Jointly optimal regulation of bank capital and liquidity*

Ansgar Walther [†]

This version: April 2014
First draft: June 2013

Abstract

Banks create excessive systemic risk through leverage and liquidity risk, as financial constraints introduce welfare-reducing pecuniary externalities. Macroprudential regulators can achieve efficiency with simple linear constraints on banks' balance sheets, which require less information than Pigouvian taxes. These can be implemented using the Liquidity Coverage and Net Stable Funding ratios of Basel III. When bank failures are socially costly, microprudential regulation of leverage is also required. Optimally, macroprudential policy reacts to changes in systematic risk and credit conditions over the business cycle, while microprudential policy reacts to both systematic and idiosyncratic risk.

Keywords: Systemic risk, leverage, maturity mismatch, macroprudential regulation, liquidity, capital requirements, fire sales.

JEL classifications: G18, G21, G28 and E44.

*Thanks are due to an anonymous referee, David Aikman, Diego Cerdeiro, Alec Chrystal, Steven Durlauf, Robert Evans, Charles Goodhart, John Jackson, Paul Klemperer, Antoine Lallour, Meg Meyer, Hitoshi Mio, Alan Morrison, Dan Quigley, Sönje Reiche, Jean-Charles Rochet, Larry Samuelson, Victoria Saporta, Alp Simsek, Selma Telalagić, John Thanassoulis and John Vickers for valuable feedback and discussions. The paper benefited from the comments of seminar participants at Birkbeck College, the Bank of England, Cambridge, Oxford, the University of Zurich and various conferences. This work was supported by the Economic and Social Research Council [grant number ES/I901957/1].

†ansgar.walther@economics.ox.ac.uk. Department of Economics, Nuffield College and INET, University of Oxford.

1 Introduction

Financial policy is historically motivated by the 'microprudential' concern that bank failures are socially costly. Following the crisis of 2008, 'macroprudential' concerns have surfaced (Hanson et al. 2011). Banks' individual risk can contribute to *systemic risk,* which causes inefficient fire sales and market freezes, thus harming the financial sector as a whole.

Systemic risk is not caused exclusively by insufficient bank capital. It is amplified if banks fund long-term investments with short-term debt (Brunnermeier 2009). In response to this problem, the Basel III Accord (BIS 2010) introduces *liquidity coverage* and *net stable funding* ratios, which reflect macroprudential concerns and target maturity structure.

This paper addresses two questions from a welfare-theoretic perspective:

1. How should capital and maturity be regulated to deal with systemic risk?
2. How should this interact with regulation against costly bank failures?

My three-period model builds on Lorenzoni (2008) and Shleifer and Vishny (2010). There are two fundamental financial frictions. First, banks need equity downpayments, or '*skin in the game*', to raise funding. Second, banks can only sell assets to outside buyers at *fire sale prices*. Fire sales are socially wasteful because outside buyers cannot extract as much surplus from assets as banks.

Banks make long-term investments which are subject to aggregate and idiosyncratic shocks. They fund themselves with equity and debt, choosing the maturity of debt endogenously. Banks' creditors have a preference for liquidity, so that long-term debt commands an interest premium. Banks trade off this premium against rollover risk to choose their maturity structure.

Fire sales occur when a bad aggregate shock creates a liquidity shortfall in the banking sector. Then, banks struggle to roll over short-term debt due to the 'skin in the game' constraint, and have to sell assets to outside buyers in order to repay short-term creditors. Fire sales happen when banks are highly leveraged, or when their balance sheets feature strong maturity mismatch.

Macroprudential regulation is justified by a pecuniary 'systemic externality'. Competitive banks have no unilateral incentive to reduce leverage or maturity mismatch to avoid wasteful fire sales, since they take fire sale prices as given. Due to the incompleteness of markets, the pecuniary externality renders the competitive equilibrium generically inefficient as in Geanakoplos and Polemarchakis (1985).

To answer my first question, I consider three modes of intervention: Centralisation by a social planner, regulation using balance sheet constraints as in Basel III, and Pigouvian taxation. The planner's choices are efficient and maximise welfare subject to a 'no fire sale condition'.

Constraint-based regulation can achieve efficiency by imposing this condition on banks. It only depends on systematic cash flow risk and the 'skin in the game' constraint, and does not require knowledge of other parameters such as funding costs, returns to investment or idiosyncratic risk. The efficient Pigouvian tax, on the other hand, generally depends on all parameters. Thus, constraint-based regulation offers significant informational advantages. This result is fairly robust to extensions of the baseline model.

For the second question, I consider an extended model where bank failures generate deadweight costs to the economy. Systemic risk and default risk are not equivalent, and an additional microprudential constraint is required to limit bank failures. The informational requirements of macro- and microprudential regulation are similar, which suggests that delegating them to separate institutions may be suboptimal.

The optimal policy can be implemented within the Basel III framework. I show that the optimal macroprudential policy can be implemented using either the Liquidity Coverage Ratio (LCR) or Net Stable Funding Ratio (NSFR) requirements of Basel III. This result supports Basel III, but the theoretical equivalence of LCR and NSFR suggest that the framework could be simplified without loss of efficiency.

My theory supports time-varying macroprudential regulation, because optimal rules should react to changes in systematic risk and credit conditions. However, microprudential rules should also be time-varying, and additionally keep track of cross-sectional idiosyncratic risk.

The next section puts the paper in the context of the related literature. Section 3 sets up the model. Section 4 analyses the competitive equilibrium and welfare. Sections 5 and 6 consider optimal macro- and microprudential regulation. Section 7 discusses the reaction of optimal regulation over the business cycle. Section 8 concludes. All proofs are in the appendix.

2 Related literature

There is a rich recent literature on pecuniary 'systemic risk' externalities. Perotti and Suarez (2011) look at optimal ways of regulating maturity in a reduced-form model without a separate leverage choice. Korinek (2012) studies a three-period model of excessive leverage, whereas Bianchi and Mendoza (2012) and Jeanne and Korinek (2010) compute optimal leverage policies in calibrated infinite-horizon models. Stein (2012) considers regulating the choice between short-term and long-term debt through 'cap-and-trade' mechanisms. Gersbach and Rochet (2012) demonstrate a systemic externality in a model based on productivity shocks and moral hazard. Finally, Goodhart et al. (2013) study the impact of multiple regulations by simulating a complex general equilibrium model.[1]

In this context, this paper contributes by proposing optimal constraint-based regulation targeting both leverage and maturity mismatch, and offering an explicit comparison with Pigouvian taxes. Moreover, I characterise the interplay of optimal macro- and microprudential regulation analytically in a model with several externalities.

The classic corporate finance literature emphasises maturity choices based on asymmetric information. Flannery (1986) shows that firms can use short-term borrowing as a signal of quality. In Diamond (1991), firms choose debt maturity by trading off the risk of inefficient liquidation by short-term creditors against the possibility of improved credit-ratings and cheap refinancing. This paper proposes an alternative story specific to banks, where the trade-off is driven by possible fire sales and the liquidity preference of creditors. A similar mechanism is explored by Chen et al. (2013), who model maturity choice as determined by rollover risk due to debt overhang and investors' exposure to liquidity needs.

Fire sales also arise in the macroeconomic literature on the 'financial accelerator' (Kiyotaki and Moore 1997, Bernanke et al. 1999, Shin 2010 , He and Krishnamurthy 2012). Additional sources of financial instability include 'margin spirals', when 'skin in the game' requirements rise in bad times (Geanakoplos 2009, Brunnermeier and Pedersen 2009), uncertainty about complex financial networks (Caballero and Simsek 2009) and irrational expectations (Gennaioli et al. 2012).

Bank runs are another cause of financial fragility. Diamond and Dybvig (1983) sparked a vast literature on this subject based on multiple equilibria. More recently, Gertler and Kiyotaki (2013) analyse bank runs in a dynamic economy with endogenous liquidity mismatch. Bank runs do not occur in my model because bank debt is secured and there is no sequential service problem. If unsecured debt were introduced, runs on unsecured debt and 'skin in the game' constraints on secured debt would work together to exacerbate bank funding problems and fire sales.

[1] Farhi and Tirole (2012), Jeanne and Korinek (2013) and Benigno et al. (2013) address the issue of ex post policies such as bailouts, central bank loans and quantitative easing. Combining their arguments with the ex ante analysis of this paper is an interesting topic for future research.

3 The model

Agents and time. There are three types of agents: Banks, creditors and outside buyers. All agents are risk-neutral and nobody discounts the future. There is a unit measure of each type. The model has three dates $t \in \{0, 1, 2\}$ and one consumption good called cash, which can be stored costlessly over time by all agents.

Aggregate uncertainty. The aggregate state is good or bad: $s \in \{g, b\}$. The bad state occurs with probability $P[s = b] = \alpha$, and the good state occurs with probability $1 - \alpha$. The aggregate state becomes public information at $t = 1$.

Individual uncertainty among banks. For bank $i \in [0, 1]$, the individual state is high or low: $z^i \in \{H, L\}$. The low individual state occurs with probability $P[z^i = L] = \beta$, and the high state occurs with probability $1 - \beta$. The individual state is independent of the aggregate state, and independent across banks. Individual states also become public information at $t = 1$.

Bank projects. Banks can invest in risky long-term projects at $t = 0$, which cost one unit of cash. At $t = 1$, each project yields a state-contingent cash flow $v_{1s} + \varepsilon_{z^i}$. v_{1s} is the aggregate cash flow, and $v_{1g} > v_{1b} \geq 0$. ε_{z^i} is the idiosyncratic shock, and $\varepsilon_H > \varepsilon_L$. Without loss of generality, assume that $E[\varepsilon_{z^i}] = (1 - \beta)\varepsilon_H + \beta\varepsilon_L = 0$.[2]

At $t = 2$, each project yields v_{2s}, where $v_{2b} < v_{2g} \leq 1$.[3] The $t = 2$ cash flow is a partial repayment of the initial investment, and the fraction repaid is higher in the good state. Let $R = E[v_{1s} + v_{2s}] - 1$, and assume that $R > 0$, so that projects have positive expected net present value.

After cash flows are received at $t = 1$, projects are traded in a competitive secondary market. The secondary market price for projects at $t = 1$ in aggregate state s is p_s.

Collateral constraint. Banks can raise debt from creditors, using projects as collateral. As in Shleifer and Vishny (2010), there is an exogenous 'marked-to-market' collateral constraint:

$$\text{loan} = (1 - h) \times \text{market value of collateral} \tag{1}$$

where $h \in (0, 1)$ is the 'haircut' on debt. Other things being equal, a larger haircut decreases the likelihood of default, since more collateral is pledged per unit borrowed. h is assumed to

[2] If $E[\varepsilon_{z^i}] = \bar{\varepsilon} \neq 0$, one could simply redefine $\hat{v}_{1s} = v_{1s} + \bar{\varepsilon}$ for all s, and $\hat{\varepsilon}_{z^i} = \varepsilon_{z^i} - \bar{\varepsilon}$ for all z^i.

[3] I assume away idiosyncratic risk at $t = 2$. This is for clarity of exposition and does not affect the qualitative results.

be large enough to rule out any bank default in the baseline model - an explicit condition is given below.[4]

Creditors and liquidity preference. Banks make 'take it or leave it' offers of short- and long-term debt contracts to creditors. Short-term debt contracts last one period and can be issued at $t = 0$ and $t = 1$. Long-term debt lasts two periods and is only available at $t = 0$. Each creditor has an endowment of Y at $t = 0$ and I assume that Y is large, so that the bank never exhausts creditors' endowment at any date.

Creditors have a preference for liquidity due to a potential investment opportunity at $t = 1$, which yields a net return of $q > 0$ at $t = 2$. Alternatively, one can think of creditors having a potential liquidity need at $t = 1$, e.g. due to illness, and a marginal utility of $1+q$ of servicing this need. Creditors are heterogeneous, and uniformly distributed on the unit interval. For creditor $k \in [0, 1]$, the investment opportunity arises with probability $\lambda(k)$, where $\lambda(0) = 0$ and $\lambda'(k) > 0$, independently across creditors.

Banks optimally offer interest payments to make creditors indifferent between debt contracts and holding cash. No interest payment is required on short-term debt, as long as Y is large enough so that banks can borrow freely from creditors without an investment opportunity at $t = 1$. The required long-term interest rate for creditor k is $\lambda(k)\, q > 0$, which compensates for the expected cost of forgone opportunities.

Note that long-term debt is not only costly for banks, but also reduces the social surplus. Long-term debt reduces socially valuable *maturity transformation* by intermediaries.

Bank investments at $t = 0$. Each bank has a fixed equity endowment of e_0.[5] Since banks are ex ante identical, I suppress i-superscripts and analyse the decisions of the representative bank ('the bank'), contingent on aggregate and individual states.

The bank invests in n_0 projects funded by (and pledged as collateral against) *short-term debt*. By (1), it raises $(1-h)\, n_0$ in short-term debt, and contributes hn_0 of its own equity.[6]

The bank invests in $\bar{n}_0$ projects funded by *long-term debt*. It raises $(1-h)\, \bar{n}_0$ in long-term

[4]Borrowing constraints can be derived from inalienable returns (Hart and Moore 1994) or moral hazard (Holmström and Tirole 1997). Generalising my analysis to endogenous haircuts is a subject for future research.

[5]The assumption of fixed equity is fairly standard in the related literature, and represents a parsimonious approach to modelling costs of or limits to outside equity issues, for instance due to informational asymmetries (Myers and Majluf 1984). Additionally, I assume that no additional equity can be raised at $t = 1$. Relaxing this would only affect my results if banks were able to raise outside equity in times of crisis, i.e. in the bad state at $t = 1$. However, it is generally accepted that doing so is very difficult due to time pressure or debt overhang problems (see Hanson et al. 2011).

[6]I use the convention that the 'market value' of projects at $t = 0$ is one, as this is the ratio at which cash can be turned into projects.

debt and contributes $h\bar{n}_0$ of its own equity. The bank is obliged to hold the collateral, $\bar{n}_0$ projects, until the debt matures.[7]

The cheapest way to borrow $(1-h)\,\bar{n}_0$ units long-term is to go to the creditors who are least likely to have an investment opportunity. Thus, the bank borrows Y units from all creditors $k \in [0, (1-h)\,\bar{n}_0/Y]$, promising each of them an interest payment of $\lambda(k)\,qY$. This implies that the (minimised) interest payment at $t=2$ is equal to

$$\int_0^{\frac{(1-h)\bar{n}_0}{Y}} \lambda(k)\,qY\,dk \equiv r(\bar{n}_0)$$

It is easy to verify that the function r is strictly increasing, strictly convex and twice differentiable, with $r(0) = r'(0) = 0$.

Any equity not spent on downpayments is held as *cash*, denoted c_0.[8] The bank's choices at $t=0$ are summarised by $\mathbf{x}_0 = (c_0, n_0, \bar{n}_0) \in \mathbb{R}^3_+$, and its budget is

$$e_0 \quad = \quad h\,(n_0 + \bar{n}_0) + c_0 \tag{2}$$

Let $B_0 \subset \mathbb{R}^3_+$ be the set of bank choices $\mathbf{x}_0$ that satisfy the budget.

Diseconomies of scale. Investing in risky projects requires careful monitoring and risk management, which becomes increasingly costly as the scale of investment increases. This implies that there are diseconomies of scale to investment in risky projects. The bank incurs a disutility of monitoring effort at $t=0$ which is equal to $g(n_0 + \bar{n}_0)$, where the function g is strictly increasing, strictly convex and twice differentiable.[9]

Bank cash flows at $t=1$. After states s and z are revealed at $t=1$, the bank receives the cash flow $v_{1s} + \varepsilon_z$ for the $n_0 + \bar{n}_0$ projects it invested in at $t=0$. It also repays its short-term creditors $(1-h)\,n_0$.

[7] One does not need to require the bank to hold the projects themselves as collateral, but merely assets of equivalent value. This would not change my main results, as the bank would still be unable to liquidate the collateral to finance itself at $t=1$.

[8] The bank does not invest in unlevered projects that are funded in full by equity. It can be shown that this assumption is without loss of generality, since the cash flow from an unlevered project can be replicated by a combination of short-term debt and cash.

[9] The assumption of convex disutility (e.g. Allen and Gale 2000) ensures that there is an interior solution to the bank's maximisation problem, and a meaningful trade-off between investment in projects and holding cash. There are other ways to achieve this, such as limited risk tolerance or decreasing monetary returns to investment, but this formulation makes for a particularly neat exposition.

The bank's equity at $t = 1$, denoted e^z_{1s}, is defined as the sum of the net cash flow and the value of its marketable assets. Marketable assets exclude the $\bar{n}_0$ projects which are pledged as collateral against long-term debt. The remaining assets are cash c_0 and n_0 projects with a market value of p_s each. Hence, equity is

$$e^z_{1s} = c_0 + (n_0 + \bar{n}_0)(v_{1s} + \varepsilon_z) + n_0 p_s - (1 - h) n_0 \tag{3}$$

Bank investments at $t = 1$. After trading in the secondary market, the bank holds n^z_{1s} projects funded by new *short-term debt.* By (1), it raises $(1 - h) p_s n^z_{1s}$ in debt and contributes $h p_s n^z_{1s}$ of its own equity. The bank holds c^z_{1s} units of *cash.* Its choices at $t = 1$ are $\mathbf{x}^z_{1s} = (c^z_{1s}, n^z_{1s}) \in \mathbb{R}^2_+$, and its budget is

$$e^z_{1s} = h p_s n^z_{1s} + c^z_{1s} \tag{4}$$

where e^z_{1s} is its $t = 1$ equity, which is related to its first-period choices $\mathbf{x}_0$ by equation (3). Let $B^z_{1s}(\mathbf{x}_0) \subset \mathbb{R}^2_+$ be the set of bank choices that satisfy the budget.

Bank cash flows at $t = 2$ in state s. The bank receives the cash flow v_{2s} for the $\bar{n}_0 + n^z_{1s}$ projects held at $t = 1$. It repays short-term and long-term creditors. The bank's utility Π^z_s is given by the sum of the net cash flow and retained cash, minus monitoring costs incurred previously:

$$\Pi^z_s = c^z_{1s} + v_{2s}(n^z_{1s} + \bar{n}_0) - (1 - h) p_s n^z_{1s} - (1 - h)\bar{n}_0 - r(\bar{n}_0) - g(n_0 + \bar{n}_0) \tag{5}$$

Outside buyers. In addition to banks, *outside buyers* participate in the secondary market for projects at $t = 1$. Outside buyers have less project management skills than banks, and can only extract a cash flow of $\underline{p} < v_{2b}$ per project at $t = 2$.

Competitive equilibrium. Market clearing requires that the banking sector cannot be a net buyer of projects in the secondary market, since no projects are sold by anybody else. Moreover, if a strictly positive number of projects are sold by the banking sector, then their price must equal the marginal valuation of outside buyers $\underline{p}$. This value plays the role of a *fire sale price.*[10]

Note that in aggregate state s, a measure β of banks have a low individual shock $z^i = L$, and sell $n_0 - n^L_{1s}$ projects. A measure $1 - \beta$ have a high shock and sell $n_0 - n^H_{1s}$ projects. This yields the following definition of equilibrium:

[10] Shleifer and Vishny (2011) provide an excellent theoretical and empirical survey on fire sales.

Definition 1. A *competitive equilibrium* is described by asset prices p_s for $s \in \{g, b\}$ and bank choices $\mathbf{x}_0 \in \mathbb{R}^3_+$ and $\mathbf{x}^z_{1s} \in \mathbb{R}^2_+$ for $s \in \{g, b\}$ and $z \in \{H, L\}$ satisfying

1. *Optimality.* The bank's choices maximise $E\left[\Pi^z_s\right]$ subject to $\mathbf{x}_0 \in B_0$ and $\mathbf{x}^z_{1s} \in B^z_{1s}\left(\mathbf{x}_0\right)$, taking asset prices as given.

2. *Market clearing.* For all $s \in \{g, b\}$,

$$n_0 - \left(\beta n^L_{1s} + (1-\beta)\, n^H_{1s}\right) \geq 0 \tag{6}$$

   Furthermore, $p_s \geq \underline{p}$, and if (6) is a strict inequality, then $p_s = \underline{p}$.

Parametric assumptions. The following assumption makes the analysis of fire sales interesting:

Assumption 1. *Aggregate cash flows at $t = 1$ satisfy*

$$\begin{aligned} v_{1g} &> \left(1 - \underline{p}\right)(1-h) \\ v_{1b} &< \left(1 - v_{2b}\right)(1-h) \end{aligned}$$

The first condition ensures that in the good state, aggregate bank liquidity is high, so that banks never have to sell assets to outside buyers in equilibrium. The second condition ensures that aggregate liquidity is low enough in the bad state to make fire sales a possibility.

Moreover, I impose a condition guaranteeing that bank debt is risk free in the baseline model. As discussed above, this requires a lower bound on the haircut h.

Assumption 2. *For all $\bar{n}_0 \in [0, e_0/h]$, the haircut satisfies*

$$h > 1 - \underline{p} + r\left(\bar{n}_0\right)$$

This condition states that the bank can always sell its assets in the secondary market, service its outstanding debt and interest obligations, and have cash left over. Thus, it has positive continuation value at $t = 1$ and will not default.

4 Competitive equilibrium

Bank profits. The bank earns a basic expected net return of R on each of the $(n_0 + \bar{n}_0)$ projects it invests in. It has to pay interest on long-term debt and incurs monitoring costs.

Hence, its expected basic profits are

$$R\left(n_0+\bar{n}_0\right)-r\left(\bar{n}_0\right)-g\left(n_0+\bar{n}_0\right)$$

The bank may also make profits or losses from trading projects in the secondary market at $t=1$. By virtue of Assumption 1, projects will be priced fairly in the good state in equilibrium, $p_g=v_{2g}$. There are two relevant scenarios in the bad state: Projects can be priced fairly ($p_b=v_{2b}$) or underpriced ($p_b<v_{2b}$).[11]

If projects are priced fairly, then the bank cannot gain or lose from trading. If they are underpriced, the bank will optimally hold as many projects at as possible in the bad state. From the budget (4), it follows that this is achieved by holding no cash, i.e. setting $c_{1b}^z=0$ and $n_{1b}^z=e_{1b}^z/p_bh$. Its net sale of assets is then e_{1b}^z/p_bh-n_0. On each asset sold, the bank loses $v_{2b}-p_b$ (it gains when the net sale is negative).

The bad state occurs with probability α, so that expected trading losses are $\alpha\left(v_{2b}-p_b\right)$ times the expected net sale. Using the definition of equity e_{1s}^z in (3), the budget constraint (2) and the fact that $E\left[\varepsilon_z\right]=0$, expected trading losses are

$$\phi\left(p_b\right)\left[\left(n_0+\bar{n}_0\right)\left(1-p_b\left(1-h\right)-v_{1b}\right)-\bar{n}_0\left(1-p_b\right)\left(1-h\right)-e_0\right] \tag{7}$$

where $\phi\left(p_b\right)=\alpha\left(v_{2b}-p_b\right)/p_bh$.

The term in square brackets is the bank's *expected liquidity shortfall,* which measures the difference between its $t=1$ equity and the amount required to hold on to n_0 assets. The factor $\phi\left(p_b\right)$ is the *marginal value of bank liquidity* at $t=1$. It is the product of the likelihood of the bad state, the undervaluation of projects, and the number of assets that can be bought with one unit of liquidity, which is $1/p_bh$.

Lemma 1. *In any competitive equilibrium, asset prices satisfy* $p_g=v_{2g}$ *and* $p_b\in\left[\underline{p},v_{2b}\right]$. *The bank's expected profits satisfy* $E\left[\Pi_s\right]=V\left(\mathbf{x}_0,p_b\right)$, *and its choices solve the problem* $\max_{\mathbf{x}_0\in B_0}V\left(\mathbf{x}_0,p_b\right)$, *where*

$$\begin{aligned} V\left(\mathbf{x}_0,p_b\right) &= R\left(n_0+\bar{n}_0\right)-r\left(\bar{n}_0\right)-g\left(n_0+\bar{n}_0\right) \\ &- \phi\left(p_b\right)\left[\left(n_0+\bar{n}_0\right)\left(1-p_b\left(1-h\right)-v_{1b}\right)-\bar{n}_0\left(1-p_b\right)\left(1-h\right)-e_0\right] \end{aligned} \tag{8}$$

Optimality conditions. Assuming that the solution to the bank's maximisation problem is interior, its choices are characterised by two marginal conditions:[12]

[11] The proof of Lemma 1 verifies that these are the only possibilities.

[12] Appendix B derives parametric conditions that guarantee an interior solution.

$$
\begin{aligned}
r'\left(\bar{n}_0^\star\right) &= \phi\left(p_b\right)\left(1-p_b\right)\left(1-h\right) && (9)\\
R-g'\left(n_0^\star+\bar{n}_0^\star\right) &= \phi\left(p_b\right)\left[1-p_b\left(1-h\right)-v_{1b}\right] && (10)
\end{aligned}
$$

Equation (9) determines optimal maturity structure. The left-hand side is the marginal cost of long-term funding, driven by creditors' liquidity preference. The right-hand side is the marginal liquidity cost of short-term funding. It is equal to the marginal value of liquidity times the liquidity injection required to roll over short-term debt.

Equation (10) determines optimal investment. The left-hand side is the marginal basic profit of investment in projects, net of monitoring costs. The right-hand side is the marginal benefit of cash, driven by the fact that cash offers liquidity in the bad state. It is equal to the marginal value of liquidity times the decrease in the expected shortfall when cash is substituted for projects.

4.1 Fire sales

When there is an *aggregate liquidity shortfall* at $t=1$, banks must sell assets to outside buyers. By the law of large numbers, the aggregate liquidity shortfall is the same as the expected liquidity shortfall of an individual bank, i.e. the term in square brackets in (7). If this is positive, the banking sector is an aggregate net seller of projects in the bad state. Consequently, there is a *fire sale* and the price has to drop to the valuation of outside buyers $\underline{p}$.

The focus of this paper is on situations where fire sales arise in competitive equilibrium. This occurs when investment in projects is sufficiently attractive, and when long-term debt is sufficiently costly. In that case, banks find it worthwhile to invest a large proportion of their initial equity in projects funded by short-term debt, and hold few cash reserves, which naturally creates an aggregate liquidity shortfall.

Projects are attractive when the net present value R is high. Long-term debt is costly when creditors have a strong liquidity preference, which corresponds to a high return q on their potential investments.

Proposition 1. *There are two thresholds $R_f>0$ and $q_f>0$, which are functions of the parameters other than R and q, such that when $R>R_f$, and $q>q_f$, the unique competitive equilibrium has a fire sale, with $p_b=\underline{p}$.*

In the remainder of the paper, I assume that there is a fire sale in equilibrium. Thus, I will focus on the parametric region where $R > R_f$ and $q > q_f$.

4.2 The cost of fire sales and systematic risk

Fire sales are a systematic phenomenon, as they are driven by aggregate illiquidity. I now analyse how the cost of fire sales is affected by increases in systematic risk. Increased systematic risk is captured by mean-preserving spreads in the aggregate cash flows v_{1s} and v_{2s}.

I have assumed that there is some systematic risk in the economy ($v_{1g} > v_{1b}$), or equivalently, that there is positive correlation in cash flow risk across banks. If cash flow risk were entirely idiosyncratic ($v_{1b} = v_{1g}$), fire sales would not arise, as banks with high cash flows would buy assets from banks with low cash flows, and outside buyers would not need to get involved. This is analogous to the point on aggregate liquidity shortages in Holmström and Tirole (1998). In their model, there is no role for public liquidity provision when shocks are purely idiosyncratic, since firms can insure each other. Here, there is no role for regulation when cash flow shocks are purely idiosyncratic.

In my model, systematic risk is sufficiently high to cause fire sales in equilibrium. Fire sales are costly, as banks make losses by selling projects below value. The losses in equilibrium are equal to (7), evaluated at the equilibrium price $p_b = \underline{p}$ and the optimal choices $n_0^\star$ and $\bar{n}_0^\star$.

Fire sale costs do not depend on the individual shock ε_z, and are unaffected by idiosyncratic risk. They do, however, respond to changes in systematic risk.

Proposition 2. *A mean-preserving spread in v_{1s} increases the equilibrium cost of fire sales if and only if*

$$g''\left(n_0^\star + \bar{n}_0^\star\right) > \frac{\phi\left(\underline{p}\right)\left(1 - \underline{p}\left(1-h\right) - v_{1b}\right)}{\left(n_0^\star + \bar{n}_0^\star\right)}$$

A mean-preserving spread in v_{2s} increases the cost of fire sales if $g''\left(n_0^\star + \bar{n}_0^\star\right)$ is sufficiently close to this lower bound.

To understand this result, note there are direct and indirect effects of increased systematic risk. A mean preserving spread in v_{1s} decreases v_{1b}, which directly increases fire sale costs by reducing cash flow liquidity. However, banks optimally react by investing less, which reduces their liquidity shortfall and the cost of fire sales.[13] Costs increase on balance when the first effect dominates. This occurs when banks' demand for investment is inelastic, i.e. when the curvature of monitoring costs g'' is big enough.

A mean-preserving spread in v_{2s} decreases v_{2b}, which directly lowers cost by diminishing the fire sales discount and lowering the marginal value of liquidity ϕ. However, banks optimally respond to a lower ϕ by investing more and issuing less long-term debt, which increases their liquidity shortfall. Costs increase when the second effect dominates. This occurs when banks' demand for investment is not too inelastic, i.e. when g'' is not too big.

An alternative interpretation of these results is in terms of the correlation between banks. The correlation between the $t = 1$ cash flows of bank i and j is

$$Corr\left(v_{1s} + \varepsilon_{z^i}, v_{1s} + \varepsilon_{z^j}\right) = \frac{1}{1 + Var\left(\varepsilon_z\right) / Var\left(v_{1s}\right)}$$

A change in correlation affects the cost of fire sales if and only if it is driven by an increase in systematic risk through $Var\left(v_{1s}\right)$. If correlation changes due to changes in systematic risk through $Var\left(\varepsilon_z\right)$, the costs are unaffected.

4.3 The social planner's choice

I now study the choices of a benevolent planner who dictates $t = 0$ bank choices $\mathbf{x}_0 = \left(c_0, n_0, \bar{n}_0\right)$ but has to satisfy the bank's budget constraint (2). He leaves banks to optimise given $\mathbf{x}_0$ and market prices at $t = 1$. His choices induce a *planned equilibrium.*

There are three types of agents: Banks, creditors and outside buyers. Creditors and outside buyers are always indifferent between dealing with the bank and consuming their exogenous endowment, so that their utility is the same in any planned equilibrium. Hence, the social planner seeks to maximise expected bank profits in planned equilibrium. His optimal choices are called *constrained efficient.* Constrained efficiency differs from full Pareto efficiency in that my social planner cannot freely transfer wealth between groups of agents, e.g. between creditors and banks.

One vector of social planner's choices $\mathbf{x}_0$ may induce multiple planned equilibria. This is due to a self-fulfilling debt-deflation spiral, which implies that both high and low asset prices may clear the market: When asset prices are high, banks have no funding problems and do

[13]This indirect effect is closely linked to the point on maturity and systematic risk in Chen et al. (2013). In their dynamic model, firms with high systematic risk exposure choose a longer debt maturity. Condition (9) shows that the optimal maturity of debt also lengthens with an increase in systematic risk in my model.

not sell assets. When asset prices are low, banks are forced to sell. To facilitate the analysis, I assume that the market selects the 'better' equilibrium without a fire sale.

Assumption 3. *If the social planner's choices induce multiple planned equilibria, the one with the highest equilibrium price p_b is selected with probability 1.*

It is helpful to examine what the social planner needs to do to avoid a fire sale. He has to choose $t = 0$ investments such that fair pricing in all states ($p_s = v_{2s}$) is an equilibrium. This can only be the case if, given fair prices, there is no aggregate liquidity shortfall.

Lemma 2. *In planned equilibrium prices satisfy $p_g = v_{2g}$. Furthermore, $p_b = v_{2b}$ if the planner's choice $\mathbf{x}_0$ satisfies the 'no fire sale' condition*

$$(n_0 + \bar{n}_0)(1 - v_{2b}(1 - h) - v_{1b}) - \bar{n}_0 (1 - v_{2b})(1 - h) \leq e_0 \tag{11}$$

and $p_b = \underline{p}$ otherwise.[14]

This characterisation illustrates the *two basic trade-offs* the planner faces if he wishes to avoid a fire sale. First, he trades off investment in projects $n_0 + \bar{n}_0$ against holding cash reserves. The no fire sale condition is more likely to hold when cash reserves are high and $n_0 + \bar{n}_0$ is low, because cash provides a liquidity cushion. The downside is that projects have a higher net present value than cash.

Second, the planner trades off short-term against long-term borrowing. The no fire sale condition (11) is more likely to hold when long-term debt is used, since it alleviates the rollover problem. However, long-term debt is expensive due to the social value of bank maturity transformation.

4.4 Generic inefficiency of equilibrium

Recall that in competitive equilibrium, the bank invests much of its equity in projects funded by short-term debt, which leads to a fire sale. I establish that the inefficiency of competitive equilibrium is generic. For a range of parameter values, the social planner chooses not to replicate banks' choices in competitive equilibrium.

[14] I assume that the social planner always invests in some projects funded by short-term debt, or $n_0 > 0$. For $n_0 = 0$, then there would be no projects for sale at $t = 1$ and the secondary market would shut down. $n_0 = 0$ would never be optimal since projects have positive NPV.

Proposition 3. *There exists an open set of values $R > R_f$ and $q > q_f$ for which the competitive equilibrium is constrained inefficient. Then the unique constrained efficient choice, denoted $\mathbf{x}_0^E$, solves the problem*

$$\begin{aligned} & \max_{\mathbf{x}_0 \in B_0} R\left(n_0 + \bar{n}_0\right) - r\left(\bar{n}_0\right) - g\left(n_0 + \bar{n}_0\right) \\ \textit{subject to} \quad & \left(n_0 + \bar{n}_0\right)\left(1 - v_{2b}\left(1-h\right) - v_{1b}\right) - \bar{n}_0\left(1 - v_{2b}\right)\left(1-h\right) \leq e_0 \end{aligned} \tag{12}$$

Aggregate actions in competitive equilibrium lead to a situation with fire sales and reduced individual profitability. This creates a 'systemic externality': The choices of individual banks, by contributing to aggregate illiquidity and low equilibrium prices, reduce the profitability of others. Thus, banks may be better off if they are forced to coordinate on lower aggregate risk-taking by a social planner.

Systemic externalities are *pecuniary externalities* because they work through equilibrium prices. Pecuniary externalities affect welfare when financial markets are incomplete (Geanakoplos and Polemarchakis 1985). Incompleteness arises here because of binding borrowing constraints.[15] Raising the equilibrium price relaxes this constraint, which benefits banks more than it harms buyers. The argument of Greenwald and Stiglitz (1986) on the neutrality of pecuniary externalities breaks down.

To understand the characterisation of the efficient choice, note that when the competitive equilibrium is constrained inefficient, the social planner will choose to prevent a fire sale in the bad state by satisfying the no fire sales condition.[16] Subject to that condition, he will wish to maximise bank profits, as stated in the proposition.

4.5 A graphical illustration

Figure 1 illustrates the welfare analysis. The social planner dictates $t = 0$ bank investments $\mathbf{x}_0 = (c_0, n_0, \bar{n}_0)$. Given the project investments n_0 and $\bar{n}_0$, cash holdings are determined by the budget constraint in equation (2). There are two free choice variables, n_0 and $\bar{n}_0$. The feasible set is the area under the budget line, which has slope -1.

Leverage and maturity mismatch can be visualised in the figure. Leverage corresponds to a high total number of projects $n_0 + \bar{n}_0$. Leverage is high in the north-east of the figure,

[15] Other applications to finance include Kehoe and Levine (1993), Gromb and Vayanos (2002) and Caballero and Krishnamurthy (2003).

[16] Any choice that induces a fire sale is dominated by a replication of the competitive equilibrium.

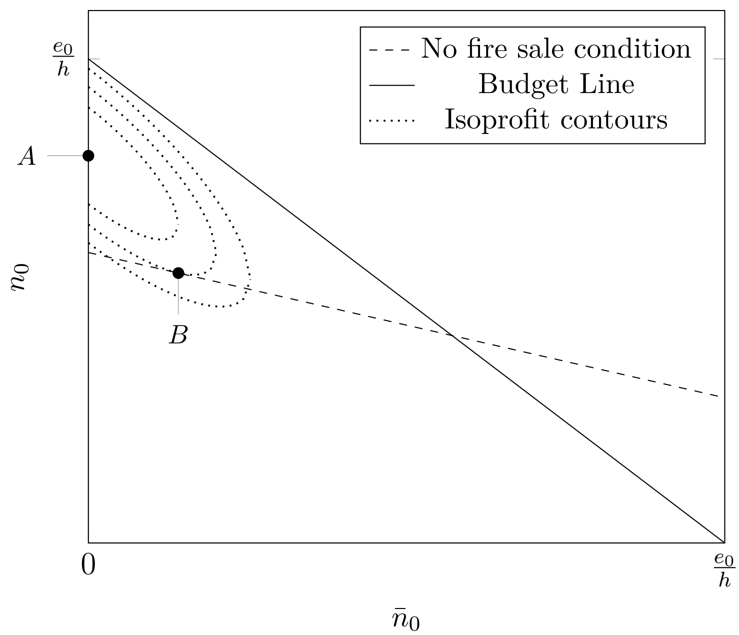

Figure 1: Welfare analysis

when the choice is close to the budget line. Maturity mismatch corresponds to a high ratio of short-term debt to total debt $n_0/(n_0 + \bar{n}_0)$. Maturity mismatch is high in the north-west of the figure.

The dashed line illustrates the no fire sale condition (11). The social planner needs to choose a point on or below the line to avoid a fire sale. The slope of the line is flatter than the budget line, because substituting long-term debt for short-term debt alleviates liquidity issues.

The planner maximises the objective in (12) subject to the no fire sales condition. The isoprofit contours are level curves of the objective function, and are ellipses around the unconstrained optimum at point A. Point A would be the choice of unregulated banks given $p_b = v_{2b}$. Since A lies above the no fire sale condition, $p_b = v_{2b}$ is not a competitive equilibrium.

The constrained efficient point is at point B, where the isoprofit curves are tangent to the no fire sale condition. This point features both reduced leverage and reduced maturity mismatch compared to the unconstrained choice A.

5 Optimal macroprudential regulation

This section discusses how financial regulation can be used to avoid inefficient fire sales in a decentralised equilibrium. In the language of Hanson et al. (2011), regulation against fire sales is *macroprudential* regulation, as it is concerned with aggregate behaviour and systematic risk.

I consider two macroprudential tools: Constraint-based regulation and Pigouvian taxation. Constraint-based regulation requires that bank choices $\mathbf{x}_0$ lie in some non-empty set $Q_0 \subset B_0$. Pigouvian taxation requires banks to pay the regulator τ per unit of investment, and receive a rebate $\bar{\rho}$ per unit of investment which is funded by long-term debt. Each constraint-based or Pigouvian regulatory regime induces a *regulated equilibrium.* Unlike in previous studies of Pigouvian taxes against systemic risk, I model a two-tier tax regime. A simple tax would not be able to achieve efficiency, as it cannot give nuanced incentives for reduced leverage and maturity mismatch.

As in the previous section, I impose and assumption to deal with multiple regulated equilibria:

Assumption 4. *If a regulatory regime induces multiple regulated equilibria, the one with the highest equilibrium price p_b is selected with probability 1.*

5.1 Constraint-based regulation

By definition, a regulator can never do better than the social planner in Section 4.3. Hence, if a regulated equilibrium is constrained efficient (i.e. if it replicates the planner's choice), then it must be optimal. Trivially, dictating that banks must replicate the planner's choice ($Q_0 = \left\{\mathbf{x}_0^E\right\}$) is an optimal regulatory constraint. However, this regime offers no informational advantage over outright centralisation.

As an alternative, the regulator can impose a constraint which mimics the no fire sale condition (11). Under this constraint, the bank's problem becomes to maximise profits subject to 'no fire sale'. But Proposition 3 shows that this is equivalent to finding the constrained efficient investment. In terms of the graphical analysis in Figure 1, if the no fire sale condition is imposed on banks as a constraint, their privately optimal choice will coincide with the constrained efficient point B, yielding an efficient allocation in regulated equilibrium.

Proposition 4. *The following regulatory constraint induces a constrained efficient regulated equilibrium:*

$$Q_0^{macro} = \{\mathbf{x}_0 \in B_0 | \, (n_0 + \bar{n}_0)(1 - v_{2b}(1-h) - v_{1b}) - \bar{n}_0 (1 - v_{2b})(1-h) \leq e_0\} \qquad (13)$$

The optimal rule (13) is remarkably simple in two ways. First, if she can observe the bank's balance sheet, the regulator only needs to know three parameters to impose Q_0^{macro}: Aggregate cash flows in the bad state v_{1b} and v_{2b}, and the haircut h. Second, it is *linear* in banks' investment choices.

It is easy to see why a linear constraint is optimal in the current model. The optimal rule mimics the no fire sale condition (11). This reduces to the requirement that bank equity at $t = 1$, which is a linear function of investment choices, must be above a certain threshold to avoid an aggregate liquidity shortfall. Therefore, even though the marginal value of bank liquidity ϕ is non-linear, the optimal regulation to ensure sufficient bank liquidity is linear.[17]

This is a key result of this paper. A simple linear rule is fully efficient, in the sense that it achieves the same level of welfare as a benevolent planner. The generality of this conclusion is discussed at the end of this section.

In contrast, a central planner generally needs to know all parameters of the model to solve the full optimisation problem (12). This comparison illustrates the considerable informational advantage of constraint-based regulation over centralisation. Limited knowledge of the value of investment R, monitoring costs g or funding costs r, for instance, does not render this policy ineffective.[18] Intuitively, the constraint Q_0^{macro} gives banks the incentive to use their information efficiently, without the regulator having to obtain it.

5.2 Pigouvian taxation

The purpose of taxes is to ensure that banks' optimal choices when there is no fire sale ($p_b = v_{2b}$) coincide with the choices of the social planner ($\mathbf{x}_0^E$). Under this condition, the regulated equilibrium with taxes will be constrained efficient.

The representative bank's problem when $p_b = v_{2b}$ is to maximise $V(\mathbf{x}_0, v_{2b})$ net of taxes. Its

[17] Bolton et al. (2011) provide a general characterisation of the (highly non-linear) marginal value of firm liquidity in a dynamic model.

[18] Even though both centralisation $Q_0 = \{\mathbf{x}_0^E\}$ and Q_0^{macro} are technically efficient in this model, it is easy to show that for any constraint $Q_0' \neq Q_0^{macro}$, there exist values of the parameters other than v_{1b}, v_{2b} and h such that Q_0' does not induce a constrained efficient equilibrium. In this sense, Q_0^{macro} is uniquely optimal.

first-order conditions are now

$$\begin{aligned} R - g'\left(n_0^\star + \bar{n}_0^\star\right) &= \tau \\ r'\left(\bar{n}_0^\star\right) &= \bar{\rho} \end{aligned}$$

An efficient tax regime must ensure that these choices coincide with the social planner's. By taking the first-order condition of the planner's program (12), it is easy obtain the following characterisation.

Proposition 5. *The unique tax regime inducing a constrained efficient regulated equilibrium is*

$$\begin{aligned} \tau &= \lambda\left[1 - v_{2b}\left(1-h\right) - v_{1b}\right] \\ \bar{\rho} &= \lambda\left(1 - v_{2b}\right)\left(1-h\right) \end{aligned}$$

where λ is the Lagrange multiplier associated with the no fire sale condition at the solution of the social planner's problem (12)*.*

This proposition shows that a two-tier Pigouvian tax can achieve efficiency. However, it does not compare favourably with constraint-based regulation when it comes to informational requirements. In order to pick the optimal tax regime τ and $\bar{\rho}$, the regulator needs to know the cash flow parameters v_{1b}, v_{2b} and the haircut h. In addition, she needs to know the social planner's Lagrange multiplier λ, which measures the social value of aggregate bank liquidity in the bad state.

In particular, one can use the planner's first-order condition to solve for λ, which yields

$$\begin{aligned} \tau &= R - g'\left(n_0^E + \bar{n}_0^E\right) \\ \bar{\rho} &= r'\left(\bar{n}_0^E\right) \end{aligned}$$

The efficient tax rates are functions of the planner's optimal choices n_0^E and $\bar{n}_0^E$. In general, these choices depend on all parameters of the model. Consequently, it appears that Pigouvian taxes are efficient, but more complex to implement than constraint-based regulation.

5.3 Implementation and Basel III

Capital requirements are insufficient to implement the optimal macroprudential regulation. They treat all debt equally, and cannot provide the differential treatment of long-term and short-term borrowing that is prescribed by Q_0^{macro}.

The Basel III Accord (BIS 2010) proposes two more nuanced tools: Net Stable Funding Ratio (NSFR) and Liquidity Coverage Ratio (LCR) requirements. Both can be used to implement optimal regulation in my model.

Net Stable Funding Ratio. The NSFR requirement works as follows:

1. *Available stable funding* (ASF) is a weighted sum of bank liabilities. Liabilities which lead to liquidity shortfalls have low weights.

2. *Required stable funding* (RSF) is a weighted sum of bank assets. Illiquid assets which cannot be sold easily have high weights.

3. The *NSFR* is calculated as the ratio of available to required stable funding. The regulatory constraint is $ASF/RSF \geq 1$.

Using the budget constraint (2), the optimal constraint Q_0^{macro} can be written as

$$\frac{ASF}{RSF} = \frac{e_0 + (1 - v_{2b})(1 - h)\bar{n}_0}{[1 - v_{2b}(1 - h) - v_{1b}](n_0 + \bar{n}_0)} \geq 1 \tag{14}$$

This formulation allows me to provide practical guidance for the calibration of weights in the NSFR requirement. In the numerator, equity receives a weight of 100%, whereas long-term debt $(1 - h)\bar{n}_0$ receives a lower weight of $(1 - v_{2b}) < 1$. Long-term debt is not quite as 'stable' as equity, because it obliges the bank to pledge assets as collateral, reducing its liquidity in a crisis as these assets cannot be pledged against new debt.

In the denominator, liquid cash receives zero weight. Projects receive a weight equal to $1 - v_{2b}(1 - h) - v_{1b} \in (0, 1)$. Their 'stability weight' is lower when systematic cash flow risk is high and when funding conditions are tight (high h), since both factors exacerbate rollover problems.

Liquidity Coverage Ratio. The LCR requirement works as follows:

1. *Net cash outflows* (NCO) are a weighted sum of bank liabilities. Liabilities which are withdrawn by creditors in a 30-day stress test scenario (determined by the regulator) have high weights.

2. *High quality liquid assets* (HQLA) are a weighted sum of bank assets. Illiquid assets have low weights.

3. The *LCR* is calculated as the ratio of high quality liquid assets to net cash outflows. The regulatory constraint is $HQLA/NCO \geq 1$.

The optimal constraint Q_0^{macro} can also be written as

$$\frac{HQLA}{NCO} = \frac{c_0 + (n_0 + \bar{n}_0)\, v_{1b}}{(1 - v_{2b})\,(1 - h)\, n_0} \geq 1$$

This yields practical insights for the design of 'liquidity weights' and the stress test scenario underlying the NCO. In the numerator, liquid cash receives a 100% weight, and projects receive a weight that is equal to their liquidity contribution in the bad state, $v_{1b} < 1$. In the denominator, representing the *optimal stress-test scenario*, long-term debt and equity are not withdrawn, whereas a proportion $(1 - v_{2b})$ of short-term debt $(1 - h)\, n_0$ is withdrawn. The withdrawal rate on short-term debt is lower when systematic long-term risk is high, since this erodes the value of projects as collateral in a crisis, again exacerbating rollover problems.

In sum, my model supports the joint application of capital requirements and new macro-prudential tools. I remain agnostic about which of the new tools in Basel III is preferable; either tool can achieve efficiency. The Basel committee's proposals include both due to worries about systemic risk at different time horizons. The LCR's weights are designed with short-term risk in mind, while the NSFR focuses on longer-term stability.

While risk at different time horizons is a valid concern (and is supported formally by my dynamic extension below), the analysis here reveals that the two tools are equivalent for dealing with systemic risk. It would arguably be beneficial to simplify the regime by having two LCR's, one with a short-term and one with a long-term focus, rather than two constraints with superficially different names and definitions.

5.4 The generality of linear optimal rules

I examine whether the linearity and simplicity of Q_0^{macro} is an artifact of my simple model economy. An obvious first observation is that if project investment did not exhibit constant returns to scale, the no fire sale condition would not be linear. One response is that a first-order approximation of the condition would still be linear, and that this may offer a useful regulatory benchmark. Another response is that the assumption of constant returns, a standard in the banking literature, is quite reasonable. Financial assets and loans to households and businesses with similar characteristics have a natural constant-returns property.

A more interesting question is whether the static nature of the model or the binary nature of fire sales (outside buyers demand any quantity at price $\underline{p}$, but nothing at any higher price) is driving the result. The following two extensions address these concerns.

Dynamic extension. Consider an extension of the model until time $T > 2$, where the individual and aggregate states, $s_t \in \{g, b\}$ and $z_t^i \in \{H, L\}$ for $t \geq 1$, evolve according to independent Markov chains. For simplicity, I continue to assume that project investment and long-term borrowing only takes place at $t = 0$. For period t, let v_t denote the per-unit cash flow of projects, c_{t-1} the aggregate cash holdings, and n_{t-1} the amount of projects held by banks and pledged against short-term debt between $t-1$ and t.[19] Denote the fair value of projects at $t = 1$ by $\hat{p}_t = E_t\left[\sum_{s=t+1}^{T} v_t\right]$ for $t \geq 1$. It is then possible to repeat the steps above to show that the condition for no fire sale in period t is

$$n_{t-1}\left(p_{t-1} - \hat{p}_t\right)(1-h) - \left(n_{t-1} + \bar{n}_0\right) v_t - c_{t-1} \leq 0$$

where $p_0 \equiv 1$. If a social planner wants to prevent fire sales, he will maximise bank profits subject to a series of such linear conditions. Thus, imposing linear constraints on banks period-by-period would again sufficient to induce efficiency.

Partial fire sales. In my model, outside buyers demand any quantity of projects at the fixed fire sale price $\underline{p}$. An alternative assumption is that they have a general downward-sloping inverse demand function for projects. Their demand for projects in state $s \in \{g, b\}$ is $\max\{0, D(p_s)\}$, where $D'(p_s) > 0$ and $D(v_{2b}) \leq 0$. Recall that the number of assets sold by banks in the bad aggregate state is equal to $1/p_b h$ times the aggregate liquidity shortfall. Market clearing now requires that[20]

$$D\left(p_b\right) = \frac{\left(n_0 + \bar{n}_0\right)\left(1 - p_b(1-h) - v_{1b}\right) - \bar{n}_0\left(1 - p_b\right)(1-h) - e_0}{p_b h} \tag{15}$$

In this extension, the social planner might settle for a 'partial fire sale', aiming for an intermediate value $p_b \in \left[\underline{p}, v_{2b}\right]$ and adjusting bank investments to satisfy (15). Let p_b^E denote the price in the optimal planned equilibrium. As noted by Lorenzoni (2008), calculating p_b^E is difficult because the planner's problem is not concave in general. However, in any case, the planner's choice of bank investment $\mathbf{x}_0^E$ will be most profitable choice that satisfies (15)

[19] These variables of course depend on the time-varying states, but I suppress the additional subscript to save notation.

[20] As in Lorenzoni (2008), a bound on the slope of D would be required to guarantee uniqueness of equilibrium.

for $p_b = p_b^E$. Therefore, the efficient choice solves the problem

$$\begin{aligned} & \max_{\mathbf{x}_0 \in B_0} V\left(\mathbf{x}_0, p_b^E\right) \\ \text{subject to } D\left(p_b^E\right) \times p_b^E h &= (n_0 + \bar{n}_0)\left(1 - p_b^E(1-h) - v_{1b}\right) - \bar{n}_0\left(1 - p_b^E\right)(1-h) - e_0 \end{aligned}$$

The planner's choice still maximises bank profits subject to a linear condition, which means that it can be decentralised with a linear regulatory constraint. However, the informational efficiency of constraint-based regulation is compromised. Solving this problem requires knowledge of p_b^E, the socially optimal price level, which generally depends on all parameters of the model.

In conclusion, it appears that the optimality of a linear regulatory rule is fairly general, while its informational efficiency partly depends on the baseline model's assumption that fire sale prices are fixed.

However, I would argue that the informational efficiency is preserved in a heuristic sense. Even with partial fire sales, a regulator can simplify her decision by solving a realistic two-step problem. First, she can decide how much of a drop in asset prices she is willing to tolerate. Conditional on this decision, she can implement the optimal policy with a linear constraint which, as in the baseline model, requires little information.

6 Optimal microprudential regulation

This section drops Assumption 2, which ensured that all bank debt was risk-free in the baseline model. A bank defaults at $t = 1$ if bad news have driven its continuation value below zero.[21] Bank resolution causes a deadweight social cost of $\kappa \geq 0$ times the measure of defaulting banks. The parameter κ captures administrative costs of resolution and the wider social costs of credit crunches and disruptions to intermediation and payment systems.

In this setting, additional regulation may be required to curb the social cost of bank default. Hanson et al. (2011) define this as *microprudential* regulation.

Agents' payoffs upon default depend on the precise mechanism of bank resolution. I make two assumptions. First, short-term debt enjoys seniority over long-term debt, and the bank's choices are safe enough to keep short-term debt risk-free. Second, the bank's asset goes to a receiver upon default. The receiver pays back short-term creditors at $t = 1$, runs the bank

[21] Since all uncertainty is resolved at $t = 1$, there is no loss of generality in assuming that all default decisions are made at this date.

as efficiently as a banker, and then passes the (maximised) proceeds to long-term creditors at $t = 2$. These conditions simplify the analysis by ensuring that the constraint Q_0^{macro} continues to rule out fire sales. If short-term debt were risky or the receiver inefficient, bank default would exacerbate the fire sale, creating a need for stricter macroprudential regulation as well as an additional microprudential constraint. I also continue to assume that we are in the parametric region where it is efficient to prevent a fire sale.

Proposition 6. *When $\kappa = 0$, the constraint Q_0^{macro} as defined in* (13) *induces a constrained efficient regulated equilibrium. When κ is sufficiently large, the constraint $Q_0^{macro} \cap Q_0^{micro}$ induces a constrained efficient equilibrium, where*

$$Q_0^{micro} = \{\mathbf{x}_0 \in B_0 | \left(n_0 + \bar{n}_0\right)\left(1 - v_{1b} - \varepsilon_L - v_{2b}\right) + r\left(\bar{n}_0\right) \leq e_0\} \tag{16}$$

Without deadweight costs, the macroprudential constraint Q_0^{macro} remains sufficient for efficiency. Long-term interest rates reflect default risk as well as the liquidity premium. This leads the bank to internalise the losses of long-term creditors in default, and there is no additional externality. With $\kappa > 0$, nobody will internalise the social deadweight cost, and the regulated equilibrium may be inefficient.

When κ is large, the planner, who maximises bank profits net of deadweight costs, chooses to rule out bank default. A necessary and sufficient condition is that a bank with a low individual shock ($z = L$) in the bad aggregate state ($s = b$) has a non-negative continuation value.

This translates to the requirement that bank choices lie in the set Q_0^{micro}. Proceeding as in the analysis of fire sales, the planner's choices maximise bank profits subject to the no fire sale condition *and* Q_0^{micro}. Consequently, it is efficient to impose both constraints on banks.

Optimal regulation is then based on two constraints - a macroprudential and a microprudential part. In general, neither constraint implies the other, so that both are necessary for efficiency.

Lemma 3. *Suppose that the individual shock ε_L satisfies*

$$v_{1b} + v_{2b} - (1 - h) < |\varepsilon_L| < h v_{2b}$$

Then the microprudential constraint Q_0^{micro} is neither a superset nor a subset of the macroprudential constraint Q_0^{macro}.

Intuitively, 'no fire sale' does not imply 'no default' because banks with low idiosyncratic shocks may default even though there is no aggregate liquidity shortfall. This requires a lower bound the magnitude of idiosyncratic risk $|\varepsilon_L|$. 'No default' does not imply 'no fire sale' because even long-run solvent banks can have short-run liquidity problems. This requires that the no default condition cannot be 'too strict', which translates to an upper bound on $|\varepsilon_L|$.

Informational requirements. The macroprudential part of the optimal regulation requires the same information as before: v_{1b}, v_{2b} and h. The microprudential part requires these three parameters plus the idiosyncratic shock ε_L and the interest payment on long-term debt $r(\bar{n}_0)$. Regulating against default is more informationally costly than regulating against fire sales, as both 'micro' and 'macro' information is necessary.

Note that there is considerable overlap in the information required for micro- and macroprudential regulation. This exposes a potential weakness of recent reforms. Many governments have established macroprudential regulators which are institutionally separate from existing microprudential agencies. This dichotomy may inhibit information sharing between agencies. My model shows that information sharing is indeed valuable, as optimal micro- and macroprudential regulations depend on many common factors.

Implementation. In the Basel regulatory framework, the optimal microprudential constraint Q_0^{micro} can be implemented by a tool that resembles a capital requirement. Rearranging (16) yields

$$\frac{e_0}{n_0+\bar{n}_0} \geq 1 - v_{1b} - \varepsilon_b - v_{2b} + \frac{r(\bar{n}_0)}{n_0+\bar{n}_0}$$

The left-hand side is just as in a traditional capital requirement - the ratio of equity capital to risky assets. Unlike in a traditional capital requirement, which constrains this ratio to lie above a constant value, the right-hand side is modified to account for interest payments. This is because banks may default due to high outstanding interest payments, not just due to a high face value of debt. However, this term may be negligible if interest rates are close to zero, so that a capital requirement would be approximately optimal.

7 Time-varying regulation and risk measures

Many commentators have isolated the lack of *time-variation* in financial policy as one of its key flaws prior to 2008 (Brunnermeier et al. 2009, Hanson et al. 2011). They emphasise that new macroprudential tools should be applied in a time-varying fashion, with the stringency of rules adapting to the business cycle, credit conditions and fluctuating systematic risk.

My model supports this point, as the optimal macroprudential regulation depends on the economy's risk profile.

The optimal macroprudential constraint Q_0^{macro} in (13) does not depend on the individual shock z, and changes in idiosyncratic risk do not affect macroprudential regulation. Changes in systematic risk do matter. Their precise implications depend whether long-term or short-term cash flows are affected.

A mean preserving spread in v_{1s} decreases v_{1b}, so that the (positive) coefficient on total investment $(n_0 + \bar{n}_0)$ in Q_0^{macro} increases. Risky investments now provide less liquidity in the bad state, and regulation must be tougher on leverage. A mean preserving spread in v_{2s} decreases v_{2b}, so that the coefficient on total investment increases and the coefficient on investment funded by long-term debt $\bar{n}_0$ decreases (becomes more negative). With a decrease in future asset values, borrowing constraints at $t = 1$ are tighter, rollover problems are more severe, and regulation must be tougher on both leverage and maturity mismatch.

Another risk measure is the tightness of funding conditions, captured by the haircut h. When h falls, the coefficient on total investment increases, and the coefficient on $\bar{n}_0$ decreases (becomes more negative). With relaxed funding conditions, banks lever up more, exacerbating rollover problems, and regulation must again be tougher on leverage and maturity mismatch.

Moreover, Section 6 shows that microprudential regulation should also adapt to changes in risk. The optimal microprudential constraint Q_0^{micro} in (16) depends on both systematic and idiosyncratic risk. An mean-preserving spread in either v_{1s}, v_{2s} or ε_z raises the coefficient on total investment $(n_0 + \bar{n}_0)$. All increased risk implies default risk, regardless of its source, and regulation must become stricter on leverage.

This leads to another critique of the dichotomy between macro- and microprudential regulation. Neither time-variation nor a concern with systematic risk are are macroprudential concerns. They should be part of the micro- and the macroprudential toolkit.

8 Conclusion

This paper has focused on a setting where banks have incentives to create excessive systemic risk through leverage and maturity mismatch. I proved that efficiency can be achieved through a relatively simple linear macroprudential constraint on banks' balance sheets, which requires less information than central planning or Pigouvian taxation. The Liquidity Coverage and Net Stable Funding ratios of Basel III are both capable of implementing the optimal policy. Macroprudential regulation should react to changes in systematic risk in the economy and credit conditions over the business cycle, but not to changes in the idiosyncratic risk of individual institutions.

In an extended model with potential socially costly bank failures, additional microprudential regulation against default is needed. This can be implemented with a constraint resembling a capital adequacy requirement, and needs to track changes in both systematic and idiosyncratic risk.

While my results offer support for recent regulatory reforms, they shed a critical light on the emerging view of macro- and microprudential regulation as separate tasks. My analysis demonstrates that both types of regulation ought to be time-varying and react to changes in systematic risk. Moreover, I have argued that micro- and macroprudential regulators benefit considerably from the exchange of information, which speaks against institutional separation.

A Proofs

Lemma 1

Given the argument in the text, it remains to be verified that in any competitive equilibrium, asset prices satisfy (i) $\underline{p} \leq p_s \leq v_{2s}$ and (ii) $p_g = v_{2g}$.

(i) Suppose $p_s > v_{2s}$ for some s. Then the bank optimally sells all projects at $t = 1$ in state s, $n_{1s}^z = 0$. By market clearing, it follows that $n_0 = 0$. Now consider the other state $s' \neq s$. We have $p_{s'} \geq v_{2s'}$, because otherwise, the bank would choose $n_{1s'} > 0$ and the market would not clear. Hence $p_s \geq v_{2s}$ for all $s \in \{g, b\}$. But then it is easy to show that the bank would optimally set $n_0 > 0$, a contradiction.

(ii) Suppose that $v_{2g} > p_g \geq \underline{p}$. Then it is optimal for the bank to buy as many projects as possible, setting $n_{1g}^z = e_{1g}^z / p_g h$. Using (3) for e_{1g}^z and $E[\varepsilon_z] = 0$, this yields

$$n_0 - \left(\beta n_{1s}^L + (1-\beta)\, n_{1s}^H\right) = \frac{n_0 \left[(1-p_g)(1-h) - v_{1g}\right] - \bar{n}_0 v_{1g} - c_0}{p_g h} < 0$$

where the inequality follows from Assumption 1 and the fact that one of n_0, c_0 and $\bar{n}_0$ is strictly positive by (2). This contradicts market clearing.

Proposition 1

The aggregate liquidity shortfall chosen by the bank given the price p_b is

$$(n_0^\star + \bar{n}_0^\star)\left[1 - p_b(1-h) - v_{1b}\right] - (1-p_b)(1-h)\,\bar{n}_0^\star - e_0$$

where $n_0^\star$ and $\bar{n}_0^\star$ are defined by (9) and (10). We have $d(n_0^\star + \bar{n}_0^\star)/dR > 0$ and, since $r'(\bar{n}_0)$ is increasing in q for all $\bar{n}_0$, $d\bar{n}_0^\star/dq < 0$. Thus, the aggregate liquidity shortfall is increasing in R and q. As R and q become large, holding other parameters fixed, optimal choices converge to the corner solution $\bar{n}_0^\star = 0$, $n_0^\star = \frac{e_0}{h}$ and $c_0^\star = 0$, for all $p_b \in \left[\underline{p}, v_{2b}\right]$. At this limit, the aggregate liquidity shortfall is strictly positive by Assumption 1.

Therefore, we can find two numbers $R_f > 0$ and $q_f > 0$ such that $R = R_f$ and $q = q_f$ implies

$$\min_{p_b \in \left[\underline{p}, v_{2b}\right]} (n_0^\star + \bar{n}_0^\star)\left[1 - p_b(1-h) - v_{1b}\right] - (1-p_b)(1-h)\,\bar{n}_0^\star - e_0 = 0$$

When $R > R_f$ and $q > q_f$, the aggregate liquidity shortfall is strictly positive for all possible p_b. Therefore, the unique equilibrium price is $p_b = \underline{p}$ by Definition 1.

Proposition 2

Let $k = \left(1 - \underline{p}\,(1-h) - v_{1b}\right)$, $\bar{k} = \left(1 - \underline{p}\right)(1-h)$, $\underline{\phi} = \phi\left(\underline{p}\right)$, $y_0^\star = (n_0^\star + \bar{n}_0^\star)$. The cost of fire sales in equilibrium is $\underline{\phi}\left[k y_0^\star - \bar{k}\bar{n}_0^\star - e_0\right]$.

(i) Mean-preserving spread in v_{1s}. The cost does not depend on v_{1g} and by an application of the implicit function theorem to (9) and (10), its derivative with respect to v_{1b} is

$$k\frac{dy_0^\star}{dv_{1b}} - y_0^\star = k\frac{\underline{\phi}}{g''\left(y_0^\star\right)} - y_0^\star$$

This is negative, implying that the mean-preserving spread increases cost, if and only if the proposed condition holds.

(ii) Mean-preserving spread in v_{2s}. The cost (7) does not depend on v_{2g} and it only depends on v_{2b} through $\underline{\phi}$, which is strictly increasing in v_{2b}. Its derivative with respect to $\underline{\phi}$ is

$$\left[k y_0^\star - \bar{k}\bar{n}_0^\star - e_0\right] + \underline{\phi}\left[k\frac{dy_0^\star}{d\underline{\phi}} - \bar{k}\frac{d\bar{n}_0^\star}{d\underline{\phi}}\right] = \left[k y_0^\star - \bar{k}\bar{n}_0^\star - e_0\right] - \phi\left[\frac{k^2}{g''\left(y_0^\star\right)} + \frac{\bar{k}^2}{r''\left(\bar{n}_0^\star\right)}\right]$$

When g'' is at the proposed lower bound, the terms involving $y_0^\star$ cancel and the expression is strictly negative. Hence, it is negative, implying that the mean-preserving spread increases cost, when g'' is close to the bound.

Lemma 2

By a parallel argument to Lemma 1, prices in planned equilibrium satisfy $\underline{p} \leq p_b \leq v_{2b}$ and $p_g = v_{2g}$ (as long as $n_0 > 0$). First, suppose the planner's choices satisfy (11). If $p_b = v_{2b}$ then banks are indifferent between all feasible $t = 1$ investments, the aggregate liquidity shortfall is non-positive by (11), and it is feasible for banks to set $\beta n_{1s}^L + (1-\beta)\, n_{1s}^H = n_0$. Thus $p_b = v_{2b}$ is an equilibrium price, and will be selected by Assumption 3. Second, suppose the planner's choices do not satisfy (11). Then for all $\underline{p} \leq p_b \leq v_{2b}$, the aggregate liquidity shortfall is positive, because it is positive for $p_b = v_{2b}$ and decreasing in p_b. All feasible bank choices then have $\beta n_{1s}^L + (1-\beta)\, n_{1s}^H < n_0$. Thus $p_b = \underline{p}$ is the only equilibrium price.

Proposition 3

(i) Generic inefficiency. I show that for R and δ sufficiently close to R_f and q_f, there exists a choice $\mathbf{x}_0^A \in B_0$ such that the planned equilibrium induced by $\mathbf{x}_0^A$ yields higher profits for the banks than the competitive equilibrium. Define

$$\hat{\sigma} = \min_{p_b \in \left[\underline{p}, v_{2b}\right]} \left(n_0^\star + \bar{n}_0^\star\right)\left[1 - p_b\left(1-h\right) - v_{1b}\right] - \left(1-p_b\right)\left(1-h\right)\bar{n}_0^\star - e_0$$

and let $\hat{p}$ denote any minimiser of the right-hand side. From the definition of R_f and q_f (see the proof of Proposition 1) and Berge's maximum theorem, it follows that $\hat{\sigma} \downarrow 0$ as $(R, q) \downarrow (R_f, q_f)$, and that $\hat{p}$ converges to some $\hat{p}_f \in \left[\underline{p}, v_{2b}\right]$. I prove that there is a welfare-improving choice in two steps.

First, suppose $\hat{p}_f > \underline{p}$. Making the dependence of optimal choices on prices explicit, consider the choice $\mathbf{x}_0^A$, defined by $n_0^A = n_0^\star\left(\hat{p}\right) - \epsilon$ and $\bar{n}_0^A = \bar{n}_0^\star\left(\hat{p}\right)$, where $\epsilon \geq 0$ is chosen to ensure that the choices satisfy the no fire sale condition if necessary. Define the bank's indirect utility as $W\left(p_b\right) = \max_{\mathbf{x}_0 \in B_0} V\left(\mathbf{x}_0, p_b\right)$. I show that as $(R, q) \downarrow (R_f, q_f)$, the planned equilibrium yields higher limiting profits than the competitive equilibrium. It is easy to see that $\epsilon \downarrow 0$, so that the planned equilibrium induced by $\mathbf{x}_0^A$ yields limiting profits equal to $W\left(\hat{p}_f\right)$, whereas the competitive equilibrium yields $W\left(\underline{p}\right)$. It remains to be shown that $W\left(\hat{p}_f\right) > W\left(\underline{p}\right)$ in the limit. By the envelope theorem and the fact that $\hat{\sigma} \downarrow 0$, the limiting case satisfies $W'\left(p_b\right) > 0$ for all $p_b < \hat{p}_f$, which implies $W\left(\hat{p}_f\right) > W\left(\underline{p}\right)$ as required.

Second, suppose $\hat{p}_f = \underline{p}$. Suppose the social planner picks $n_0^A = n_0^\star\left(\hat{p}\right)$ and $\bar{n}_0^A = \bar{n}_0^\star\left(\hat{p}\right)$. For R and q sufficiently close to R_f and q_f, these choices satisfy the no fire sales condition, so that the planned equilibrium yields profits $V\left(\mathbf{x}_0^A, v_{2b}\right) > W\left(\hat{p}\right)$. The competitive equilibrium yields $W\left(\underline{p}\right)$. It remains to be shown that $W\left(\hat{p}\right) \geq W\left(\underline{p}\right)$. By the envelope theorem, we have $W'\left(p_b\right) > 0$ for all $p_b > \underline{p}$, which implies $W\left(\hat{p}\right) \geq W\left(\underline{p}\right)$ as required.

(ii) Characterisation of optimum. By Lemma 2, the planner knows his choices will induce $p_b \in \left\{\underline{p}, v_{2b}\right\}$. For $p_b = \underline{p}$, the highest welfare possible is $W\left(\underline{p}\right)$, which is equal to welfare in competitive equilibrium. This is inefficient by assumption, so a choice inducing $p_b = v_{2b}$ must be optimal. The planner then maximises $V\left(\mathbf{x}_0, v_{2b}\right)$ subject to (11) as required.

Proposition 6

(i) $\kappa = 0$. By assumption, the efficient choice maximises bank profits, which are zero in states where the bank defaults, subject to (11), which continues to guarantee no fire sale due to the assumptions about resolution. This again coincides with the bank's objective when constraint Q_0^{macro} is imposed.

(ii) κ large. The efficient choice maximises bank profits minus κ times the measure of defaulting banks, subject to (11). It is easy to see that as $\kappa \to \infty$, since profits are bounded above, this converges to a choice where default is ruled out. This choice must maximise bank profits subject to (11) and the requirement that the bank's continuation value is positive in every state at $t = 1$. Since $v_{tg} > v_{tb}$ and $\varepsilon_H > \varepsilon_L$, it is sufficient that the continuation value is positive in state (b, L). Given that (11) is satisfied, we have $p_b = v_{2b}$, and positive continuation value is equivalent to

$$(v_{1b} + \varepsilon_L + v_{2b})(n_0 + \bar{n}_0) + c_0 - (1-h)(n_0 + \bar{n}_0) - r(\bar{n}_0) \geq 0$$

By the budget (2), this is in turn equivalent to the proposed requirement Q_0^{micro}.

Lemma 3

(i) $Q_0^{micro} \subsetneq Q_0^{macro}$. Consider $\bar{n}_0 = 0$, $n_0 = e_0/(1 - v_{1b} - \varepsilon_L - v_{2b})$. This choice satisfies the requirement in Q_0^{micro} with equality, but lies outside Q_0^{macro} if and only if (using $\varepsilon_L < 0$)

$$\begin{aligned} e_0 \frac{1 - v_{1b} - v_{2b}(1-h)}{1 - v_{1b} - \varepsilon_L - v_{2b}} &> e_0 \\ \Leftrightarrow |\varepsilon_L| &< h v_{2b} \end{aligned}$$

(ii) $Q_0^{macro} \subsetneq Q_0^{micro}$. Consider $c_0 = 0$, which implies $n_0 + \bar{n}_0 = e_0/h$, and n_0 chosen to satisfy the requirement in Q_0^{macro} with equality. This choice lies outside Q_0^{micro} if and only if

$$\begin{aligned} \frac{e_0}{h}(1 - v_{1b} - \varepsilon_L - v_{2b}) + r(\bar{n}_0) &> e_0 \\ \Leftrightarrow |\varepsilon_L| &> v_{1b} + v_{2b} - (1-h) - hr(\bar{n}_0) \end{aligned}$$

So both lack of sufficiency and lack of necessity are guaranteed by the proposed condition (using $r(\bar{n}_0) > 0$ for the second part).

B Conditions for interior solutions

This appendix derives parametric restrictions under which the bank's first-order conditions (9) and (10) are necessary and sufficient for optimality. By the concavity of the bank's problem, this is the case as long as the choices they imply are feasible. The feasibility conditions, implied by the budget constraint (2) and non-negativity of the bank's choices, are

$$\begin{aligned} 0 &\leq n_0^\star + \bar{n}_0^\star \leq \frac{e_0}{h} \\ 0 &\leq \bar{n}_0^\star \leq n_0^\star + \bar{n}_0^\star \end{aligned}$$

For the total investment in (10) to satisfy the first condition for all $p_b \in \left[\underline{p}, v_{2b}\right]$, we need

$$\begin{aligned} R - \phi\left(\underline{p}\right)\left[1 - \underline{p}\left(1-h\right) - v_{1b}\right] &\geq 0 \\ R &\leq g'\left(\frac{e_0}{h}\right) \end{aligned}$$

The investment funded short-term debt satisfies $\bar{n}_0^\star \geq 0$ since $r'\left(0\right) = 0$. Thus, to obtain $\bar{n}_0^\star \leq n_0^\star + \bar{n}_0^\star$ for all $p_b \in \left[\underline{p}, v_{2b}\right]$, we need

$$\left(r'\right)^{-1}\left(\phi\left(\underline{p}\right)\left(1-\underline{p}\right)\left(1-h\right)\right) \leq \left(g'\right)^{-1}\left(R - \phi\left(\underline{p}\right)\left[1 - \underline{p}\left(1-h\right) - v_{1b}\right]\right)$$

Since r and g are strictly convex, r', g' and their inverses are strictly increasing functions. It is then easy to see that the above can be guaranteed by a suitable upper bound on $\phi\left(\underline{p}\right) = \alpha\frac{v_{2b}-\underline{p}}{\underline{p}h}$.

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