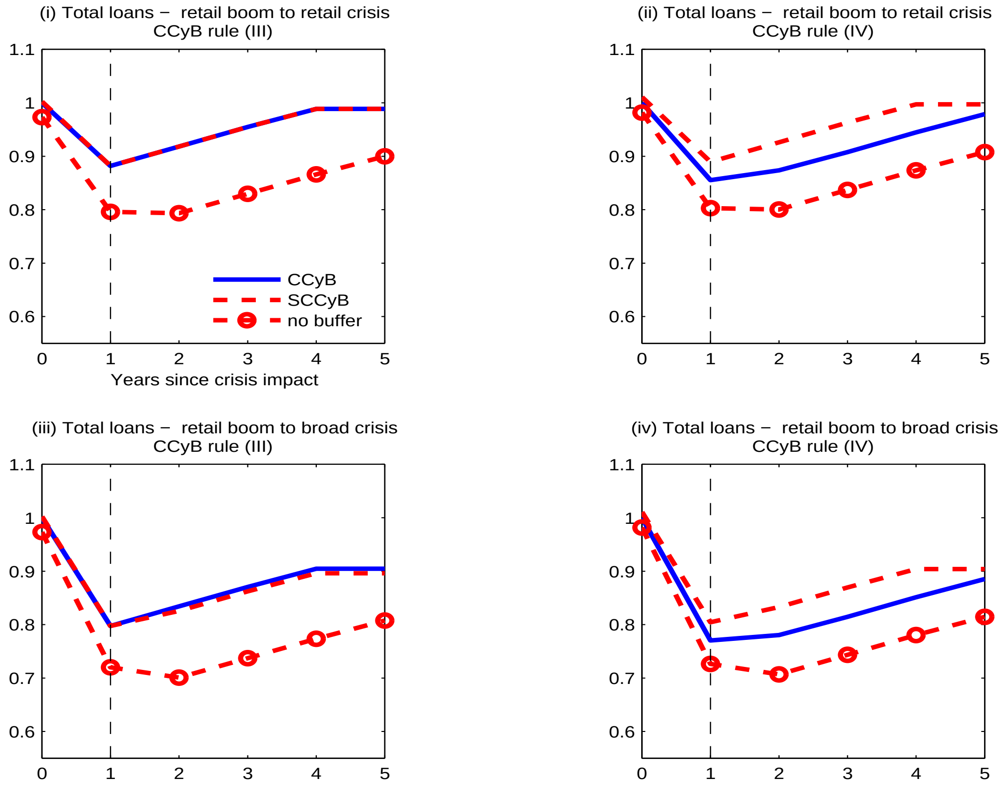
[9] One the one hand, a buffer requirement leads to higher capital requirements in booms (thereby discouraging lending). On the other hand, it removes the need for the bank to self-insure in booms (thereby stimulating lending).

Figure 7: One-sector banks: Retail boom to crisis



Notes: The chart shows the evolution of lending in the *sector* system in the transition from retail boom to crisis. In the top panels (i) and (ii), the crisis is retail-specific. In the bottom panels, the crisis is in both the retail and c&i sector. We compare a *no buffer* (rule I) and a *sector buffer* SCCyB of 2.5 percent on retail loans (rule II) with two regimes for the *broad-buffer* CCyB (rule III and IV). In the left-hand panels (i) and (iii), the CCyB is 2.5 percent (rule III). In the right-hand panels (ii) and (iv) the CCyB is calibrated such that the pre-crisis unweighted capital ratio is at the same level as in the SCCyB rule. In all panels, the series are normalised with the period 0 value in the CCyB regime.

Importantly, the crisis-impact of buffer rules changes in the *sector* system compared to the *universal* system. In the *sector* system, the SCCyB lead to a very different outcome than a CCyB that is calibrated to give the same pre-crisis unweighted capital ratio as the SCCyB (see Figure 7, panels (ii) and (iv)). Consequently, in this case a broad-based buffer policy will induce more credit volatility in crisis times. The reason is that the broad-based buffer is untargeted. It provides the same relative relaxation in capital requirements to both sectors, when in fact the capital constraint is more binding in retail lending.[10] It is thus also intuitive that the difference in effect between a targeted

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[10] In contrast, from panel (i) and (iii) in Figure 7 we see that if the broad-based CCyB is set to 2.5

and untargeted buffer rule is less stark in a universal banking system, since the universal bank reallocates capital towards the most constrained sector in a crisis.

One result from this exercise is that the impact of a broad-based crisis is far more modest in the *universal* system than in the *sector* system. This reflects the greater flexibility available to the universal bank in setting its risk-weighted capital ratio. Since the optimal level of c&i lending falls drastically during a crisis, the universal bank can sustain a higher level of retail lending after a negative shock to its equity than a pure retail bank.

In this calibration, a sectoral buffer is clearly an advantage in a retail-boom if the banking system is sectoral. In a universal banking system, the advantages of a sectoral buffer are uncertain. A sectoral buffer improves lending in good times, but leads to a larger drop in lending in a broad crisis.

3.3.2 Sectoral buffer on c&i loans

We now redo the same exercise as above, but this time it is the c&i sector that is booming. Figure 8 shows the results for the *universal* system, and Figure 9 for the *sector* system.

For both banking systems, the top panels in both figures show the irrelevance of the capital requirement rule when the crisis is contained in the c&i-sector. This is simply because of the very low profitability of c&i loans during crisis times, as mentioned above.

For the universal bank, we note that having a buffer does dampen the drop in credit supply in a broad-based crisis (panels (iii) and (iv) in Figure 8), but there are only small differences across the various buffer rules (II-IV).

In contrast, the capital requirement rule has a large impact on the sector banks in a broad-based crisis. While the SCCyB improved outcomes in a retail boom (Section 3.3.1), a broad-based CCyB is preferable in a c&i-boom. Since removing a buffer in crisis times has almost no stimulative effect on c&i lending during a crisis, having a pure c&i buffer is detrimental to total lending in a broad-based crisis. A broad CCyB, calibrated such that unweighted capital ratios are the same as with an SCCyb rule, does stimulate crisis lending somewhat (panel (iv) Figure 9). However, the broad buffer is only 0.75 percent, which is not sufficient to dampen the drop in credit supply in the retail sector. A buffer of 2.5 percent will in this case induce more stable lending. This

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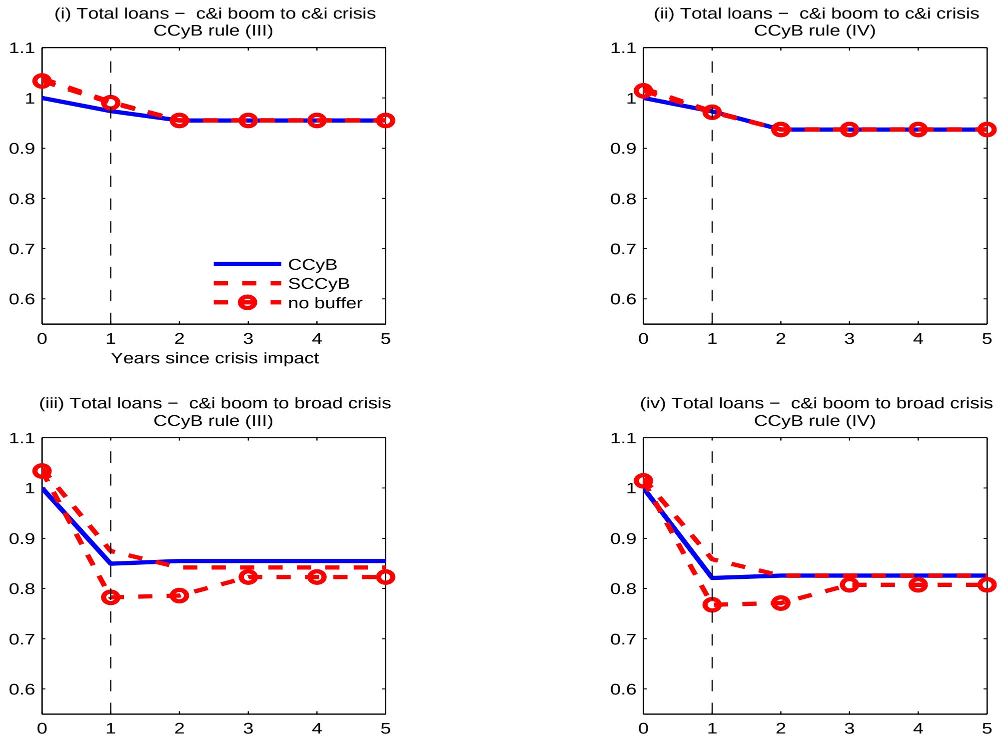
percent, the outcome is almost equivalent to the SCCyB rule. The only difference between the SCCyB and the 2.5 percent CCyB, is that in the CCyB the c&i bank is also subject to a 2.5 percent buffer. The equivalence between SCCyB and CCyB in this case reflects that the c&i bank optimally chooses to cut c&i-lending, regardless of capital requirement rules The reason for this is that c&i-lending, as discussed in Section 3.2, has very low profitability during crisis times in this calibration.

is not surprising, given the findings in Section 3.3.1, where a retail-specific buffer of 2.5 percent was preferable to a broad-based buffer, unless the broad-based buffer was also 2.5 percent.

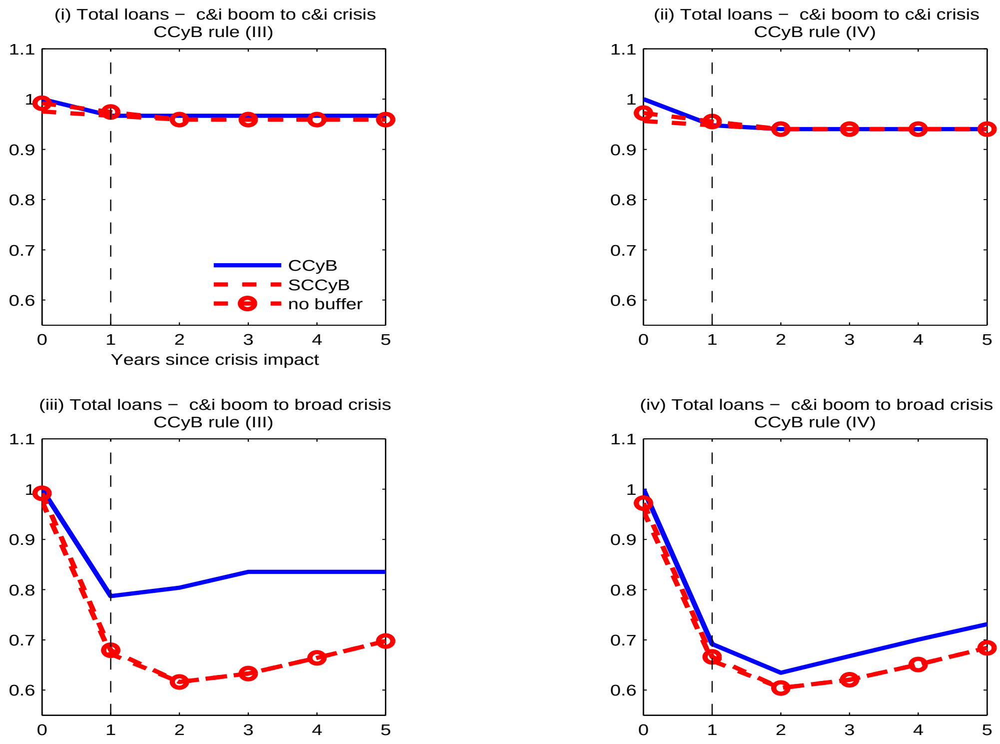
These simulations demonstrate that heterogeneity across sectors in the elasticity of crisis lending with respect to capital requirements is crucial when comparing a broad vs. a sector specific buffer. If policymakers impose a sector-specific buffer on a sector with low elasticity, and the crisis is broad, the potential for stimulating lending by removing buffers is small. In a universal banking system, however, the consequence of implementing an inefficient policy is dampened by the fact that the bank itself transferrers capital across sectors.

Figure 8: Universal bank: Corporate boom to crisis



Notes: The chart shows the evolution of lending in the *universal* system in the transition from c&i boom to crisis. In the top panels (i) and (ii), the crisis is c&i-specific. In the bottom panels, the crisis is in both the retail and the c&i sector. We compare a *no buffer* (rule I) and a *sector buffer* SCCyB of 2.5 percent on c&i loans (rule II), to two regimes for the *broad-buffer* CCyB (rule III and IV). In the left-hand panels (i) and (iii), the CCyB is 2.5 percent (rule III). In the right-hand panels (ii) and (iv), the CCyB is calibrated such that the pre-crisis unweighted capital ratio is at the same level as in the SCCyB rule. In all panels, the series are normalised with the period 0 value in the CCyB regime.

Figure 9: One-sector banks: Corporate boom to crisis



Notes: The chart shows the evolution of lending in the *sector* system in the transition from c&i boom to crisis. In the top panels (i) and (ii), the crisis is c&i-specific. In the bottom panels, the crisis is in both the retail and the c&i sector. We compare a *no buffer* (rule I) and a *sector buffer* SCCyB of 2.5 percent on c&i loans (rule II) with two regimes for the *broad-buffer* CCyB (rule III and IV). In the left-hand panels (i) and (iii), the CCyB is 2.5 percent (rule III). In the right-hand panels (ii) and (iv), the CCyB is calibrated such that the pre-crisis unweighted capital ratio is at the same level as in the SCCyB rule. In all panels, the series are normalised with the period 0 value in the CCyB regime.

3.3.3 Discussion – what if corporate loans looked more like retail loans?

An important feature of the calibration is the considerable difference between the c&i and the retail sector , with regard to both risk weights and non-performing loans (NPL) in a crisis. C&i loans receive higher risk weights and have a higher share of NPLs than retail loans. A reasonable question to ask is how this affects the trade-off between the SCCyB and the broad-based CCyB. Consider therefore an alternative model, in which the risk weight on c&i loans and the share of NPLs are identical to those for retail loans. In this hypothetical scenario, the trade-off between sectoral and broad-based buffers is less complex. In the case of a broad-based crisis, both sectors would be equally constrained and the effect of lowering capital requirements would be identical across the two sectors. Hence, a broad-based buffer would improve crisis lending relative to a sectoral buffer, as the former by definition provides the correct level of targeted regulation. Of course, if the crisis is sector-specific, the broad-based buffer (calibrated to give the same pre-crisis unweighted capital ratio as the SCCyB), would not only provide an insufficient boost to lending in a retail crisis, but also in a c&i crisis.

4 Concluding remarks

Using a dynamic banking model with forward-looking, profit-maximising bank behaviour, we compare two types of time-varying capital requirements: a broad-based countercyclical buffer and a sectoral buffer.

If policymakers can perfectly predict when a crisis will occur and what kind of crisis it will be, any result obtained with a broad-based buffer can be replicated with a sectoral buffer. However, in reality the policymaker has limited information about the current and future state of the economy. Thus, when attempting to implement a targeted policy such as a sector-specific, time-varying buffer, regulators are at the risk of implementing an inefficient policy.

We find that the effect of capital requirements will depend on both the structure of the banking system (universal banks vs. sector-specific banks), the degree of heterogeneity between sectors (regulatory risk weights and the return on lending in a crisis), and the degree of asymmetry of sectoral cycles (sector-specific vs. broad-based crisis)

- A universal banking system is more "forgiving” than a single-sector banking system in that it can make an internal trade-off between sectors. The cost of a policy mistake in the form of imposing the "wrong” buffer is therefore smaller.
- Imposing a sectoral buffer on a low risk-weight, low-NPL sector generally has a stronger stabilising effect than imposing a buffer on a high risk-weight, high-NPL sector, since a relaxation of capital requirements has less impact on bank lending in the latter sector.

In a universal banking system, an SCCyB might be an efficient policy compared to a broad-based CCyB if the c&i sector is very volatile, as the cost of an SCCyB in a broad-based crisis is relatively small. However, if losses in the c&i sector are expected to be more moderate, the stabilising effect of applying a broad buffer in a crisis will increase.

In a sectoral banking system, the gains of implementing a sectoral buffer are considerable if the sectoral buffer is applied to a low-volatility sector. However, implementing a sectoral buffer can lead to considerable losses if a boom in a high-volatility sector is followed by losses in the low-volatility sector.

In short, in a universal system the gains of implementing a sectoral buffer seem to be fairly small, but the risks of using a sectoral buffer are also small. The choice of a sectoral buffer will therefore primarily depend on what is politically most important–the ability to have a more directed impact on credit in good times or slightly better insurance against bad times if a crisis is should develop.

In a sectoral banking system, the choice between a sectoral and a broad-based buffer depends on the willingness to gamble on possible outcomes. If the most vulnerable sectors can be targeted, there are potential gains from applying a sectoral buffer. However, if the wrong sector is targeted, the potential losses will be considerable.

A Calibration

The parametrisation is based on a combination of external and internal calibration.

In the model, we consider the dynamic decision problem of a single big bank. In the data, we assume our big bank to be the asset-weighted average of the seven largest Norwegian banking groups (as of 2015Q4). We identify the largest Norwegian banks according to total lending to the Norwegian corporate and retail sector.[11]

A.1 Aggregate shock

We begin the calibration by estimating the stochastic process for the aggregate macro shock z_t. The aggregate shock z_t is assumed to fluctuate between three states, $z_t \in \{z_g, z_n, z_c\}$, which we refer to as the good, neutral, and crisis state, respectively, measured by GDP for mainland Norway. The good and neutral states reflect normal business cycles, with respective booms and busts. The crisis state captures the rarer event of a severe banking crisis with a significant decline in activity and a sharp increase in non-performing loans.

Let p_{ij} denote the probability of switching from state i to state j. The transition matrix is given by:

$$F(z', z) = \begin{bmatrix} p_{gg} & p_{gn} & p_{gc} \\ p_{ng} & p_{nn} & p_{nc} \\ p_{cg} & p_{cn} & p_{cc} \end{bmatrix} \tag{18}$$

Table 2 reports all annual transition probabilities and normalised state values.[12] The estimation of the z_t process is done in two steps, where we separately estimate the crisis state and normal time fluctuations.

First, regarding the crisis state, we use a quarterly panel dataset for 20 OECD countries in the period 1975Q1-2014Q2 to determine the transition in and out of a crisis. The identified financial crises are the same as in Anundsen et al. (2016) and rely on Laeven and Valencia (2008, 2010, 2012), Reinhart and Rogoff (2008, 2009a,b) and Babecky et al. (2014). The probability of entering a crisis is based on the frequency of crisis starts in the data. We identify 32 crisis starts from a total of 3160 quarters, where

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[11] The identified seven largest banks are: DNB Bank, Nordea Bank Norge, SpareBank 1 SR-Bank, Sparebanken Vest, SpareBank 1 SMN, SpareBank 1 Nord-Norge and Sparebanken Sør.

[12] The parameters are estimated on quarterly data. We transform the quarterly transition probabilities into annual probabilities by $p_{ii} = (p_{ii}^Q)^4$ where $i = g, b, c$. The annual probability of entering a crisis is set by $p_{ic} = 1 - (1 - (p_{ic}^Q))^4$ where $i = g, n$.

Table 2: Calibration of aggregated shock

Parameter/state description	**Parameter/state**	**Values**
Aggregate shock	z_g, z_n, z_c	1 0.975 0.96
Transition probabilities from good state	p_{gg}, p_{gn}, p_{gc}	0.75 0.21 0.04
Transition probabilities from bad state	p_{ng}, p_{nn}, p_{nc}	0.21 0.75 0.04
Transition probabilities from crisis state	p_{cg}, p_{cn}, p_{cc}	0 0.29 0.71

Sources: Statistics Norway and Norges Bank.

405 quarters are crisis observations and 2755 quarters are normal times observations.[13] Based on the frequency of entering a crisis from normal times, we find a conditional quarterly probability of 1.1%. We set the annual probability, $p_{gc} = p_{nc} = 0.04$, which is somewhat lower than the probability associated with our dataset, but in line with other findings in the literature, see e.g. Bordo et al. (2001) and Schularick and Taylor (2012). Further, we normalise the good state to unity and set $z_c = 0.96$ to match the decline from our good state to the crisis trough. This is line with the findings of Anundsen et al. (2016), who, based on 33 financial crisis episodes, find a decline in the output gap from peak to trough of 4 percentage points. The probability of recovery from crisis is based on the observed duration of a crisis. We observe 33 quarters of recovery from crisis, which gives a conditional annual probability of crisis recovery of 29%. We assume that recovery from crisis always occurs through the bad state, hence $p_{cn} = 0.29$.

Next, we consider the process for normal business cycle fluctuations (z_g, z_n). Based on an estimated AR(1)-process on the output gap in the period 1978Q1-2015Q4, we determine the discrete transition probabilities following the method proposed by Tauchen and Hussey (1991).[14] The annual transition probabilities are estimated to $p_{gn} = p_{ng} = 0.21$. It follows that the probability of remaining in either the good or bad state is $p_{nn} = p_{gg} = 0.75$.[15] The contraction from average business cycle boom to average business cycle bust is estimated at 2.54 percentage points and hence we set $z_n = 0.9746$ to match the average contraction.

To facilitate implementation of time-dependent capital requirements, we augment

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[13] If the end of the crisis is not specified, we assume a crisis duration of eight quarters.

[14] The output gap is calculated as the deviation of the log of GDP for mainland Norway from a two-sided HP trend using a smoothing parameter of $\lambda = 6400$.

[15] The transition probabilities capturing normal business cycle fluctuations are estimated at $p^N_{gn} = p^N_{ng} = 0.22$ and $p^N_{nn} = p^N_{gg} = 0.78$. We scale the transition probabilities capturing normal business fluctuations proportionally, taking account of the annual 4% probability of entering a crisis from either the good or bad state.

the three-state Markov process for z_t with a recovery state z_r. This state is indentical to z_n. The purpose of this state is to differentiate z_n-times that are preceded by the crisis state. This allows us to specify a more flexible time dependency for capital requirements. In the simulation exercises, we assume that the buffer requirement remains at zero in a post-crisis recovery phase until the economy reaches the z_g. This will leave the bank at least one year to prepare for the higher capital requirement.

A.2 External calibration of bank-specific parameters

A subset of the bank-specific parameters (r^a, r^d, r^b, c_s) is taken directly from corresponding long-run averages observed in the data, see Table 3 . The interest rate (r^a) on banks' securities is determined by net profit and losses on financial instruments, interest income on bonds and certificates and other interest income. Net income is measured relative to the banks' financial instruments and fixed assets.

The interest rate on banks' funding (r^d) is determined by the interest rate set by banks on customer deposits and the interest rate on wholesale funding such as issued certificates and bonds. As part of the crisis scenario, we assume that when $z_t = z_c$, the cost of funding is raised to the level of the interest rate on securities.

For the unit cost of lending, we assume $c_{ret} = c_{C\&I} = c$. In the data, we measure this as total net non-interest expenses, determined by the banks' personnel expenses, IT costs and net provision income on loans over total lending to customers.

Finally, the interest rate on short-term liquidity (r^b) is based on a financial macro indicator: three-month NIBOR (Norwegian Interbank Offered Rate).

A.2.1 Calibration of banks' defaulting loans

Let the event of crisis impact be denoted as $Z_I = \{z_t \in (z_g, z_n) \quad \& \quad z_{t+1} = z_c\}$. The default relationship is given by:

$$P_s(r_{st}, z_t, z_{t+1}) = \begin{cases} P^s_{impact} & , (z_t, z_{t+1}) \in Z_I \\ \eta^s_0 + \eta^s_1 z_{t+1} + \eta^s_2 r_{st} & , (z_t, z_{t+1}) \notin Z_I. \end{cases} \tag{19}$$

At crisis impact, the number of new problem loans is assumed to rise considerably, reflecting the sudden strain on the position of both enterprises and households. At other times, default rates are linear in the loan rate r_{st} and end of period macro shock z_{t+1}. To quantify the latter relationship, we run the following fixed effect regression using data

Table 3: External calibration of bank-specific parameters

Parameter description	**Parameter**	**Value**
Real funding rate1)	r^d	1.84
Real interest rate on securities1)	r^a	1.98
Non-interest expenses1)	c	0.52
Real short term rate	r^b	1.76
Loss given default - good and bad state	$\lambda_{g,b}$	10
Loss given default - crises state	λ_c	30
Risk weight - retail exposures, IRB approach2)	$\omega^{IRB,ret}$	21
Risk weight - corporate exposures, IRB approach2)	$\omega^{IRB,C\&I}$	84
Risk weight - retail exposures, Basel I3)	$\omega^{BI,ret}$	50
Risk weight - corporate exposures, Basel I3)	$\omega^{BI,C\&I}$	100
Risk weight - market risk4)	ω^A	3
Risk weight - operational risk and other credit exposures5)	ω	7

1) The sample period is 2001Q1-2015Q4. The sample average is based on the weighted average of the top seven banks. Values correspond to annual rates.
2) Risk weights are based on the average reported risk weights of IRB banks in 2015Q4, see Finanstilsynet (2016). Risk weights are based on the foundation IRB approach.
3) Risk weights are based on the Basel I framework.
4) Risk weight is calibrated to match a 1% ratio of market risk to total risk-weighted assets in 2015Q4, see Finanstilsynet (2016).
5) Risk weight is calibrated to match a 49% ratio of risk-weighted assets to total assets in 2015Q4.
Sources: Finanstilsynet (Financial Supervisory Authority of Norway), SNL Financial, banking groups' quarterly reports, Statistics Norway and Norges Bank

on problem loans:

$$\tilde{P}_{ist} = \tilde{\eta}^s_{0,i} + \tilde{\eta}^s_1 y_{gap,t} + \tilde{\eta}^s_2 \tilde{r}_{ist} + \epsilon_{ist}, \tag{20}$$

where $\tilde{P}_{ist}$ represents bank i's new problem loans in period t to sector s in percent of total lending to the sector. $y_{gap,t}$ represents the output gap for mainland GDP as an indicator for mainland activity.[16] Bank i's annual real lending rate to sector s, $\tilde{r}_{ist}$, is measured in percentage points and based on the reported sector-specific interest rates in ORBOF. $\tilde{\eta}^s_{0,i}$ and $\epsilon^s_{i,t}$ are bank fixed effects and residuals respectively. To account for seasonal variation, the regression also includes seasonal dummies.

Table 4: Estimation results: New problem loans in percent of lending to the sector

Variable	Corporate	Retail	Customers
$y_{gap,t}$	-0.13***	-0.027***	-0.073***
$r^L_{i,t}$	0.07*	0.033**	0.059**
N	364	364	364
Groups	7	7	7

The data covers a panel of the top seven banks over the period 2001Q4-2015Q4. The asterisks denote significance level; * = 10%, ** = 5% and *** = 1%.
Sources: Statistics Norway and Norges Bank

The results for the corporate sector, the retail sector and all customers are reported separately in Table 4.

During an average crisis, which lasts about 3 years, we assume that accumulated new problem loans will be about 14% of bank lending. Laeven and Valencia (2012) report the mean peak level of non-performing loans in an international crisis database. For 31 OECD countries, the reported mean peak level of non-performing loans averages 14% during crisis times in the period 1970-2011. This is close to the 16.4% mean peak of non-performing loans that was observed during the Norwegian banking crisis in the early 1990s, see Laeven and Valencia (2012). To match the ratio of 14%, we assume that the share of new problem loans rises to 10% of total lending at crisis impact ($P^{ret}_{impact} = P^{C\&I}_{impact} = 0.10$). In the remaining years of the crisis, new problem loans to each sector follow the specification given by equation 20.

Regarding loss given default, we assume a common value $\lambda(z_{t+1})$ across sectors. The loss depends partly on the value of banks' collateral and the equity ratios of households

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[16] The output gap is calculated as the deviation of the log of real GDP for mainland Norway from a two-sided HP trend using a smoothing parameter of $\lambda = 6400$.

and firms. Thus we assume $\lambda(z_{t+1})$ to be state-dependent in the model, see Table 3. For $z_{t+1} \in (z_g, z_n)$ we set $\lambda(z_{t+1})$ to match the long-run average of the ratio of banks' loan losses to new problem loans. In the period 2001Q4-2015Q4, the ratio of banks' loan losses to new problem loans was about 10%. By determining λ from the data, we also account for the average gain of recovered problem loans and additional realised losses on new problem loans.

For the crisis state, our choice of $\lambda(z_{t+1})$ is in line with established parameters used in Norges Bank's annual stress testing exercise, see Syversten et al. (2015). $\lambda(z_{t+1})$ is set to 30% for both sectors, see Table 3. It follows that at the beginning of the crisis loan losses rise to 3% of total lending.

A.2.2 Banks' capital requirement

In the model, we focus on the Common Equity Tier 1 (CET1) capital ratio defined as CET1 capital divided by total risk-weighted assets. As a simplification, we use the bank's equity capital as a proxy for the bank's CET1 capital.

Total risk-weighted assets cover banks' credit risk, operational risk and market risk. We note that credit risk is by far the largest component, see Finanstilsynet (2016). In the model, we consider the following simplified implementation of risk-weighted assets:

$$H(L^{ret}, L^{C\&I}, A) = h(L^{ret}, L^{C\&I}) + \omega^A A + \omega(L^{ret} + L^{C\&I} + A) \tag{21}$$

where $h(\cdot)$ corresponds to corporate and retail credit risk and ω^A to market risk. The last term, ω, corresponds to all other risk measures.

With the implementation of the Basel II framework in 2007, banks were allowed to internally calculate risk weights (the IRB approach) for their loan exposures. However, lower limits were set for the minimum capital requirement, see Borchgrevink (2012). The current transitional rule sets a lower limit on the sum of risk-weighted assets applied by IRB banks, which are required to be at least 80% of the risk-weighted assets calculated under the Basel I requirements. Several of the IRB banks are bound by the transitional floor. Therefore, we account for the transitional rule by determining the bank's credit risk on retail and corporate exposures as follows:[17]

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[17] As a simplification, we assume that all banks fully implement the foundation IRB approach when determining risk weights on loans to the corporate and retail sector. We do not account for risk weights based on the standardised approach or the advanced IRB approach.

$$h(L^{ret}, L^{C\&I}) = \max(\omega^{IRB,ret} L^{ret} + \omega^{IRB,C\&I} L^{C\&I}, 0.80 * (\omega^{B1,ret} L^{ret} + \omega^{B1,C\&I} L^{C\&I})) \tag{22}$$

where $\omega^{IRB,s}$ is the risk weight on loans to sector s using the IRB approach and $\omega^{B1,s}$ is the risk weight on loans to sector s under Basel I. The risk weights for the IRB approach are based on the reported average risk weights on residential mortgages and corporate loans for Norwegian IRB banks in 2015Q4, see Finanstilsynet (2016) and Table 3. The risk weight on loans to the retail sector under Basel I, denoted by ω_r^{B1}, is set to 50%, reflecting the Basel I risk weight on residential mortgages with a loan-to-value ratio below 80%. ω_c^{B1} is set to 100%, reflecting the Basel I risk weight on corporate loans. In the model, securities are assumed to be safe, but we still add a risk weight noted by ω^A, to capture market risk, which in 2015Q4 amounted to approximately 1% of total risk-weighted assets for IRB banks, see Finanstilsynet (2016).

As a simplification, to account for the components of operational risk and credit risk from exposures other than retail and corporate exposures, we add an additional component to banks' risk-weighted assets as a fixed share of banks' total assets. Given the seven banks' reported mix of assets, the risk weight on banks' total assets, denoted by ω, is set to 7% to match the 49% risk-weighted assets to total assets ratio.[18]

A.2.3 Calibrating banks' loan demand

We parameterise the aggregate loan demand function $L_{st}^A = f_s(r_{st}, z_t)$ as:

$$f_s(r_{st}, z_t) = \exp(\alpha_s + \gamma_s r_{st} + \eta_s z_t) \tag{23}$$

For the aggregate loan demand function, we take the semi-elasticity of demand with respect to the real loan rate from Akram (2014) ($\gamma_{ret} = -3.8$ and $\gamma_{C\&I} = -4.67$) and assume a unit elasticity of demand with respect to the aggregate shock, $\eta_s = 1$. Finally, we normalise the constant term such that when the interest rate is 3.3% and 3.4%, then credit demand relative to GDP is 3.7 and 2.8 in the household and enterprise sector respectively. These interest rates and ratios correspond to the sample average over the period 2001Q1 -2015Q4.

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[18] According to the banks' annual reports, the ratio of risk-weighted assets to total assets was 49% in 2015Q4.

For the other credit suppliers' response, we assume the following functional form:

$$M_s(z_t, L_{st}) = L^o_{s,*}(z_t) - \rho_s(L_{st} - L_{s,*}(z_t)) \tag{24}$$

where $(L^o_{s,*}(z_t), L_{s,*}(z_t))$ are benchmark loan allocations, calibrated such that when the interest rate is 3.3% and 3.4% in the retail and corporate sector respectively, total loan demand in each sector is split between our bank and other credit suppliers by average market shares over the period 2001Q1-2015Q4. Formally, $L_{st} = L_{s,*}(z_t) \iff L^o_s = L^o_{s,*}(z_t)$ where $L_{ret,*}(z_t) = 0.5 f_{ret}(0.033, z_t)$ and $L_{C\&I,*}(z_t) = 0.4 f_{C\&I}(0.034, z_t)$. The calibration of ρ_s is explained in Section A.3.

A.2.4 Calibrating loan maturity

In Norway, the average maturity of mortgages at origination is around 20 years (see Finanstilsynet (2013)). Assuming a uniform distribution of mortgage age structure, the average maturity of mortgages outstanding is 10 years. The ORBOF database provides a time series of the average (across sectors) remaining loan maturity. Assuming a retail loan maturity equal tomortgage maturity (10 years), we can impute the maturity for corporate loans. Given a loan portfolio as in the data, an average of 4 years' remaining maturity on corporate loans gives a remaining maturity on the total portfolio as in the data. Hence we set the parameters $m_{ret} = 0.1$ and $m_{C\&I} = 0.25$.

A.2.5 Adjustment cost

The adjustment cost parameter is assumed to be the same across the retail and corporate sector. We set the parameter value such that the magnitude of the adjustment cost relative to average lending in the model is in line with the adjustment cost in De Nicolo et al. (2014). In their dynamic banking model, loan liquidation takes the same functional form as in the present model. However, they apply shorter loan maturity than we do, which all else equal would imply lower loan liquidation costs. Hence we set the parameter to $\psi = 153.8$, which implies that the adjustment cost associated with reducing loan supply (to both sectors) by 50% from one period to another is the same as in De Nicolo et al. (2014).

A.3 Internal calibration of bank-specific parameters

We determine the remaining parameters $(\rho_{ret}, \rho_{C\&I}, d, \kappa, \beta)$ by matching model-simulated moments to corresponding data moments. All data moments are based on the weighted averages of the top seven banks. Specifically, we calibrate the response parameter of other credit suppliers in the retail market (ρ_{ret}) such that we match the interest margin (loan rate net of non-performing loans relative to the deposit rate). For the corporate market we calibrate the response parameter $(\rho_{C\&I})$ such that we match the observed 2015Q4 share of corporate loans to total lending on the banks' balance sheets.[19] The bank's external funding (d) is calibrated to match the observed ratio of securities to total assets[20] in 2015Q4. The fixed cost (κ) is calibrated to match the cost of other net operational costs relative to lending. Other net operational costs include revenue and costs from lease and rental, and equipment expenses. Finally, the bank's discount factor (β) is set to match a nominal return on equity of 12%. This is at the lower end of the reported nominal return on equity of large Norwegian banks in the period 2001-2013, see Aronsen et al. (2014). However, tighter banking regulation and increased equity ratios can lead to reduced return on equity. Aronsen et al. (2014) suggest that it is reasonable to expect that large Norwegian banks have a long-run return on equity of about 12%.

All moments are matched by simulating the model with a fixed capital requirement of 14%. This requirement is somewhat higher than the 12% CET1 capital requirement under Pillar I for systemically important financial institutions in 2015Q4.[21] However, in late 2015, several Norwegian banks continued to build capital to reach announced capital targets in 2016. Since 1 July 2016, systemically important banks have faced a CET1 capital requirement under Pillar I of 13.5%. In addition, banks have had to fulfill individual Pillar II requirements set by the Financial Supervisory Authority of Norway.

We choose to match the observed composition of the top seven banks' balance sheets in 2015Q4. Banks' risk weights and capital requirements have gone through considerable changes in recent years. Thus we keep the calibrated model in line with current capital requirements and recent adjustments of the banks' balance sheets as observed in the data.

Table 5 provides the moments generated by the calibrated model and compares them

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[19] Total lending in the data is defined as total lending to customers.

[20] As a simplification, we determine the top seven banks' share of loans and total securities to total assets by subtracting the amount of short-term lending (cash and claims on other credit institutions) from the banks' assets and short-term borrowing on the liability side.

[21] As the two largest banks in our sample are defined as systemically important, we will also consider the buffer for systemically important banks.

with the corresponding data moments. We notice that several of the moments are close to their targets.

Table 5: The model and the data

Description	**Parameters**		**The data**	**The model**$^{5)}$
Share of lending to the corporate sector$^{1)}$ (%)	$\rho_{c\&i}$	0.7	32	28
Securities/Total assets$^{1)}$ (%)	d	5.64	22	20
Net interest margin, real$^{1)}$ (%)	ρ_{ret}	0.95	1.6	1.9
Fixed cost to lending ratio$^{1)}$ (%)	κ	0.0112	0.29	0.24
Nominal return on equity$^{2)}$ (%)	β	0.955	12	12
Bank risk-weighted assets/total assets$^{3)}$			49	49
Difference in lending rate between sectors$^{1)}$			0.19	1.4
Bank loan losses/gross lending$^{1)}$ (%)			0.17	0.19
Std. dev. lending gap/std. dev. output gap$^{4)}$			2.6	2.8
Std. dev. lending gap, retail/std. dev. output gap$^{4)}$			1.5	2.4
Std. dev. lending gap, C&I/std. dev. output gap$^{4)}$			3.7	3.7

Moments below the line correspond to data moments not targeted during the calibration.
1) The sample average is based on the weighted average of the top seven banks. The sample period is 2001Q1-2015Q4. For lending rates and loan losses the sample period is 2001Q4-2015Q4. The bank's balance sheet composition is based on 2015Q4.
2) See Aronsen et al. (2014).
3) Based on the banking groups' quarterly reports. Top seven banks in 2015Q4.
4) Based on all banks and mortgage companies in the period 1992Q1-2015Q4. Gaps are calculated as deviation of the log of variables from a two-sided HP trend with $\lambda = 6400$.
5) The model is simulated over 10 000 periods in the good and bad state.
Sources: Banking groups' quarterly reports, SNL Financials, Statistics Norway and Norges Bank

In the model, the bank faces considerably higher risk weights and loan losses on lending to the corporate sector. Thus, the bank charges a higher loan rate on corporate loans. In line with the data, the model projects a higher optimal interest rate on loans to the corporate sector, see Table 5. However, the interest needed to compensate the bank for lending to the corporate sector is about 1.2 percentage points higher than the observed spread.

The close match of the bank's asset composition in 2015Q4 generates a ratio of total risk-weighted assets close to 49%, see Table 5.

Last, Table 5 shows that the model replicates the more volatile adjustment in bank lending to the corporate sector. The higher volatility of the default share, higher risk weights and the shorter maturity of corporate loans contribute to the higher volatility of corporate loans in the model.

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