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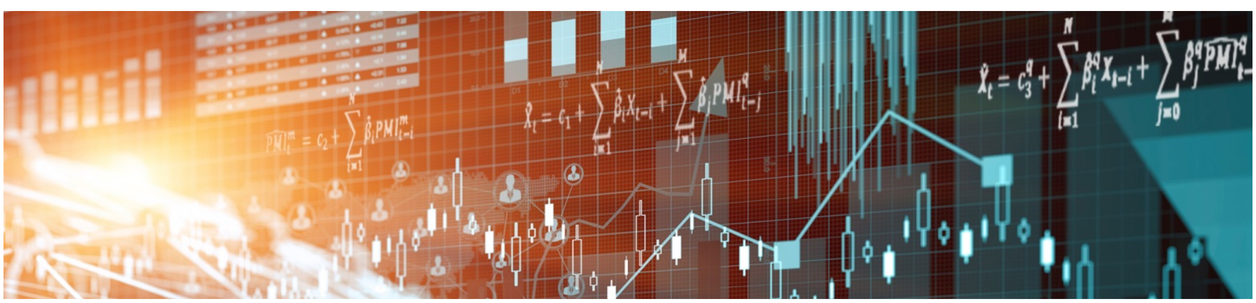
A Microfounded Design of Interconnectedness-Based Macroprudential Policy



by José Fique

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A Microfounded Design of Interconnectedness-Based Macroprudential Policy

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Abstract

To address the challenges posed by global systemically important banks (G-SIBs), the Basel Committee on Banking Supervision recommended an “additional loss absorbency requirement” for these institutions. Along these lines, I develop a microfounded design of capital surcharges that target the interconnectedness component of systemic risk. These surcharges increase the costs of establishing interbank connections, which leads to a non-monotonic welfare effect. While reduced interconnectedness decreases welfare by restricting the ability of banks to insure against liquidity shocks, it also increases it by reducing contagion when an interconnected bank fails. Thus, the regulator faces a trade-off between efficiency and financial stability. Furthermore, I show that capital requirements are more effective than default fund contributions when tail-risk exposure is the private information of banks. I conclude by analyzing how resolution regimes and stable funding requirements interact with these surcharges.

JEL classification: D82, D85, G21, G28
Bank classification: Financial institutions; Financial system regulation and policies

Résumé

Pour surmonter les défis associés aux banques d’importance systémique mondiale, le Comité de Bâle sur le contrôle bancaire recommande d’imposer à ces institutions une exigence de capacité additionnelle d’absorption des pertes. Dans cette optique, j’examine des exigences supplémentaires de fonds propres fondées sur des bases microéconomiques et conçues pour cibler la composante du risque systémique ayant trait à l’interconnectivité des banques. Ces exigences supplémentaires font augmenter les coûts d’établissement des liens interbancaires et ont ainsi un effet non monotone sur le bien-être. Si une interconnectivité réduite fait diminuer le bien-être en limitant la capacité des banques de se protéger contre un choc de liquidité, elle l’améliore par ailleurs en restreignant la contagion d’une défaillance entre les établissements interreliés. Les autorités de réglementation doivent par conséquent trouver un arbitrage entre efficience et stabilité financière. Je montre en outre que lorsque l’exposition à des risques extrêmes est une information détenue exclusivement par les banques, les exigences en fonds propres sont un instrument plus efficace que les contributions à un fond de défaut. En conclusion, j’analyse l’interaction entre, d’une part, les régimes de résolution et les obligations relatives à un financement stable et, de l’autre, ces exigences supplémentaires.

Classification JEL : D82, D85, G21, G28
Classification de la Banque : Institutions financières ; Règlementation et politiques relatives au système financier

Non-technical summary

The failure of large and interconnected banks has severe consequences for the real economy. To address the challenges posed by globally systemically important banks (G-SIBs), the Basel Committee on Banking Supervision recommended an "additional loss absorbency requirement" for these institutions. This instrument requires banks that are classified as G-SIBs to hold more capital according to their systemic importance, which depends partly on the importance of the contractual obligations these institutions establish with the rest of the financial system. Since this instrument affects the incentives of these institutions to establish these connections in the first place, it is important to understand how banks respond to the instrument in order to achieve the desired policy outcome.

In my model, banks establish connections to insure against idiosyncratic liquidity shocks. However, since some banks are exposed to tail risk (i.e., low-probability–high-impact default events), the failure of one bank may be propagated to others through this network of contractual obligations.

Given that banks do not internalize the costs that these contagious defaults impose on the regulator, they choose to become over-connected from a social standpoint. To ensure that interconnectedness does not exceed the socially optimal level, the regulator imposes capital requirements that depend on banks' network position. In a frictionless environment, this objective could easily be achieved. However, the regulator's ability to realign incentives may be impaired when it is unable to verify ex ante banks' exposure to tail risk and it cannot commit *not* to bail out failed interconnected banks when the banking system is weak.

When capital is costly, these interconnectedness-based capital requirements induce banks to become less interconnected. I show that this has a non-monotonic welfare effect. While reduced interconnectedness decreases welfare by restricting banks' ability to insure against liquidity shocks, it also increases welfare by reducing contagion. Thus, the regulator faces a trade-off between efficiency and financial stability. Furthermore, this trade-off is steeper on the correlation between liquidity shocks and tail risk exposure. This finding underscores the importance of understanding the economic rationale behind financial networks in the design of policies that aim to affect their structure.

I conclude by analyzing the role of alternative and complementary policy instruments in the design of this type of capital requirements.

1 Introduction

The aftermath of the financial crisis brought a macroprudential layer to banking regulation. This layer consists of a set of instruments designed to mitigate systemic risk. One example of these instruments is the "additional loss absorbency requirement" recommended by the Basel Committee on Banking Supervision (BCBS) for globally systemically important banks (G-SIBs). This instrument requires banks that are classified as G-SIBs to hold more capital according to their systemic importance. The classification of a bank as a G-SIB depends on, among other criteria, its interconnectedness. That is, the G-SIB status depends, to some extent, on how exposed to losses other institutions are in case of its failure. The argument for the adoption of this criterion is the following:

> Financial distress at one institution can materially increase the likelihood of distress at other institutions given the network of contractual obligations in which these firms operate. A bank's systemic impact is likely to be positively related to its interconnectedness vis-à-vis other financial institutions. (BCBS, 2011, p. 7)

The adoption of this criterion reveals regulatory concern over contagion and also suggests that market discipline alone is unable to mitigate this problem.[1] As seen during the financial crisis, in a situation where the threat of contagion materializes, the entities entrusted with preserving financial stability are prompted to intervene, exposing taxpayers to potentially large losses. However, when banks make their decisions, namely with respect to how interconnected they will be with the rest of the financial system, they do not take into account these costs. Therefore, regulation is required to ensure that private and social incentives are aligned. Motivated by this instrument of macroprudential policy, I analyze a microfounded design of interconnectedness-based capital requirements in order to unveil the trade-off between efficiency and financial stability implied by this instrument and how market frictions, namely asymmetric information and implicit government guarantees, constrain its design.

In my model, I combine exogenous heterogeneity of banks — which leads to endogenously determined systemic risk through banks' decisions to form the interbank network — with an asymmetrically informed regulator that faces a time-inconsistency problem. In the first stage, nature determines bankers' ability, which determines banks' tail risk exposure through the choice of the type of assets they wish to hold. In the second stage, the regulator sets a capital requirements schedule based on the connections that banks choose to establish among themselves. Finally, in

[1] One example that illustrates this channel of contagion is the financial distress experienced by the Reserve Primary Fund on September 16, 2008. This Money Market Mutual Fund experienced substantial financial distress on account to its $785 million exposure to commercial paper issued by Lehman Brothers. This event might have contributed to heightening the instability in financial markets, which led federal authorities to intervene shortly after. Even though this example speaks to a distress event that occurred in the shadow banking system and not in the regulated sector, which is the focus of this paper, it illustrates the negative externalities that emerge from contagion.

the last stage, the interbank network emerges as the outcome of a network formation game where banks make their interconnectedness decisions taking their own type and capital requirements as given.

After bankers learn their ability, they invest in a mixed portfolio of liquid and illiquid assets. These illiquid assets are heterogeneous: some are vulnerable to tail risk while others are not. Even though bankers can learn the type of the assets in the market at a cost, their ability may lead them to choose vulnerable assets since low-ability bankers have a comparative disadvantage in screening vulnerable assets. This induces heterogeneity in the vulnerability to tail risk in the banking system. However, regardless of the type of these assets, they need to be refinanced before maturity in an idiosyncratic amount. To insure against this liquidity shock, bankers can either invest a higher fraction of available funds in liquidity or establish interbank credit lines with counterparties with negatively correlated liquidity shocks, i.e., banks endogenously form a network. Since tail risk exposure is heterogeneous, some banks may fail. If that is the case, the regulator is called to resolve the banking crisis either by bailing out or closing the failed bank. Furthermore, since banks establish interbank connections, through which financial distress may be propagated, the exogenous heterogeneity of banks leads to endogenously determined systemic risk. However, since banks fail to internalize the financial distress costs imposed on the regulator/social planner, this level of systemic risk is not socially optimal. Thus, to internalize this externality, before the interbank network forms, the regulator sets an interconnectedness-based capital requirement that affects banks' incentives to establish linkages.

Interconnectedness-based capital surcharges increase the cost of establishing interbank connections, which results in a non-monotonic welfare effect. Decreased interconnectedness reduces welfare by limiting banks' ability to rely on outside sources of liquidity to face idiosyncratic liquidity shocks, which in turn reduces their ability to allocate funds to illiquid but more profitable assets. Notwithstanding, decreased interconnectedness also limits the spread of financial distress across the interbank network, which is welfare improving. Given the dual role of interbank connections, the socially optimal network must allow for an efficient liquidity allocation while ensuring that default propagation does not exceed the socially desired level. In order for this goal to be achieved, vulnerable banks should be restrained from participating in the interbank network, while sound ones should not. In frictionless markets, this goal could easily be achieved since lending conditions would completely reflect counterparty risk and/or vulnerable banks would be removed by the regulator. However, in my model, there are two frictions in the banking sector: i) tail risk exposure is banks' private information;[2] and ii) systemically important banks benefit from implicit govern-

[2] As previously argued by Blum (2008), very large banks are complex organizations, whose assets are opaque such that even supervisors may be unable to assess perfectly *ex ante* the exposure to low-probability–high-impact events. Also, if there is no asymmetry of information to begin with, then capital requirements can be replaced with quantitative risk restrictions since bank behavior is perfectly anticipated. Flannery et al. (2013) provides empirical evidence on

ment support. Consequently, the design of interconnectedness-based capital surcharges requires an understanding of how these market frictions affect banks' incentives to become interconnected. That is, the regulator needs to design the requirement such that banks voluntarily select the socially optimal interconnectedness level according to their type.[3]

I find that the resulting incentive compatible interconnectedness-based capital surcharges are characterized by a trade-off between efficiency and financial stability. Moreover, this trade-off is increasing in the correlation between liquidity and return shocks. This is the case because if vulnerable banks are more likely to be hit by a negative liquidity shock they value relatively more interbank connections. Thus, the higher is the incremental profit brought by one additional connection the higher are the capital surcharges required to align incentives, which ultimately reduces the profits of banks that are not vulnerable to tail risk.

The model delivers some potentially important policy implications. First, credible resolution and recovery regimes that lend credibility to ex post failed bank closure policies reduce the capital surcharge needed to realign incentives. This is the case because when the probability of a bailout is reduced vulnerable banks pay higher interbank rates, which reduces the incremental profit brought by one additional connection. Second, stable funding requirements, such as the Net Stable Funding Ratio (NSFR) brought by Basel III, can improve the effectiveness of interconnectedness-based capital requirements since these can reduce the correlation between liquidity and return shocks that worsens the trade-off between efficiency and financial stability. Finally, I also show that while the regulator could use alternatively interconnectedness-dependent deposit insurance fees or default fund contributions to reduce the costs of banking crises, these instruments do not have a differentiated impact on sound and vulnerable banks' incentives to establish interbank connections. While deposit insurance fees or default fund contributions only affect banks profits when illiquid assets succeed capital requirements introduce an opportunity costs in all states of nature. Thus, capital requirements based on interconnectedness still play a role when the informational friction is relevant.

The rest of the paper is organized as follows. Section 2 presents a brief summary of the "additional loss absorbency requirement." Section 3 discusses how this paper fits in the literature. Section 4 describes the basic setup. Section 5 characterizes the equilibrium in the absence of capital regulation. Section 6 analyzes the regulator's problem under complete and incomplete information.

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the relative opaqueness of banks' assets in times of crises. Furthermore, banks of systemic importance may choose optimally to misreport their true tail risk exposures (see Huizinga and Laeven, 2012) since it not only makes them subject to higher capital surcharges but also they may anticipate regulatory forbearance.

[3]In the model, this corresponds to solving the game by backward induction and choosing capital surcharges as the solution to an unconstrained (constrained) optimization problem when the regulator has complete (incomplete) information with respect to banks' tail risk exposure. When the regulator is asymmetrically informed, the constraints of the optimization problem correspond to the participation and incentive compatibility constraints in a standard principal-agent model. In this setting, the incentive compatibility constraints have the particular meaning of being the equilibrium network stability conditions of the pair-wise stability concept (Jackson and Wolinsky, 1996).

Section 7 discusses the model's policy implications. Finally, Section 8 concludes.

2 G-SIBs' "additional loss absorbency requirement"

G-SIBs' "additional loss absorbency requirement" follows an indicator-based approach that takes into account (with equal weight) size, interconnectedness, substitutability, complexity and cross-jurisdictional activity.[4] G-SIBs are then allocated across four buckets as shown in Table 1.

Table 1: G-SIBs list as of November 2015

Bucket	Institution	Bucket	Institution
2.5%	HSBC, JP Morgan Chase	1.0%	Agricultural Bank of China, Bank of China, Bank of New York Mellon, China Construction Bank, Group BPCE, Group Crédit Agricole, Industrial and Commercial Bank of China Limited, ING Bank, Mizuho FG, Nordea, Royal Bank of Scotland, Santander, Société Générale, Standard Chartered, State Street, Sumitomo Mitsui FG, UBS, Unicredit Group, Wells Fargo
2.0%	Barclays, BNP Paribas, Citigroup, Deutsche Bank		
1.5%	Bank of America, Credite Suisse, Goldman Sachs, Mitsubishi UFJ FG, Morgan Stanley		

Source: Financial Stability Board (2015)

Importantly, this allocation is not static, it is subject to periodical revisions. Thus, banks have an incentive to re-optimize their risk profile.[5] When considering their interconnectedness decisions, banks internalize the costs stemming from higher capital requirements. This observation implies that capital surcharges have an impact on the equilibrium interbank network, which can naturally be analyzed using a network formation game.

3 Related literature

This paper is related to several strands of literature. First, it is related to the literature on financial contagion and interbank markets, which gained momentum after the 2007–09 crisis.[6] Allen and

[4]The interconnectedness criterion, which is the focus of this paper, is measured by three (also equally weighted) indicators: intra-financial system assets, intra-financial system liabilities and securities outstanding. See appendix and BCBS (2011) for further details.

[5]"The assessment methodology provides a framework for periodically reviewing institutions' G-SIB status. That is, banks have incentives to change their risk profile and business models in ways that reduce their systemic spillover effect. ... banks can migrate in and out of G-SIB status, and between categories of systemic importance, over time" BCBS (2011, 13–14).

[6]Allen and Babus (2009) provide a useful review. Examples of more recent papers on the topic are Acemoglu et al. (2015), Elliot et al. (2014), Farboodi (2014), Bluhm et al. (2014), Caballero and Simsek (2013), Georg (2013), Ladley (2013), Memmel and Sachs (2013), Zawadowski (2013), Battiston et al. (2012), Anand et al. (2012), Gai et al. (2011) and Gai and Kapadia (2010).

Gale (2000) develop a model where an unanticipated liquidity shock triggers an initial default that propagates through the interbank network of deposits. In their setting, an additional connection contributes to the dilution of the losses imposed on the counterparties of the failed institution. Thus, denser networks tend to exhibit more resilience. Along similar lines, Freixas et al. (2000) study the impact of the structure of the interbank network on financial stability and characterize the regulator's response to banking crises when the failure of a money center bank poses a threat to the rest of the system. Even though my paper follows this "domino view" of the unravelling of financial distress, I focus on the gap between private and social incentives to establish these connections and how regulation can realign those incentives to induce the network that yields the socially optimal level of systemic risk. The discussion on the optimal financial network reverts back to Leitner (2005), who shows that the danger of contagion may motivate healthy banks to rescue counterparties in distress and consequently improve financial stability. In contrast to Leitner (2005), this paper concentrates on the role of the regulator to enhance welfare and not on the private incentives to "bail-ins." It is also closely related to Castiglionesi and Navarro (2007), albeit with a different focus. Following their game theoretic approach, I analyze the role of market frictions in the context of regulatory design. More recently, Allen et al. (2012), also within a network formation game context, show that banks' private incentives to form financial connections may be misaligned with the social ones because financial institutions may not be able to select explicitly the composition of their portfolios leading to a suboptimal network. The market failure in my paper differs from theirs since, in my setting, banks fail to take into account the negative externality that their decisions impose on the deposit insurer/regulator. Bluhm et al. (2014) also study the effects of regulatory measures, such as systemic risk surcharges, on the endogenous formation of the financial network. The authors analyze the effect of macroprudential policy on the endogenous structure of the dynamic network within an agent-based model. The main difference is that in my paper the focus is on the policy design that induces banks to form the socially efficient network in the presence of market frictions. My paper follows a mechanism design approach to network formation related to Mutuswami and Winter (2002). This approach provides a unique perspective on the incentives that banks have to establish connections, which allows the analysis of the importance of complementary instruments for the effectiveness of interconnectedness-based capital requirements. The paper that is closest to mine is Wang (2015) who shows how an externality arising from the inability to write contingent contracts leads to a network that may exhibit both over- and under-connectedness from a social point of view. As in Wang (2015), in my paper the regulator can induce banks to change their interconnectedness decisions since the network is endogenous. However, in my paper the regulator is constrained both because of an informational friction and because it is unable to commit to closing failed banks when financial stability is at stake. This difference allows me to analyze the design of the instruments available to the regulator in the presence of the aforementioned frictions. More broadly speaking, this paper is also related to the role of interbank markets in shaping banks' asset choices. For example, Castiglionesi et al. (2010; 2014) show how depositors' stochastic preference shocks create a role for banks as facilitators of risk-sharing. As in my model, banks use the interbank market to insure against idiosyncratic liquidity shocks, which allows them to hold more profitable but illiquid assets. However, unlike in my model, the financial network does not allow for the propagation of financial distress.

Second, the paper is also related to the literature on systemic risk contribution based on the network position of financial institutions (e.g., Tarashev et al. [2009]; Gai et al. [2011]; Staum [2012]; Drehmann and Tarashev [2013]; Bluhm and Krahnen [2014]). However, unlike these papers based on the Shapley (1950) value, the topology of the network is not assumed to remain fixed. This is particularly important when banks have different incentives to become interconnected and the regulator faces an informational disadvantage.

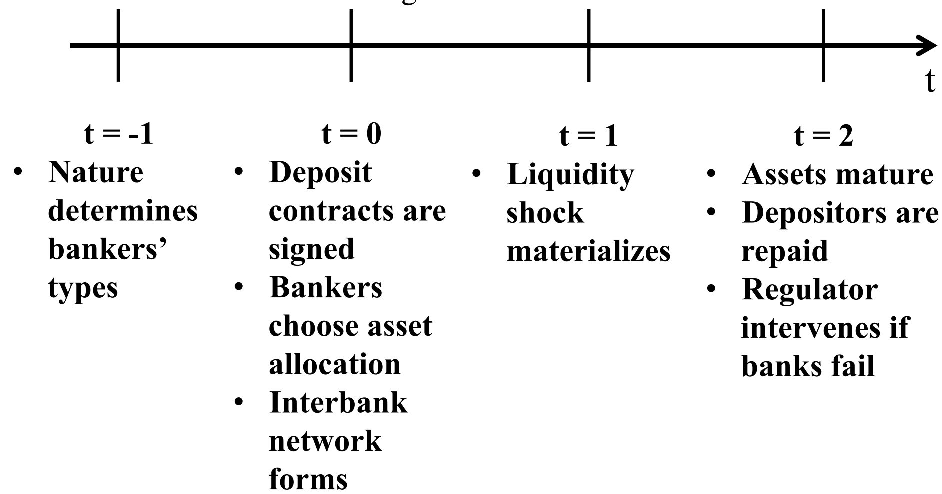
Finally, the paper is also related to the literature on the effects of capital requirements under asymmetric information (e.g., VanHoose [2007] and references therein; Blum [2008]; Vollmer and Wiese [2013]) and incentive-based regulation (e.g., Campbell et al. [1992]; Chan et al. [1992]; Giammarino et al. [2013]).

4 The model

Consider an economy with three regions (indexed by $i = 1,2,3$), each region having a representative bank (b_i) and a continuum of depositors of measure one. Time is discrete and is divided into four dates $(t = -1,0,1,2)$. Depositors are only endowed with one unit of the *numeraire* at $t = 0$ and nothing at subsequent dates. Depositors are fully insured and have a passive role in the model. Banks are owned and managed by a banker. Bankers use their own capital (k) and their depositors' endowments to invest in a mixed portfolio of liquid (y) and illiquid (x) assets. In return, depositors receive 1 unit of the *numeraire* at $t = 2$. Depositors are either repaid by their banker or, in case the banker is not able to, by the deposit insurance fund administrator/regulator/social planner. There is no discounting.

The liquid asset is the standard storage technology and is available in every period. There are two types of illiquid assets: sound and vulnerable. Vulnerable assets are exposed to tail risk, that is, with a small probability they return 0 at $t = 2$. The choice between sound and vulnerable assets depends on the ability of the banker, which is assigned by nature at $t = -1$. Regardless of their type, illiquid assets require additional cash injections at $t = 1$ in order to mature at $t = 2$. To insure against this idiosyncratic liquidity shock, bankers can either hold more liquidity in their balance sheets or establish interbank credit lines. The set of these credit lines constitutes the interbank network. When banks' assets fail to succeed, making the bank unable to repay its creditors, the regulator intervenes either by closing or bailing out the failed bank. The timeline of the model is displayed in Figure 1.

Figure 1: Timeline



I now describe the model starting from date $t = 2$ and then proceed backwards. For convenience, I denote variables specific to each bank with subscripts and I remove them when I am referring to the banking system as a whole.

4.1 Bailouts

In my model, the regulator has the objective of minimizing the cost of bank failures. When banks are unable to repay their creditors, the regulator chooses between bailing out and closing the bank. A bailout implies that creditors are repaid in full. I denote by $\tilde{v}$ the cost of bailing out all creditors with the exception of depositors. Alternatively, the regulator can choose to liquidate the failed bank and bear, in addition to the deposit insurance costs, the systemic costs of bank failures. I assume that these costs are an increasing and (discrete) convex function of the number of failed banks and denote them by $\eta\,(\#defaults)$. As in Freixas (1999) and Gong and Jones (2013), I treat these costs as exogenous. Even though treated as exogenous here, these costs can be rationalized as the liquidation costs of illiquid assets at firesale prices in the context of a longer time horizon model as in Acharya and Yorulmazer (2007; 2008) where failed banks' assets have a positive continuation value if they are sold to outside investors and an even higher one if they are acquired by surviving banks. The assumption that these costs are increasing and convex in the number of failed banks can be justified as the result of the scarcity of surviving banks' resources to acquire failed banks' illiquid assets as argued by Acharya and Yorulmazer (2008).

4.2 Return shocks

The illiquid asset may be subject to a return shock at maturity, which occurs at $t = 2$, if it is vulnerable to tail risk. An asset is vulnerable if it yields $R(> 1)$ at maturity per unit of the *numeraire* invested at $t = 0$ with probability $\beta(< 1)$ and nothing otherwise.[7] Conversely, an asset is sound if it returns R at maturity per unit of the *numeraire* invested at $t = 0$ with probability one. Table 2 displays assets' cash flows.

Table 2: Assets' cash flows

Asset		$t=0$	$t=1$	$t=2$
Illiquid asset (x)	sound	-1	0	R
	vulnerable	-1	0	$\begin{cases} R & \text{with prob. } \beta \\ 0 & \text{otherwise} \end{cases}$
Liquidity (y)		-1	1	-
		-	-1	1

Even though an illiquid asset's quality is heterogeneous ex post, without additional information, bankers are unable to distinguish between vulnerable and sound assets at $t = 0$. Moreover, I assume that the liquidation value of this asset before maturity is zero.[8] Notwithstanding, bankers can eliminate their exposure to tail risk at a cost.[9] Let $C(\theta_i)$ denote the cost to banker i of screening

[7]One can think of sound and vulnerable assets as a pool prime mortgages and collateralized debt obligations, respectively. During normal times (i.e., pre-crisis), these assets received the same rating. However, after the crisis, their returns were significantly different. Griffin and Tang (2012) show that a sample of corporate bonds and collateralized debt obligations (CDOs), which received the AAA rating before the crisis, exhibited significant heterogeneity in their ratings after the crisis. While the majority of corporate bonds retained the AAA rating, roughly half of the sample CDOs were either downgraded to non-investment grade or defaulted.

[8]This assumption can be motivated by considering the loss in value brought by asymmetry of information with respect to asset quality.

[9]For example, instead of relying only on credit ratings, banks can invest in internal risk models that provide a better assessment of asset's cash flows. This distinction in Morrison and White (2005) is motivated by differences in access to monitoring technologies. Also, note that assuming that the probability of success is equal to one is without real loss of generality. All results follow from the difference between success probabilities and not from their levels. This assumption can be further motivated by the contrasting resilience that financial institutions displayed during the 2007 crisis. As Senior Supervisors Group (2008, 3) puts it, "firms that faced more significant challenges in late 2007 generally had not established or made rigorous use of internal processes to challenge valuations. They continued to price the super-senior tranches of CDOs at or close to par despite observable deterioration in the performance of the underlying RMBS collateral and declining market liquidity. Management did not exercise sufficient discipline over the valuation process: those firms generally lacked relevant internal valuation models and sometimes relied too passively on external views of credit risk from rating agencies and pricing services to determine values for their exposures. Given that the firms surveyed for this review are major participants in credit markets, some firms' dependence on external assessments such as rating agencies' views of the risk inherent in these securities contrasts with more sophisticated internal processes they already maintain to assess credit risk in other business lines. Furthermore, when considering how the value of their exposures would behave in the future, they often continued to rely on estimates of asset correlation that reflected more favorable market conditions."

sound assets from a pool of seemingly identical assets. If the banker chooses not to select a sound asset, the banker is left with a vulnerable asset but does not incur $C(\theta_i)$. Moreover, I assume that $C(\theta_L) > C(\theta_H)$. That is, high-ability bankers have a comparative advantage in screening sound assets.

I assume that banks know their own type, but outsiders only observe ex ante the distribution of Θ. As a baseline, I assume b_1 and b_3 are managed by low-ability bankers and b_2 by a high-ability banker, respectively. The assignment of b_2 as the sound bank is without loss of generality; only the distribution of the types is relevant. The particular choice of the distribution of $\Theta = \{\theta_1, \theta_2, \theta_3\}$ is discussed in the conclusion.

4.3 Liquidity shocks

Before these illiquid assets mature, however, bankers face the need to refinance the illiquid share of their portfolios at $t = 1$. Without this injection of cash, illiquid assets fail to mature, that is, they return 0 at $t = 2$. Let $\gamma_i(\omega) \in \{\gamma_L, \bar{\gamma}, \gamma_H\}$ denote the amount of liquidity the banker i needs to refinance the illiquid asset at $t = 1$ in state ω, with $\gamma_H > \gamma_L$ and $\bar{\gamma} = (\gamma_H + \gamma_L)/2$. I assume these are "pure" liquidity shocks. If banker i is required to inject an above-average cash amount at $t = 1$, the above-average cash injection is returned at $t = 2$. That is, if at $t = 1$, the banker faces a shock equal to γ_L, then the asset at maturity returns $xR - (\bar{\gamma} - \gamma_L)$ in success states. Table 3 describes the distribution over the set of liquidity shocks Ω (with typical element ω).

Table 3: Regional liquidity shocks

ω	Prob.	b_1	b_2	b_3
ω_1	ϕ_1	γ_L	$\bar{\gamma}$	γ_H
ω_2	ϕ_2	γ_L	γ_H	$\bar{\gamma}$
ω_3	ϕ_3	$\bar{\gamma}$	γ_L	γ_H
ω_4	ϕ_4	$\bar{\gamma}$	γ_H	γ_L
ω_5	ϕ_5	γ_H	γ_L	$\bar{\gamma}$
ω_6	ϕ_6	γ_H	$\bar{\gamma}$	γ_L

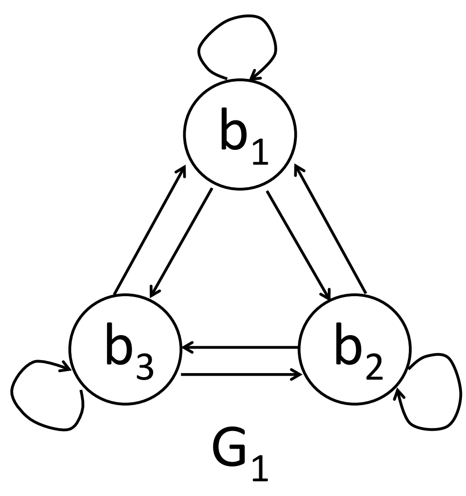
These liquidity shocks can be rationalized as the result of guarantees provided by banks to off-balance sheet entities. Examples of these entities are conduits that issue Asset Backed Commercial Paper (ABCP) to finance the underlying assets and benefit from explicit liquidity guarantees from commercial banks. Since ABCP has a short maturity and is used to finance assets with long maturities, conduits are exposed to rollover risk. This risk is mitigated to some extent by the liquidity guarantees provided by sponsoring banks. Thus, in this context, a high liquidity shock, $\gamma_i = \gamma_H$, can be interpreted as a run experienced by the ABCP issuer that requires the liquidity support of the bank i.[10] Importantly, this interpretation of the liquidity shocks is not inconsistent with the payoff structure defined for the illiquid assets. As Acharya et al. (2013) show, the guarantees provided by banks to ABCP conduits did not produce the expected substantial transfer of risk. This meant that the risk of the underlying assets returned to banks' balance sheets.

I assume that idiosyncratic liquidity shocks are uniformly distributed and are independent of return shocks. That is, $\phi_1 = \phi_2 = ... = \phi_6 = \frac{1}{6}$. In Section 7, this assumption is replaced with a more realistic one where liquidity and credit shocks are allowed to be correlated. Combining return and liquidity shocks, the state space is defined as the Cartesian product of credit and liquidity shocks $\left(\Omega \times \tilde{R}\right)$ with typical element $(\omega, \tilde{r})$, where ω and $\tilde{r}$ are the sets of realized asset returns and liquidity shocks, respectively.

4.4 Interbank credit lines

To face these liquidity shocks, banks can invest in the storage technology or establish ex ante bilateral credit lines (see Cocco et al., 2009). Let $\mathscr{B}$ be the set of borrowers and $\mathscr{L}$ the set of lenders. These credit lines are directed[11] such that a bank can be a borrower $(b_i \in \mathscr{B})$ without being simultaneously a lender $\left(b_j \in \mathscr{L}\right)$. For example, in states $(\omega_6, \tilde{r})$, through a credit line, b_1 can obtain liquidity from b_3. In this example, the credit line is represented as $\{(b_3, b_1)\}$ or graphically by $b_3 \to b_1$. Figure 2 depicts the network where all banks are connected via bilateral credit lines.

Figure 2: Complete network, G_1



[10]Covitz et al. (2013) document the stress experienced in the ABCP market during the financial crisis and its potential implications for the stability of the financial system.

[11]Note that, in this context, directed credit lines have a different interpretation of what is given in the literature of directed networks. In my model, even though credit lines, or arcs, are directed, their existence requires agreement between two banks.

The collection of all these credit lines constitutes the interbank network. In network theory terminology, the interbank market is a directed homogeneous network (G).

Definition 1. *Interbank network: An interbank network G is a subset of $\mathscr{G} := (\mathscr{L} \times \mathscr{B})$ with typical element (b_i, b_j) such that, for all potential lenders $b_i \in \mathscr{L}$, the section of G at b_i given by*

$$G(b_i) := \{b_j \in \mathscr{B} : (b_i, b_j) \in G\}$$

is non empty. Moreover, let $z_i^j(G, \omega)$ denote the amount of liquidity available to bank i through the credit line with j in state $(\omega, \tilde{r})$, with $z_i^i(G, \omega) = 0$ by convention.

Even though these interbank credit lines allow banks to insure against liquidity shocks, the existence of vulnerable banks also exposes lenders to the potential of a default by contagion. A default by contagion occurs whenever the lender is unable to fulfill its obligations with its own depositors due to the failure of a borrower. Since the model assumes pure liquidity shocks, the liquidation value of the lender's portfolio must be sufficient to repay depositors in order to remain solvent. Given that bank i can only be a lender if the liquidity shock, γ_i, at the interim date is less than y, the residual value at maturity $(1-y)R - (\bar{\gamma} - \gamma_L)$ needs to be greater than 1 to ensure solvency in case the borrower defaults.[12]

In the absence of market frictions, the interest rate on these credit lines would reflect the borrower's true exposure to tail risk. Let $\tilde{\beta}_i^j \geq \beta$ denote the effective probability of success of borrower i from lender $j's$ perspective. This probability can differ from the fundamental probability of success for two reasons. First, the expectation of government support in states where tail risk materializes dampens market discipline. Anticipating that the borrower will be bailed out leads to a higher effective probability of success and consequently reduces the interest rate required by the lender. Second, since tail risk exposure is private information, the interbank interest rate captures the average counterparty risk instead of the borrower's individual counterparty risk implied by his exposure to tail risk. This assumption is based on the empirical evidence that, prior to the financial crisis, market signals were distorted by implicit government guarantees (see Miller et al. 2015). The formal derivation of the equilibrium value of $\tilde{\beta}$ is provided in Section 5. Thus, assuming, for the sake of simplicity, that the borrower holds all the bargaining power,[13] the expected interbank interest rate is given by

[12] These credit lines can be substantial in practice. Upper (2011) reports that interbank loans can amount to several multiples of banks' equity in some European countries prior to the crisis. Alternatively, these credit lines can be thought of as over-the-counter (OTC) contracts in general that expose banks to the failure of their counterparties.

[13] Any other interest rate within the banks' reservation price range, for example, resulting from Nash bargaining, would not qualitatively change the results. For an example of how Nash bargaining can be used in a network context see Braun and Gautschi (2006).

$$r_{IB,i}\left(G,y,k,\tilde{\beta},R\right)=\sum_{j\in G_i^-}\tilde{\phi}_j\frac{1-\tilde{\beta}_i^j}{\tilde{\beta}_i^j}\left\{\left[\left(1+k_j-y_j\right)R-1-\delta k_j\right]\times 1_{|contagion_j}+\left(\bar{\gamma}-\gamma_L\right)\times\left(1-\mathbf{1}_{|contagion_j}\right)\right\}, \tag{1}$$

where G_i^- is the set of all banks that are potential lenders to bank i; δ is the opportunity cost of capital; $\tilde{\phi}_j=\sum_{\omega\in\Omega}\left[\mathbf{1}_{|y_i+z_i^j(G,\omega)\geq\gamma_i(\omega)}-\mathbf{1}_{|y_i\geq\gamma_i(\omega)}\right]/6$ is the probability of occurrence of the state where i can only survive the liquidity shock by drawing on the credit line with j; and $1_{|contagion_j}$ is an indicator function that takes the value 1 if j is not able to repay his depositors as a consequence of the loss sustained on the interbank credit line with the default of i. y and k are the liquidity and capital choices of all banks in the system.

Essentially, equation (1) can be decomposed into two terms. The first is the interest rate j requires in order to lend to i when j defaults in consequence of the default of i given the size of the interbank credit lines. This interest rate makes j indifferent between lending and not lending to i. It is obtained by equating the expected payoff for j when i does not default, $\tilde{\beta}_i^j\left(r_{IB,i}+\left(1+k_j-y_j\right)R-1-\delta k_j\right)$, with the payoff for j when the banker does not lend, $\left(1+k_j-y_j\right)R-1-\delta k_j$.[14] The second term is the interest rate j requires in order to lend to i when j does not default in consequence of the default of i given the size of the interbank credit lines. If the loss j sustains with the default of i is not sufficient to compromise i's ability to repay its depositors, then j only loses the amount loaned to i. As in the previous term, the interest rate is the one that makes j indifferent to lending or not lending.

4.5 Intermediation

In addition to bilateral liquidity insurance, the interbank network also allows for intermediation. Intermediation extends the amount of liquidity, $z_i\left(G,\omega\right)$, available to bank i through the network G in states $\left(\tilde{r},\omega\right)$ beyond what direct lenders can provide through bilateral credit lines. For example, even in the absence of a credit line between b_1 and b_3, b_1 can still obtain the needed liquidity provided that both b_1 and b_3 have opposite credit lines with b_2. In describing how intermediation operates in this model, it is useful to define a path. Formally, a sequence of credit lines $\left\{\left(b_i,b_j\right)_l\right\}_{l=1}^2$ forms a path between b_i and b_m if

$$\exists\left\{\left(b_i,b_j\right)_1,\left(b_j,b_m\right)_2\right\}\subseteq G,$$

[14] Note that, the choice of the type of illiquid asset by the lender does not play a role in the determination of r_{IB}. This is the case because return shocks are assumed to be independent across banks, such that both the expected payoffs of lending and not lending are adjusted equally by the lender's own probability of default.

with $b_i \neq b_j \neq b_m$.

In states where banks cannot obtain liquidity directly from their counterparties, they can overcome the liquidity shortage if a bank with excess liquidity can provide it through an intermediary. For this to be possible, the bank with the liquidity shortage and the one with excess liquidity must be connected through a path of length 2. In order for counterparty risk involved in intermediation to be fully accounted for, I assume the interbank network is common knowledge.[15]

When bankers intermediate a transfer of funds, they have to borrow the needed liquidity from the surplus bank to then lend it to the deficit bank. Thus, under the assumption that the interbank network is common knowledge, the expected fees owed to the intermediary reflect not only the borrower's expected risk, but also the expected counterparty risk of the intermediary. For simplicity, I keep the assumption that the borrower holds all the bargaining power such that both the lender and the intermediary are only compensated for the counterparty risk involved in providing liquidity to the borrower. Thus, the fees the borrower pays in addition to the interest rate on the credit line are given as follows:

$$\varepsilon_i\left(G, y, k, \tilde{\beta}, R\right) =$$

$$\begin{cases} \sum_{m\in\tilde{\mathscr{M}}} \frac{1-\tilde{\beta}_i^m}{\left(\tilde{\beta}_i^m\right)^2}\tilde{\phi}_m\left[(1+k_m-y_m)R-1-\delta k_m\right]\times\mathbf{1}_{|contagion_m}+ & \text{if } i \text{ borrows via} \\ \sum_{j\in\tilde{\mathscr{I}}} \frac{1-\tilde{\beta}_i^j}{\tilde{\beta}_i^j}\tilde{\phi}_j\left(\bar{\gamma}-\gamma_L\right)\times\left(1-\mathbf{1}_{|contagion_j}\right) & \text{intermediary } j \\ 0 & \text{if } i \text{ borrows from} \\ & \text{direct lender} \end{cases},$$

where $m \in \tilde{\mathscr{M}} \setminus \left\{G_i^-\right\}$ is any bank in the set of banks with a liquidity surplus that is not a potential lender of i and $j \in \tilde{\mathscr{I}}$ is any intermediary in the set of banks positioned in the path between i and m.[16]

4.6 Banker's problem

Given the distribution of the return on the assets, the liquidity shocks and the closure policy of the regulator, banker i's expected profits at $t = 0$ are given by

[15]This assumption is not strictly necessary. Intermediation fees can be derived based on only a limited knowledge of the network. See Caballero and Simsek (2013) for an exposition on how Knightian uncertainty can be accounted for in the context of a financial network.

[16]See the derivation of the interbank interest rate for the details on this function.

$$\mathbb{E}\left[\pi_i\left(G,k,y,\theta,s\right)\right]=\begin{cases}\begin{array}{c}\left[\left(1+k_i-y_i\right)R-1-r_{IB,i}\left(G\right)\right]\phi_i\left(G\right)-\\ \varepsilon_i\left(\cdot\right)-\delta k_i-C\left(\theta_i\right)\end{array} & if\ s=sound\\ \begin{array}{c}\left[\left(1+k_i-y_i\right)R-1-r_{IB,i}\left(G\right)\right]\beta\phi_i\left(G\right)-\\ \varepsilon_i\left(\cdot\right)\beta-\delta k_i\end{array} & if\ s=vulnerable\end{cases}, \qquad (2)$$

where $\phi_i\left(G\right)=\sum_{\omega\in\Omega}\left[\sum_{l\in\{b_1,b_2,b_3\}}\mathbf{1}_{|y^i+z_i^l(G,\omega)\geq\gamma^i(\omega)}\right]/6$ is the network dependent probability of survival to the liquidity shock of bank i and $\varepsilon_i\left(G,y,k,\tilde{\beta},R\right)$ are the net intermediation fees.

If the banker chooses to invest in the illiquid sound asset, the expected profit has four components. $(1+k_i-y_i)$ is the return on the amount invested in the illiquid asset net of the interest rate on deposits and credit lines. However, this return is only realized if the bank survives the liquidity shock at the interim date, which occurs with probability $\phi_i\left(G\right)$. $\varepsilon_i\left(\cdot\right)$ are the net intermediation fees; δk_i is the opportunity cost of capital; and $C\left(\theta_i\right)$ is the cost of the screening technology.

If the banker chooses to invest in the vulnerable illiquid asset, expected profit changes. The banker no longer faces $C\left(\theta_i\right)$, but in addition to the liquidity shock also faces the return shock. That is, the illiquid asset matures only with probability β.

Then, the optimization problem solved by bankers can be described as

$$\max_{G_i,k_i,y_i,s_i}\mathbb{E}\left[\pi_i\left(G,k,y,\theta,s\right)\right] \qquad (3)$$

s.t.

$$1+k_i\geq y_i\geq 0 \qquad (4)$$

$$k_i\geq 0 \qquad (5)$$

where equations (4) and (5) are the feasibility and capital non-negativity constraints, respectively. Note that, in addition to the balance sheet allocation, bankers also make network proposals that affect the equilibrium interbank network G.

4.7 Equilibrium

This equilibrium network is defined using the pair-wise stability concept of Jackson and Wolinsky (1996).

Definition 2. *Pair-wise stable network: An interbank network $G\in\mathcal{G}$ is pair-wise stable (PWS) if*

(i) for all $(i,j)\in G$ ($i,j\in\{b_1,b_2,b_3\}$ and $i\neq j$) we have

$$\mathbb{E}\left[\pi_k\left(G,\cdot\right)\right] \geq \mathbb{E}\left[\pi_k\left(G\backslash\left(i,j\right),\cdot\right)\right],\ \textit{with}\ k=i,j$$

and (ii) for all $(i,j) \notin G$ $(i,j \in \{b_1,b_2,b_3\}$ *and* $i \neq j)$ *we have*

$$\mathbb{E}\left[\pi_j\left(G,\cdot\right)\right] > \mathbb{E}\left[\pi_j\left(G\cup\left\{(i,j)\right\},\cdot\right)\right] \Rightarrow \mathbb{E}\left[\pi_i\left(G,\cdot\right)\right] < \mathbb{E}\left[\pi_i\left(G\cup\left\{(i,j)\right\},\cdot\right)\right].$$

Statement (i) requires that it is not possible for either of the two banks to have a profitable deviation by severing one connection. That is, the additional credit line established between i and j makes both banks at least as well off as without the liquidity insurance opportunity. Statement (ii), in its turn, requires that, if one of the parties is strictly better off with the deviation, then it must be that the other party is strictly worse off. Thus, adding a credit line requires that both banks agree; however, severing a connection can be done unilaterally.

Definition 3. *Equilibrium: An equilibrium in the banking system is defined as a set of portfolio allocations, capital holdings and a set of PWS interbank networks that solves problem (3) subject to constraints (4) and (5) for each banker* $i \in \{b_1,b_2,b_3\}$*, and a closure policy that minimizes the ex post costs to the regulator for solving banking crises.*

4.8 Assumptions

To preserve the economic interest of the model such that contagion is a regulatory concern, as suggested by the policy under analysis, I make the following assumptions:

Assumption 1. $\delta > R$.

Assumption 1 states that the opportunity cost of capital exceeds the return of the illiquid asset in success states. This assumption ensures that the banker's optimization problem has an interior solution.

Assumption 2. $\gamma_H > \frac{1+\gamma_L}{2} \wedge \frac{1+\bar{\gamma}-\gamma_L}{1-\bar{\gamma}} > R > \frac{1-(\bar{\gamma}-\gamma_L)}{1-\gamma_H}$.

Assumption 2 has a dual role. It ensures that, in isolation, banks do not wish to fully insure against the liquidity shock. Also, it provides the necessary conditions for defaults by contagion.

Assumption 3. *(a)* $C(\theta_L) > \frac{2}{3}(1-\beta)\left[(1-\bar{\gamma})R-1\right]$. *The cost of the screening technology is sufficiently high for a low-ability banker to prefer the vulnerable asset even when the banker does not have access to the interbank market.*

(b) $C(\theta_H) < (1-\beta)\left\{\left[(1-\bar{\gamma})R-1-r_{IB,i}(G_1,\bar{\gamma},\cdot)\right]\right\}$. *The cost of the screening technology is sufficiently low for a high-ability banker to prefer the sound asset even when the banker has full access to the interbank market.*

Assumption 3 ensures fundamental risk heterogeneity of banks' assets.

Assumption 4. $\beta \geq \frac{1+\sqrt{13}}{6}$.[17]

Finally, Assumption 4 states that the probability of success is high enough to ensure that vulnerable banks are not rationed in the interbank market.

5 Equilibrium in the absence of capital regulation

In this section, I characterize the equilibrium by analyzing the capital, liquidity, illiquid asset and network connectivity choices that arise in equilibrium when banks take the regulator's optimal closure policy into account and there is no capital regulation. I start by analyzing the optimal closure policy.

5.1 Optimal closure policy

The optimal closure policy minimizes the costs of bank failures. These costs, however, depend on the state of nature and the structure of the interbank market. Thus, the decision to bail out or close a failed bank may depend on whether the banking system is weak (i.e., $\tilde{r} = (0,R,0)$) or strong (i.e., $\tilde{r} = (0,R,R)$ or $\tilde{r} = (R,R,0)$).

Let us first consider the states of nature in which the banking system is weak. Since a bailout does not prevent the failure of a counterparty that has failed fundamentally, I assume that the systemic costs are such that the regulator does not bail out a vulnerable bank when its failure does not lead to the failure by contagion of a fundamentally solvent counterparty.[18] Conversely, when the failure of the vulnerable bank leads to the failure of the sound bank, the costs of closing the failed bank are equal to $\eta(3)+3-(1-y)R$, which comprise the sum of the systemic costs of three bank

[17]Note that this assumption is a sufficient condition for the participation of vulnerable banks in the interbank market. A less restrictive condition applies for the effective probability of success, which increases the fundamental probability of success via the anticipation of bailouts and the informational friction in the interbank market. The full derivation of this assumption is in the appendix.

[18]Note that, even though ex ante the regulator cannot distinguish between sound and vulnerable banks, state of nature becomes common knowledge when the return shocks realize.

failures and the costs of deposit insurance net of the liquidation value of the sound bank's assets. If the regulator chooses to bail out the bank instead, the costs are equal to $\eta(1)+2+\tilde{v}$, which comprise the costs of closing the failed isolated bank and the bailout of all of the creditors of the failed connected bank. Thus, a bailout is ex post optimal whenever

$$\eta(3)-\eta(1)>(1-y)R-1+\tilde{v}. \tag{6}$$

However, when the banking system is strong, the costs of closing a failed connected bank amount only to $\eta(2)+2-(1-y)R$, while the bailout costs amount to $\tilde{v}+1$. In these states of nature, a bailout is ex post optimal whenever

$$\eta(2)>(1-y)R-1+\tilde{v}. \tag{7}$$

The following proposition summarizes these results.

Proposition 1. *The ex post optimal closure policy is as follows:*

(i) if both conditions (6) and (7) hold, then the regulator always bails out a connected failed bank;

(ii) if equation (6) is satisfied but equation (7) is not, then the regulator only bails out a connected failed bank if the banking system is weak;

(iii) if only condition (7) is satisfied, then the regulator bails out the connected failed bank only when the banking system is strong;

(iv) if neither conditions hold, the regulator closes the failed bank regardless of the state of banking system.

Note that the ex post optimal closure policy does not necessarily coincide with the ex ante one. Ex ante the regulator would like to commit to close failed banks, which would eliminate the advantages that vulnerable banks benefit from with the expectation of a bailout and which could potentially induce vulnerable banks to become less interconnected. However, ex post, the regulator may find it optimal to choose a bailout. This time-inconsistent problem motivates additional regulatory measures that will be treated in sections 6 and 7.

Since the probability of a bailout may depend on the solvency of the lender and the state of nature, the probability that the counterparty i will be able to fulfill its obligations with respect to lender j, denoted by $\tilde{\beta}_i^j$, may depend on the solvency of j. Thus, the cases described in Proposition 1 have a direct correspondence with $\tilde{\beta}_i^j$ as specified in the next Lemma.

Lemma 1. *The effective probability of success, which combines the fundamental probability of default, the probability of a bailout and the asymmetry of information in the interbank market, is in case* *(i)* $\tilde{\beta}_i^v = \tilde{\beta}_i^s = 1$. *Since failed banks are always bailed out, there is no counterparty risk.*

(ii) $\tilde{\beta}_i^v = (1+\beta)/2$ *and* $\tilde{\beta}_i^s = 1-\beta(1-\beta)$. *Bailouts only reduce the counterparty risk that sound lenders are exposed to.*

(iii) $\tilde{\beta}_i^v = \beta(2-\beta)+(1-\beta)^2/2$ *and* $\tilde{\beta}_i^s = \beta(2-\beta)$. *Bailouts reduce the counterparty risk that all lenders are exposed to.*

(iv) $\tilde{\beta}_i^v = (1+\beta)/2$ *and* $\tilde{\beta}_i^s = \beta$. *In the absence of bailouts, the effective probability of default is the conditional average given the lender's own type.*

Proof. The proof is in the appendix. □

The empirical evidence (see, for example, Völz and Wedow 2011, Ueda and Weder di Mauro 2013 and Santos 2014) supports the claim that large banks have a funding advantage. However, the bankruptcy of Washington Mutual shows that even large banks are not immune to failure. Thus, it seems unreasonable to assume that either bailouts are non-existent or that they are always a reality. Moreover, based on insights from the government interventions that occurred during the financial crisis and the regulatory reform that followed it, it can be argued that interconnectedness may play a role in the bailout decision.[19] Consequently, I start by assuming that the regulator bails out failed banks when the banking system is weak and then I verify the consistency of this policy with the equilibrium decisions of banks. It is also worth mentioning that, even though the effective probability of default may differ across banks, the possibility of bailouts distorts interest rates such that these are a poor indicator of risk-taking as found in the empirical literature.

5.2 Bankers' choices

Given the ex post optimal closure policy of the regulator, the equilibrium private choices are as follows.

Lemma 2. *Capital choice: Under Assumption 1, in any unregulated equilibrium, banks choose to hold* $k^\star = 0$.

Proof. The proof is in the appendix. □

The result that banks do not wish to hold any capital follows directly from the assumption that the opportunity cost of capital exceeds the return of the illiquid asset in the success states of nature. That is, regardless of the bank illiquid asset's type, an additional unit of capital unambiguously reduces profits. Moreover, since interbank credit lines are priced such that banks with a cash surplus are indifferent to lending or not lending, lenders do not wish to hold capital to withstand the default of a borrower.

[19]The interconnectedness of AIG was indicated as one of the reasons of why it was bailed out. See Bernanke (2009).

I turn now to the choice of liquidity. Bankers can either choose to use credit lines to insure against the liquidity shock or hold enough liquidity to cover the negative liquidity shock $\gamma = \gamma_H$. The liquidity allocation $y = \gamma_H$ involves a risk-return trade-off. This allocation allows banks to survive the liquidity shock in all states of the world at the cost of a less profitable portfolio. Lemma 3 characterizes the liquidity allocation in isolation.

Lemma 3. *Liquidity choice in isolation: Under Assumption 2, the liquidity allocation in isolation is equal to the average liquidity shock.*

Proof. The proof is in the appendix. □

Assumption 2 ensures that banks choose to hold in isolation the amount of the average shock in liquidity. Furthermore, without aggregate uncertainty, holding $\bar{\gamma}$ units of liquidity is sufficient to ensure that all banks survive the liquidity shock, provided that the interbank network can redistribute it efficiently. Thus, provided that the effective counterparty risk is low enough, banks will choose $y = \bar{\gamma}$ and use the interbank network to insure against liquidity shocks. This allows them to preserve a more ex ante profitable portfolio without risking failing to re-finance their illiquid asset. This situation amounts to holding the banks' balance sheet constant while allowing the use of interbank credit lines to insure against the liquidity shocks. Given the liquidity allocation, the size of the interbank credit lines is immediately determined. Note $y = \bar{\gamma}$ implies that each credit line extended by the liquidity surplus bank j to liquidity deficit bank i amounts to $z_i^{j\star}(G,\omega) = \gamma_H - \bar{\gamma} = \bar{\gamma} - \gamma_L$, the remainder needed to cover the adverse liquidity shock γ_H.

In characterizing the equilibrium, I assume that $y^\star = \bar{\gamma}$ and then, show under which conditions this is the case. I start by analyzing how a fundamental default takes place and then, after determining how counterparty risk is priced into these interbank connections, I ask whether banks wish to behave as I claim they do. Given that a bank can only be a lender if the liquidity shock at the interim date is less than $\bar{\gamma}$ when $y = \bar{\gamma}$, the return at maturity $(1 - \bar{\gamma})R - (\bar{\gamma} - \gamma_L)$ needs to be greater than 1 to ensure solvency. Assumption 2 ensures that this is not the case, which implies that defaults by contagion may occur in equilibrium. This assumption is a sufficient condition for the probability of a default cascade to be positive. That is, if a borrower obtains the liquidity through an intermediary, both the intermediary and the original lender may default by contagion.[20]

Suppose $y^\star = \bar{\gamma}$, Assumption 2 and Lemma 2 then imply that in equilibrium,

[20] This is undoubtedly a strong assumption, but the model's qualitative results only require that regulator's costs in case of default are positively related to vulnerable banks' interconnectedness. Even though first-round losses may only have a limited impact on the financial stability, as argued by Glasserman and Young (2015) for example, second-round effects may include a downward spiral in asset prices (fire-sales) that may compromise financial stability. Since G-SIBs additional capital surcharges specifically identify interconnectedness as a relevant factor, this assumption follows from the instrument under analysis.

$$r^{\star}_{IB,i}\left(G,y,k,\tilde{\beta},R\right)=\sum_{j\in G_i^-}\frac{\tilde{\phi}_{j,\omega}}{\phi_i(G)}\frac{1-\tilde{\beta}_i^j}{\tilde{\beta}_i^j}\left[(1-\bar{\gamma})R-1\right], \tag{8}$$

and

$$\varepsilon^{\star}_i\left(G,\omega,y,k,\tilde{\beta},R\right)=\begin{cases}\sum_{j\in\tilde{\mathscr{I}}}\frac{1-\tilde{\beta}_i^j}{\left(\tilde{\beta}_i^j\right)^2}\left[(1-\bar{\gamma})R-1\right] & \text{if } i \text{ borrows via intermediary}\\ 0 & \text{if } i \text{ borrows from direct lender}\end{cases}. \tag{9}$$

When $\beta^\star$ is high enough there are positive profits in using intermediation to offset a liquidity shock that exceeds the bank's liquidity holdings, provided that all banks hold $y=\bar{\gamma}$ in equilibrium. That is, banks will choose $y^\star=\bar{\gamma}$ and insure idiosyncratic shocks using interbank connections. That is,

Lemma 4. *Liquidity choice: Under Assumptions 2–4, in any equilibrium without capital regulation banks choose to hold $y^\star=\bar{\gamma}$, and the liquidity allocation is independent of the interbank network.*

Proof. The proof is in the appendix. □

Since bankers with a high cost of asset selection exist, defaults may occur in equilibrium. Moreover, since the model allows for intermediation, the default of a borrower may lead to a default cascade — default of its (direct and indirect) interbank counterparties — in the spirit of Allen and Gale (2000).

After $k^\star$ and $y^\star$ have been determined, all that remains to be chosen by the banker is the quality of the illiquid asset and the interbank connections. Formally, the banker's expected profit given a network G and ability θ_i when the banker is choosing optimally the quality of the illiquid asset is given by

$$\pi_i^\star(G,\theta_i)=\max_{s_i}\mathbb{E}\left[\pi_i(G,k^\star,y^\star,\theta,s)\right].$$

Given $\pi_i^\star(G,\theta_i)$ and Assumption 3, all that remains is to characterize the interbank network, which is done in Proposition 2.

Proposition 2. *Suppose assumptions 2–4 hold; then without regulation, high- (low-) ability bankers choose the sound (vulnerable) illiquid asset, $k^\star=0$, $y^\star=\bar{\gamma}$ and the complete network, G_1, is PWS.*

Proof. Note that

$$\frac{\Delta\pi_i^\star(\cdot)}{\Delta|G^-|}=\left[(1-\bar{\gamma})R-1\right]\frac{\Delta\phi(G)}{\Delta|G^-|}-\frac{\Delta r_{IB,i}(G)}{\Delta|G^-|}-\frac{\Delta\varepsilon_i^\star(G)}{\Delta|G^-|}>0,$$

where $|G^{-}|$ is the number of incoming credit lines available to bank i. $\square$

From Assumption 4, it follows that an additional incoming credit line increases expected profit even if it leads a borrower to incur intermediation fees. Thus, a bank always wishes to establish an additional incoming credit line. Moreover, since the interest rate reflects the implicit guarantees of an adjusted probability of default, a potential lender is always willing to extend a credit line to another bank.

6 Capital regulation

In the previous section, I showed that the complete network is pair-wise stable in the absence of regulation. This implies that, in an equilibrium without capital regulation, banks fail to internalize the financial distress costs that are imposed on the regulator. Thus, they may choose to become overly interconnected from a social point of view. In this section, I analyze the conditions under which this is true both when the regulator has complete and incomplete information with respect to banks' tail risk exposure.

I assume that the regulator maximizes total welfare when setting the capital requirements schedule. Following Giammarino et al. (1993), total welfare is expressed as the sum of the banks' expected profits net of the expected financial distress costs, $\mathbb{E}\left[\rho\left(G,\theta,\omega,\tilde{r}\right)\right]$, augmented by the deadweight loss, $\lambda > 0$, introduced by funding $\rho\left(G,\theta,\omega,\tilde{r}\right)$ using distortionary taxation (see Freixas [1999]; Acharya and Yorulmazer [2007]). Financial distress costs, $\rho\left(G,\theta,\omega,\tilde{r}\right)$, include both deposit insurance costs and the systemic costs that lead to the optimal closure policy analyzed in subsection 5.1. Formally, the total welfare function is given by

$$\mathbb{W}\left(G,y,\theta,k\right)=\sum_{i=1}^{3}\pi_i^{\star}\left(G,\theta_i;y,k\right)-\left(1+\lambda\right)\mathbb{E}\left[\rho\left(G,\theta,\omega,\tilde{r}\right)\right]+3,$$

where

$$\rho\left(G,\theta,\omega,\tilde{r}\right)=\mathbb{E}\left[\#defaults|G,\theta,\omega,\tilde{r}\right]+min\left\{\widetilde{v}\left(G,\omega,\tilde{r}\right),\eta\left(\#\text{ defaults}|G,\theta,\omega,\tilde{r}\right)\right\}.$$

6.1 Capital regulation under complete information

In this subsection, I determine under which circumstances the interbank network that emerges in the unregulated equilibrium differs from the one a regulator would choose assuming the regulator is able to observe each bank's type.

Naturally, the regulator can be assumed to have the ability to freely allocate liquidity across the system after the shock materializes. However, to compare unregulated and regulated equilibria, I model the liquidity reallocation choice as an interbank network. Even though the regulator is still constrained by the distribution of bankers' ability,[21] under complete information, the regulator can choose y, k and G conditional on banks' types.[22] In this context, the network is interpreted as the transfers the regulator is willing to make, conditional on bankers' types, after observing the liquidity shortage but before the return shock materializes. Thus, the regulator's problem under complete information is given by

$$\max_{G,y,k} \mathbb{W}\left(G,y,\theta,k\right) \tag{10}$$

s.t.

$$\pi_i^{\star}\left(G,\theta_i;y,k\right) \geq 0,$$

for all $i \in \{b_1, b_2, b_3\}$.

Even under complete information, the regulator faces a trade-off when deciding to what extent the regulator should allow banks to access the interbank infrastructure. On one hand, a more interconnected interbank network increases banks' profits in the success states of the world; however, on the other hand, it also leads to defaults by contagion in default states. This trade-off becomes clear when taking discrete differences with respect to the network's connectivity in equation (10)

$$\frac{\Delta\mathbb{W}\left(\cdot\right)}{\Delta|G|} = \sum_{i=1}^{3} \frac{\Delta\pi_i^{\star}\left(\cdot\right)}{\Delta|G|} - \left(1+\lambda\right)\frac{\Delta\mathbb{E}\left[\rho\left(\cdot\right)\right]}{\Delta|G|} \gtreqqless 0. \tag{11}$$

Although equation (11) cannot be signed unambiguously, it is instructive to analyze how this trade-off is affected by changes in other parameters. From this equation, it follows that the net social value of interconnectedness of vulnerable banks is decreasing in the costs of default. Thus, the regulator never allows vulnerable banks to borrow from other banks when these costs are sufficiently high. Formally,

Proposition 3. *Let $G_1^{'}$ be a network obtained from G_1 removing some or all of the vulnerable*

[21] Alternatively, I could have considered the case where regulation acts directly by replacing vulnerable by sound bankers or, even more drastically, by withdrawing their banking license.

[22] In my model, capital only plays the role of a Pigouvian tax. This can be motivated by the focus on tail risk, that is, in order to create a buffer against low-probability–high-impact events, banks would be required to hold a considerable amount of capital that might be unfeasible. Moreover, the regulator may have limited ability to determine the precise buffer that prevents failures when banks misreport their exposures. As argued by Huizinga and Laeven (2012), the evidence that financial reports may provide a distorted picture of banks' resilience can be found in the result of the 2009 US stress tests. These tests revealed capital shortages even though reports gave the appearance that the minimum regulatory requirements were fulfilled.

banks' incoming connections. When λ is high enough, implicitly defined by

$$\lambda > \frac{\sum_{i=1}^{3} \pi_i^\star (G_1, \cdot) - \pi_i^\star \left(G_1^{'}, \cdot\right)}{\mathbb{E}\left[\rho (G_1, \theta)\right] - \mathbb{E}\left[\rho \left(G_1^{'}, \theta\right)\right]} - 1,$$

then the welfare allowed by G' is higher than the one allowed by G_1.

Proof. The proof follows directly from equation (11). Denoting G_1' as any network obtained from G_1 in which vulnerable banks are, to some extent, denied participation in the interbank market, which reduces expected financial disruption costs, the implicit condition in the proposition is the following:

$$\sum_{i=1}^{3} \frac{\Delta \pi_i^\star (\cdot)}{\Delta |G|} - (1+\lambda) \frac{\Delta \mathbb{E}\left[\rho (\cdot)\right]}{\Delta |G|} < 0 \Leftrightarrow$$

$$\Leftrightarrow \lambda > \frac{\sum_{i=1}^{3} \pi_i^\star (G_1, \cdot) - \pi_i^\star (G_1', \cdot)}{\mathbb{E}\left[\rho (G_1, \theta)\right] - \mathbb{E}\left[\rho \left(G_1', \theta\right)\right]} - 1.$$

□

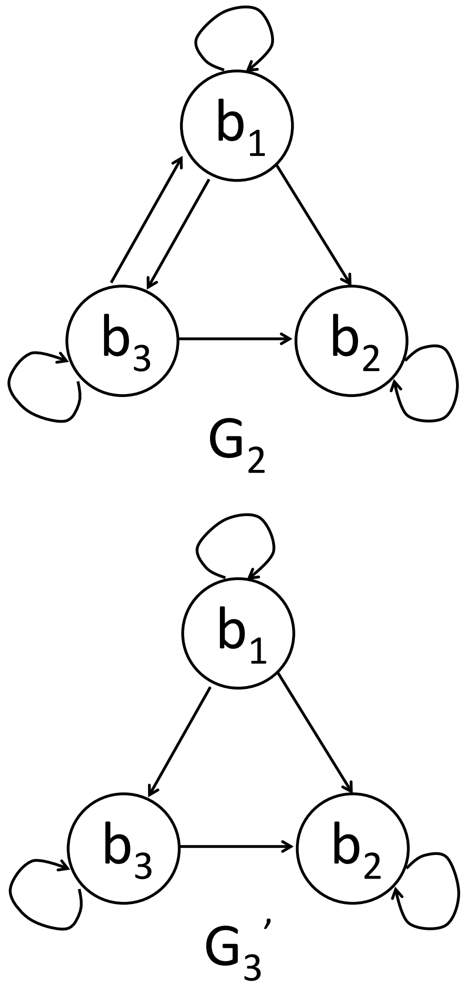
A natural question then is "What is the socially optimal network or networks?" Since even under complete information, the regulator faces a trade-off between efficiency and financial stability, the socially optimal financial network is determined by the factors that affect the steepness of this trade-off.

Lemma 5. *As the costs with the disruption of the functioning of the financial system increase, the socially optimal networks are G_1, G_2, G_3/G_3' and G_4, respectively. See Figure 3.*

Proof. The proof is in the appendix. □

There are three candidate networks, depicted in Figure 3. Network G_2 allows the sound bank to benefit from full liquidity insurance, while vulnerable banks only benefit from partial liquidity insurance. Networks G_3 and G_3' allow the sound bank to benefit from full liquidity insurance, while only one vulnerable bank benefits from partial liquidity insurance. Thus, efficiency is partially preserved and contagion is reduced only at the cost of decreasing vulnerable banks' liquidity insurance probability. Finally, in network G_4, the sound bank still obtains full liquidity insurance, but now vulnerable banks cannot insure against the liquidity shock using the interbank market. Thus, total absence of contagion is gained at the cost of confining vulnerable banks to isolation. It is also important to note that intermediation is absent in the networks depicted in Figure 3. This is the case since intermediation increases total expected distress costs while it does not increase liquidity insurance over and above what the planner would be able to achieve via bilateral reallocations.

Figure 3: Socially optimal networks



As Lemma 5 shows, when the regulator is able to design the interbank network, it would never use undifferentiated capital requirements since they are not the most effective among all the alternative instruments available. Even though the regulator wishes to limit the propagation of distress following a vulnerable bank's default, imposing capital requirements on sound ones unambiguously decreases total welfare. This observation further motivates the assumption that an informational friction may constrain regulatory design and, consequently, it deserves consideration.

6.2 Capital regulation under incomplete information

I now assume that the regulator has incomplete information with respect to banks' tail risk exposure. Since the regulator is no longer able to condition the instrument on banks' types, it must induce banks to voluntarily reveal their type through their optimal choices.

Following the "additional loss absorbency requirement" in broad terms, I assume that the regulator imposes a capital requirement κ per incoming credit line.[23] To accommodate capital requirements, I add a new date, $t = -1/2$, to the model where the regulator fixes capital surcharges. Then, during the network formation stage, banks treat the capital surcharges as an exogenous cost to form credit lines. Under incomplete information, the regulator's problem is now given by

$$\max_{G,\kappa} \mathbb{W}(G, \theta, \kappa) \tag{12}$$

s.t.

$$\pi_i^\star(G, \theta_i; \kappa) \geq 0 \tag{13}$$

$$\pi_i^\star(G, \theta_i; \kappa) > \pi_i^\star\left(G', \theta_i; \kappa\right), \tag{14}$$

$\forall\, i \in \{b_1, b_2, b_3\}$ and $\forall\, G^{'}$ obtained from $G$by a pair-wise deviation initiated by i.

The first set of constraints in equation (13) is the set of individual rationality constraints (or participation constraints) and the second set in equation (14) comprises the incentive compatibility constraints.[24] The individual rationality constraints state that, under κ, each bank is better off continuing its operations rather than exiting the market. In this case, the intersection of the second set of constraints has a particular meaning since it expresses that banks will only choose those networks that are PWS given κ.

Given that contagion costs come from vulnerable banks' interconnectedness decisions, the regulator would like to limit only vulnerable banks' participation in the interbank network. However, unconditional per-connection capital surcharges also limit sound banks' participation. Since it is not possible to restrict the participation of vulnerable banks in the interbank network without also restricting sound ones', the first best cannot be achieved. Interconnectedness-based requirements generate a trade-off to the banker between raising additional capital and benefitting from increased connectivity. This added cost can affect the interbank network that emerges as the equilibrium outcome. Thus, analyzing capital requirements within a network formation game allows one to design an instrument that takes into account how optimizing agents react to it.

From the regulator's standpoint, choosing κ involves a series of trade-offs. On one hand, by choosing higher capital requirements based on the number of incoming credit lines, the regulator can reduce interconnectedness and thus reduce financial distress costs. On the other hand, reduced interconnectedness achieved through higher capital requirements also reduces liquidity insurance and increases capital costs leading to a decrease in banks' profits. When the regulator adopts a given

[23]This assumption restricts the contract space to a linear function in interconnectedness. This assumption is relaxed in Proposition 5, where I consider capital requirements that are non-linear and depend on the position of a potential borrower along an intermediation path.

[24]As shown by Myerson (1979), this representation is without loss of generality given the revelation principle.

κ, it creates an undifferentiated added cost of adding an incoming credit line. However, banks do not benefit equally from increased interconnectedness. The heterogeneity in bankers' ability, which is translated into individual risk taking, has an immediate implication for the additional value of each connection in the interbank market. Sound banks' profits increase by the full amount allowed by insurance in additional states of the world. However, vulnerable banks only benefit with probability β from the return (net of the interbank interest rate) of additional liquidity insurance. These differences can be analyzed in detail by decomposing the incremental profit allowed by each interbank connection both for sound and vulnerable banks. That is,

$$\frac{\Delta\pi_i^\star(G,\theta_H;\kappa)}{\Delta\left|G_i^-\right|}=\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\Delta\phi_i-\Delta\varepsilon_i-\left[\delta-R\left(\Delta\phi_i+\phi_i\left(G''\right)\right)\right]\kappa, \tag{15}$$

where G'' is a network obtained from G by eliminating one incoming credit line to bank i. The incremental profit of a sound bank that is allowed by an additional incoming credit line is increasing with the return of the illiquid asset and in the probability of occurrence of the states characterized by a liquidity shock to which the credit line insures against. Also, it is decreasing in the interest rates and in the opportunity cost of capital. Similarly,

$$\frac{\Delta\pi_i^\star(G,\theta_L;\kappa)}{\Delta\left|G_i^-\right|}=\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\beta\Delta\phi_i-\beta\Delta\varepsilon_i-\left[\delta-R\beta\left(\Delta\phi_i+\phi_i\left(G''\right)\right)\right]\kappa. \tag{16}$$

That is, the incremental profit of a vulnerable bank allowed by an additional incoming credit line is increasing in the return of illiquid asset in success states, in the probability of occurrence of the liquidity shock, but decreasing in the interest rate on interbank liabilities. Then, it follows from equations (15) and (16) that sound and vulnerable bankers wish to establish an additional credit line if κ is low enough, i.e.,

$$\begin{aligned}&\frac{\Delta\pi_i^\star(G,\theta_H;\kappa)}{\Delta\left|G_i^-\right|}>0\Leftrightarrow\\&\kappa<\frac{\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\Delta\phi_i-\Delta\varepsilon_i}{\delta-R\left(\Delta\phi_i+\phi_i\left(G''\right)\right)}\equiv\kappa_s\left(\Delta\phi_i;\delta,R\right),\end{aligned}$$

and

$$\begin{aligned}&\frac{\Delta\pi_i^\star(G,\theta_L;\kappa)}{\Delta\left|G_i^-\right|}>0\Leftrightarrow\\&\kappa<\frac{\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\Delta\phi_i-\Delta\varepsilon_i}{\delta/\beta-R\left(\Delta\phi_i+\phi_i\left(G''\right)\right)}\equiv\kappa_v\left(\Delta\phi_i;\delta,R\right).\end{aligned}$$

Importantly, since the negative externality arises because vulnerable banks are overconnected from the regulator's point of view, the trade-off between financial stability and efficiency depends on how much sound and vulnerable banks value interbank connections. If sound banks value relatively more credit lines, then it is possible to induce vulnerable banks to reduce their interconnectedness without reducing the benefits of liquidity insurance to sound banks, all else being equal. Even in this case, there is a trade-off between financial stability and efficiency. By reducing the extent to which vulnerable banks participate in the interbank market and thus improving stability, efficiency is still reduced because all bankers have to invest more capital in the bank. However, if vulnerable bankers value relatively more interbank connections, then the trade-off becomes steeper, given that now more efficiency needs to be foregone to improve financial stability. To understand under which conditions each scenario arises, one needs to inspect the difference between equations (15) and (16). That is,

$$\frac{\Delta\pi_i^\star(G,\theta_H;\kappa)}{\Delta|G_i^-|}-\frac{\Delta\pi_i^\star(G,\theta_L;\kappa)}{\Delta|G_i^-|}=(1-\beta)\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\Delta\phi_i-\Delta\varepsilon_i-R\left(\Delta\phi_i+\phi_i\left(G''\right)\right)\kappa.$$

Thus, when $\Delta\phi_i$ does not depend on bankers' types, vulnerable banks value relatively more credit lines if

$$\Leftrightarrow \kappa<\left\{-\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\Delta\phi_i+\Delta\varepsilon_i\right\}/R\left(\Delta\phi_i+\phi_i\left(G''\right)\right)\equiv\bar{\kappa}<0.$$

Proposition 4 summarizes these results.

Proposition 4. *The regulator can always induce vulnerable banks to reduce their interconnectedness without affecting the extent to which sound banks participate in the interbank market provided that both types benefit equally from liquidity insurance for each additional credit line they establish.*

Proof. The proof follows directly from equations (14)–(16). The formal proof is in the appendix. □

Even though Proposition 4 refers to the simplest form of interconnectedness-based capital requirements, it also applies to more complex ones. Consider the case where the regulator imposes a capital charge whenever a bank is at the end of an intermediation path. It is straightforward to show that, as in Proposition 4, vulnerable banks are relatively more sensitive to these capital requirements.

Let $\check{\kappa}_j$ and $\tilde{\kappa}_j$ denote the capital thresholds above which banks of type j no longer wish to be at the end of two and one intermediation paths, respectively. A vulnerable bank prefers to be at the end of only one intermediation path instead of two, provided that the expected intermediation fees are lower than the increase in the opportunity costs implied by the capital requirements. That is,

$$[(1+\breve{\kappa}_v-\bar{\gamma})R-1-r_{IB,i}(G)]\beta-\breve{\kappa}_v\delta<[(1+\tilde{\kappa}_v-\bar{\gamma})R-1-r_{IB,i}(G)-\varepsilon_i(G,\cdot)]\beta-\tilde{\kappa}_v\delta\Leftrightarrow$$

$$\Leftrightarrow\breve{\kappa}_v-\tilde{\kappa}_v>\frac{\varepsilon_i(G,\cdot)}{\delta/\beta-R}.$$

The same is not true for a sound bank if

$$\breve{\kappa}_s-\tilde{\kappa}_s<\frac{\varepsilon_i(G,\cdot)}{\delta-R}.$$

Thus, for

$$(\breve{\kappa}-\tilde{\kappa})\in\left]\frac{\varepsilon_i(G,\cdot)}{\delta/\beta-R},\frac{\varepsilon_i(G,\cdot)}{\delta-R}\right[,\tag{17}$$

a sound bank will remain at the end of two intermediation paths and vulnerable banks only one.

Similarly, a vulnerable bank prefers to remain in isolation instead of dedicating additional capital in order to be located at the end of a single intermediation path if

$$[(1+\tilde{\kappa}_v-\bar{\gamma})R-1-r_{IB,i}(G)-\varepsilon_i(G,\cdot)]\beta-\tilde{\kappa}_v\delta<2[(1-\bar{\gamma})R-1]\beta/3\Leftrightarrow$$

$$\tilde{\kappa}_v>\frac{[(1-\bar{\gamma})R-1]/3-r_{IB,i}(G)}{\delta/\beta-R}.$$

The same condition for a sound bank is

$$\tilde{\kappa}_s>\frac{[(1-\bar{\gamma})R-1]/3-r_{IB,i}(G)}{\delta-R}.$$

Thus, for

$$\tilde{\kappa}\in\left]\frac{[(1-\bar{\gamma})R-1]/3-r_{IB,i}(G)}{\delta/\beta-R},\frac{[(1-\bar{\gamma})R-1]/3-r_{IB,i}(G)}{\delta-R}\right[,\tag{18}$$

a sound bank prefers to remain connected while vulnerable banks prefer to become isolated and only survive to the liquidity shock with probability $2/3$.

As long as conditions (17) and (18) hold, the regulator can reduce total distress costs by implementing intermediation-based capital requirements. This finding is summarized in the following proposition.

Proposition 5. *As long as conditions (17) and (18) hold, the regulator can induce banks to form network G_2 via intermediation-based capital requirements within the ranges specified in these conditions.*

Proof. Consider an alternative network obtained from G_2 by adding one credit line from b_2 to b_3 (or b_1). Since now b_3 (or b_1) is located at the end of an intermediation path, it is required to hold $\tilde{\kappa}$ in capital. Then, since condition (18) is assumed to hold, this network is not PWS.

Consider, alternatively, the network obtained from G_2 by severing one incoming credit line of b_2. This network is also not PWS given that condition (18) is assumed to hold.

All that remains to be shown is that no other network is PWS. Under this capital requirements schedule, PWS networks must fulfill cumulatively the following conditions:

(i) vulnerable banks cannot be at the end of an intermediation path;

(ii) sound banks have two incoming credit lines; and

(iii) vulnerable banks have one incoming credit line that does not put them at the end of an intermediation path.

It is straightforward to check that only G_2 meets all of these conditions. □

Propositions 4 and 5 show that, under incomplete information, the regulator is constrained in its ability to induce banks to form the socially optimal interbank network. Moreover, this ability is affected by the probability of bailouts. In the next section, I discuss the policy implications of the model.

7 Policy implications

7.1 Resolution regimes

In addition to the higher loss absorbency requirements discussed in this paper, the Financial Stability Board (2010) proposed measures to improve resolution and recovery regimes to "reduce the extent or impact of failure of G-SIBs" BCBS (2011, 3). The analysis carried out in this paper suggests that resolution regimes may also have an impact on the optimal design of interconnectedness-based capital requirements. Since effective resolution frameworks reduce ex post costs of G-SIBs' failures, they lend credibility to closure policies. This reduces the probability of a bailout and consequently the funding advantage that vulnerable banks benefit from when they choose to establish one additional connection. The effect of an increase in the interbank interest rate on the capital thresholds κ_v and κ_s is $\frac{\partial \kappa_v}{\partial \Delta r_{IB,i}} = -\frac{\Delta\phi_i}{\frac{\delta}{\beta} - R(\Delta\phi_i + \phi(G''))} < 0$ and $\frac{\partial \kappa_s}{\partial \Delta r_{IB,i}} = -\frac{\Delta\phi_i}{\delta - R(\Delta\phi_i + \phi(G''))} < 0$, respectively. Thus, the regulator can achieve the same incentive effects with lower capital surcharges.

7.2 Deposit insurance fees and default fund contributions

Alternatively, the regulator could choose to require banks to pay deposit insurance fees or make default fund contributions that would also depend on interconnectedness. Let us now suppose that the regulator imposes a deposit insurance fee or default fund contribution equal to τ per connection established in the interbank market. It is straightforward to find the analog of equations (15) and (16) for sound and vulnerable banks, respectively.

Conditional on τ and absent of capital regulation, the increment in profit brought about one connection for a sound bank is given by

$$\frac{\Delta\pi_i^\star(G,\theta_H;\tau)}{\Delta\left|G_i^-\right|} = [(1-\bar{\gamma}-\tau)R - 1 - \Delta r_{IB,i}]\Delta\phi_i - \Delta\varepsilon_i,$$

and the condition for a vulnerable bank is given by

$$\frac{\Delta\pi_i^\star(G,\theta_L;\tau)}{\Delta\left|G_i^-\right|} = [(1-\bar{\gamma}-\tau)R - 1 - \Delta r_{IB,i}]\Delta\phi_i\beta - \Delta\varepsilon_i\beta.$$

Thus, bankers wish to establish one additional connection if τ is low enough. This threshold for a sound bank is given by

$$[(1-\bar{\gamma}-\tau)R - 1 - \Delta r_{IB,i}]\Delta\phi_i - \Delta\varepsilon_i > 0 \Leftrightarrow \tau < \frac{[(1-\bar{\gamma})R - 1 - \Delta r_{IB,i}]\Delta\phi_i - \Delta\varepsilon_i}{R\Delta\phi_i} \equiv \tau_s,$$

and for vulnerable banks, it is given by

$$[(1-\bar{\gamma}-\tau)R - 1 - \Delta r_{IB,i}]\Delta\phi_i\beta - \Delta\varepsilon_i\beta > 0 \Leftrightarrow \tau < \frac{[(1-\bar{\gamma})R - 1 - \Delta r_{IB,i}]\Delta\phi_i - \Delta\varepsilon_i}{R\Delta\phi_i} \equiv \tau_v.$$

Since the incremental profit brought about by one additional connection is the same for both types of banks when the illiquid asset succeeds, one obtains $\tau_s = \tau_v$. This is the case because, even though the alternative instruments can internalize the costs of bank failures and induce banks to reduce their interconnectedness, these on their own do not have a different impact on the incentives of sound and vulnerable banks to establish interbank credit lines. Thus, capital requirements play a role in aligning incentives whenever the regulator is constrained by an informational friction.

7.3 Stable funding regulation

Propositions 4 and 5 were derived under the assumption that liquidity and return shocks are independent. However, it may be more reasonable to assume that vulnerable banks face higher-than-average liquidity shocks with a higher probability than do sound ones (i.e., $prob\,(\gamma=\gamma_H|s=vuln.)$ $> prob\,(\gamma=\gamma_H|s=sound)$ or $min\{\phi_2,\phi_3,\phi_4,\phi_5\} > max\{\phi_1,\phi_6\}$). This can be the case if assets with higher exposure to tail risk also need to be refinanced with a higher probability. Even though not explicitly modeled in the paper, correlation between return and (funding) liquidity risk can be motivated by a business model where banks fund illiquid assets exposed to tail risk with short-term wholesale funding. If wholesale investors are more likely to withdraw their funds from vulnerable banks, these banks value their interbank credit lines relatively more. Thus, correlation between liquidity and credit risk plays an analogous role to implicit guarantees in constraining the regulator's ability to limit the participation of vulnerable banks in the interbank market. If that is the case, a stable funding requirement akin to the Net Stable Funding Ratio (NSFR) brought by Basel III can improve the effectiveness of interconnectedness-based capital requirements by requiring banks to maintain a more stable funding structure and thus reducing the correlation between the shocks.

8 Conclusion

The 2007–09 subprime crisis triggered a major regulatory reform. In addition to strengthening microprudential standards, the new regulatory framework brought a set of macroprudential instruments that aim to contain systemic risk at socially acceptable levels. Motivated by contagion concerns, one class of these new instruments targets the connections established among financial institutions. Yet, interconnectedness is in itself an equilibrium outcome and, as such, is affected by any instrument made contingent on it. In this paper, I analyze a microfounded design of interconnectedness-based capital requirements that not only explicitly accounts for the endogenous response of the regulated institutions but also accounts for the impact of asymmetric information and implicit government guarantees in the design of the instrument. I show that this instrument of macroprudential policy implies a trade-off between efficiency and financial stability. Furthermore, the design of the instrument is not independent of market frictions. I show that, when the informational friction interacts with implicit government guarantees, the regulator imposes higher capital requirements than it would under complete information. This is the case because more capital is required to induce vulnerable banks to become less interconnected since the funding advantage provided by the perspective of bailouts makes interbank credit lines relatively more profitable. Moreover, while deposit insurance fees or default fund contributions dependent on interconnectedness reduce the costs of bank failures and make banks internalize the costs of contagion, these do not have a differentiated effect on sound and vulnerable banks' incentives to become interconnected. This is the case because deposit insurance fees or default fund contributions only affect banks profits when illiquid assets succeed, such that banks' profits in the favorable states of nature do not depend on their type. Since capital requirements introduce an opportunity cost in all states of nature, these can realign banks' incentives to become interconnected. Finally, since vulnerable banks value interbank connections relatively more if they are relatively more likely to be hit by negative liquidity shocks, the efficiency-financial stability trade-off is steeper in the correlation between liquidity and credit shocks. Thus, there is a rationale to combine interconnectedness-based capital requirements with complementary regulatory measures regarding banks' funding structure.

It is instructive to ask how this result would change when the assumptions of the model are relaxed. First, the assumption that the interbank network is perfectly observed by the regulator is undoubtedly a strong assumption. Moreover, it contrasts with the assumption that tail risk exposure is not observed by the regulator at an individual level. Even though interbank exposures may be hard to identify, tail risk exposure may be even harder to measure. The difference may lie in the fact that while, connections may already be in place, tail risk may only manifest itself at some unknown point in the future. Second, throughout the paper, I held bankers' ability distribution fixed. However, since all results are established based on the types of banks involved, the assumption regarding a particular distribution is without loss of generality. Nevertheless, the trade-off between efficiency and financial stability does depend on the costs of bank failures, which are increasing in the number of vulnerable banks. If there are very few vulnerable banks, the costs of requiring sound ones to hold capital may outweigh the benefit of restricting the access of vulnerable banks to the interbank market.

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Appendix

A.1. Details of the interconnectedness criteria of "higher loss absorbency requirements" (excerpt from the rules text, BCBS [2011, 7])

Intra-financial system assets

This is calculated as the sum of

- lending to financial institutions (including undrawn committed lines);
- holdings of securities issued by other financial institutions;
- net mark to market reverse repurchase agreements;

- net mark to market securities lending to financial institutions; and
- net mark to market OTC derivatives with financial institutions.

Intra-financial system liabilities

This is calculated as the sum of

- deposits by financial institutions (including undrawn committed lines);
- securities issued by the bank that are owned by other financial institutions;
- net mark to market repurchase agreements;
- net mark to market securities borrowing from financial institutions; and
- net mark to market OTC derivatives with financial institutions.

The scores for the two indicators in this category are calculated as the amounts of their intra-financial system assets (liabilities) divided by the sum of total intra-financial system assets (liabilities) of all banks in the sample.

A.2. Proofs

A.2.1. Proof of Lemma 1

The proof of this Lemma is shown case by case:

Case (i): bailout always occur. There is no counterparty risk since interbank loans are riskless.

Case (ii): bailout only occurs when the banking system is weak, thus only the sound lender sees its counterparty risk reduced. Conditional on lending, the probability that lender of type j is repaid is as follows:

Probability	Return shock $(\tilde{r})$	$j =$ vulnerable	$j =$ sound
$\beta(1-\beta)$	$(0,R,R)$	1	$\frac{1}{2}$
$(1-\beta)^2$	$(0,R,0)$	$\frac{1}{2}$	1
$\beta(1-\beta)$	$(R,R,0)$	$\frac{1}{2}$	$\frac{1}{2}$
β^2	(R,R,R)	1	1

Thus,

$\tilde{\beta}_i^v = \frac{3}{2}\beta(1-\beta) + \frac{1}{2}(1-\beta)^2 + \beta^2 = \frac{1+\beta}{2} > \beta$ and $\tilde{\beta}_i^s = \beta(1-\beta) + (1-\beta)^2 + \beta^2 = 1 - (1-\beta)\beta > \beta$.

Case (iii): bailout only occurs when the banking system is strong, thus both lender types see their counterparty risk reduced. Conditional on lending, the probability that lender of type j is repaid is as follows:

Probability	Return shock $(\tilde{r})$	$j =$ vulnerable	$j =$ sound
$\beta(1-\beta)$	$(0,R,R)$	1	1
$(1-\beta)^2$	$(0,R,0)$	$\frac{1}{2}$	0
$\beta(1-\beta)$	$(R,R,0)$	1	1
β^2	(R,R,R)	1	1

Thus,

$\tilde{\beta}_i^v = 2\beta(1-\beta) + \frac{1}{2}(1-\beta)^2 + \beta^2 = \beta(2-\beta) + \frac{(1-\beta)^2}{2} > \beta$ and $\tilde{\beta}_i^s = 2\beta(1-\beta) + \beta^2 = \beta(2-\beta) > \beta$.

Case (iv): bailouts do not occur. As before,

Probability	Return shock $(\tilde{r})$	$j =$ vulnerable	$j =$ sound
$\beta(1-\beta)$	$(0,R,R)$	1	$\frac{1}{2}$
$(1-\beta)^2$	$(0,R,0)$	$\frac{1}{2}$	0
$\beta(1-\beta)$	$(R,R,0)$	$\frac{1}{2}$	$\frac{1}{2}$
β^2	(R,R,R)	1	1

Thus,

$\tilde{\beta}_i^v = \frac{3}{2}\beta(1-\beta) + \frac{1}{2}(1-\beta)^2 + \beta^2 = \frac{1+\beta}{2} > \beta$ and $\tilde{\beta}_i^s = \beta(1-\beta) + \beta^2 = \beta$.

A.2.2. Proof of Lemma 2

Note that, from the first-order conditions,

$$\frac{\partial \mathbb{E}[\pi(\cdot)]}{\partial k} = \begin{cases} R\phi(G) - \delta & if\ s = sound \\ R\phi(G)\beta - \delta & if\ s = vulnerable \end{cases}.$$

It follows that $\frac{\partial \mathbb{E}[\pi(\cdot)]}{\partial k} < 0$ regardless the type of illiquid asset chosen when $\delta > R$. Thus, without regulation, banks do not wish to hold any positive amount of capital on their balance sheets.

A.2.3. Proof of Lemma 3

- expected profit in isolation of $y = \gamma_L$

$$\frac{1}{3}[(1-\gamma_L)R - 1 - (\bar{\gamma} - \gamma_L)];$$

- expected profit in isolation of $y = \bar{\gamma}$

$$\frac{2}{3}[(1-\bar{\gamma})R - 1];$$

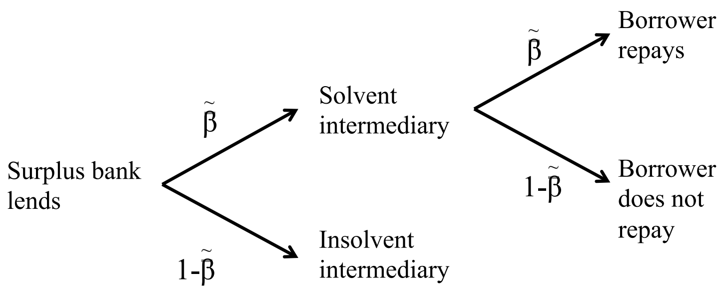
- expected profit in isolation of $y = \gamma_H$

$$(1-\gamma_H)R - 1 + (\gamma_H - \bar{\gamma}).$$

Under Lemma 2, given Assumption 2 and comparing all equations above, it can be shown that, when $\gamma_H > \frac{1+\gamma_L}{2}$,

$$y^{isolation} = \begin{cases} \gamma_L & if \quad R > \frac{1-(\bar{\gamma}-\gamma_L)}{1-\gamma_H} \\ \bar{\gamma} & if \quad \frac{1-(\bar{\gamma}-\gamma_L)}{1-\gamma_H} \geq R > \frac{1}{1-\gamma_L} \end{cases}.$$

A.2.4. Proof of Lemma 4



If there are two subsequent banks on the intermediation path, the ε that makes the original lender indifferent to lending or not lending is

$\tilde{\beta}[\varepsilon + (1-y+k)R - 1] - \delta k = (1-y+k)R - 1 - \delta k \Leftrightarrow \varepsilon = \frac{1-\tilde{\beta}}{\tilde{\beta}^2}[(1-y+k)R-1]$.

Similarly when there is only one subsequent bank, the ε that makes the original lender indifferent to lending or not lending is

$\tilde{\beta}[\varepsilon + (1-y+k)R - 1] - \delta k = (1-y+k)R - 1 - \delta k \Leftrightarrow \varepsilon = \frac{1-\tilde{\beta}}{\tilde{\beta}}[(1-y+k)R-1]$.

Finally, a bank wishes to establish an intermediation relation if, after the intermediation fees and interest rate on the interbank loan are paid, its profit is still non-negative. That is,

$[(1-y+k)R-1]\left(1 - \frac{1-\tilde{\beta}}{\tilde{\beta}} - \frac{1-\tilde{\beta}^2}{\tilde{\beta}^2}\right) \geq 0 \Leftrightarrow \tilde{\beta} \geq \frac{1+\sqrt{13}}{6}$.

Note that, in this derivation, k is set to 0 and y is the same for all banks. Since capital is costly, setting $k = 0$ yields the sufficient condition for intermediation to be beneficial for borrower.

A.2.5. Proof of Lemma 5

The proof follows from the comparison of the welfare levels associated with the different networks. Note that

$$\mathbb{W}(G_1,\cdot)=[(1-\bar{\gamma})R-1-r_{IB}]\left[2\left(\frac{8}{3}\beta-\frac{2}{3}\beta^2-1\right)+\frac{1}{3}+\frac{2}{3}\beta\right]-$$
$$(1+\lambda)\left\{\left(4-\frac{14}{3}\beta+\frac{2}{3}\beta^2\right)+min\left\{\tilde{v}(G_1),\left(\frac{8}{3}-4\beta+\frac{4}{3}\beta^2\right)\eta(2)+\frac{2}{3}(1-\beta)\beta\eta(1)\right\}\right\}.$$

$$\mathbb{W}(G_2)=\frac{5}{3}[(1-\bar{\gamma})R-1-r_{IB}]2\beta-(1+\lambda)\left\{r_d\left(4-6\beta+2\beta^2\right)+\right.$$
$$\left.min\left\{\tilde{v}(G_2),\left(2-\frac{10}{3}\beta+\frac{4}{3}\beta^2\right)\eta(2)+\frac{2}{3}(1-\beta)\beta\eta(1)\right\}\right\}.$$

$$\mathbb{W}(G_4,\cdot)=\frac{4}{3}[(1-\bar{\gamma})R-1-r_{IB,i}]\left(\beta^2+1\right)+min\left\{\tilde{v}(G_4),(1-\beta)^2\eta(2)+2(1-\beta)\beta\eta(1)\right\}.$$

For $\eta(2)$ large enough and/or $\tilde{v}(G_1)>\tilde{v}(G_2)=\tilde{v}(G_3)>\tilde{v}(G_4)$, it follows that $\mathbb{W}(G_4)>\mathbb{W}(G_2)=\mathbb{W}(G_3)>\mathbb{W}(G_1)$.

A.2.6. Proof of Proposition 4

Note that the incremental profit allowed by an additional incoming credit line for a sound bank is given by

$$\begin{aligned}\frac{\Delta\pi_i^\star(\cdot,\theta_H;\kappa)}{\Delta\left|G_i^-\right|}=&\left[\left(1+\left(\left|G_i^{''-}\right|+1\right)\kappa-\bar{\gamma}\right)R-1-r_{IB,i}(G)\right]\phi_i(G)-\varepsilon_i(G)-\delta\left(\left|G_i^{''-}\right|+1\right)\kappa-\\&C\left(\theta^i\right)-\left[\left(1+\left|G_i^{''-}\right|\kappa-\bar{\gamma}\right)R-1-r_{IB,i}\left(G''\right)\right]\phi_i\left(G^{'}\right)+\varepsilon_i\left(G^{''}\right)+\\&\delta\left|G_i^{''-}\right|\kappa+C\left(\theta^i\right)=\\=&[(1-\bar{\gamma})R-1-\Delta r_{IB,i}]\Delta\phi_i-\Delta\varepsilon_i-[\delta-R(\Delta\phi_i+\phi_i(G))]\kappa.\end{aligned}$$

Similarly, the incremental profit allowed by an additional incoming credit line for a vulnerable bank is given by

$$\frac{\Delta\pi_i^\star(\cdot,\theta_L;\kappa)}{\Delta\left|G_i^-\right|}=\left[\left(1+\left(\left|G_i^{''-}\right|+1\right)\kappa-\bar{\gamma}\right)R-1-r_{IB,i}(G)\right]\beta\phi_i(G)-$$
$$\beta\varepsilon_i(G)-\delta\left(\left|G_i^{''-}\right|+1\right)\kappa-$$
$$\left[\left(1+\left|G_i^{''-}\right|\kappa-\bar{\gamma}\right)R-1-r_{IB,i}\left(G''\right)\right]\beta\phi_i\left(G''\right)+$$
$$\beta\varepsilon_i\left(G''\right)+\delta\left|G_i^{''-}\right|\kappa=$$
$$=\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\beta\Delta\phi_i-\beta\Delta\varepsilon_i-$$
$$\left[\delta-R\beta\left(\Delta\phi_i+\phi_i\left(G''\right)\right)\right]\kappa.$$

Therefore, there is a threshold level of per-connection capital requirement above which sound banks do not wish to establish an additional interbank credit line or, alternatively, eliminate an existing one, which is given by

$$\frac{\Delta\pi_i^\star(\cdot,\theta_H;\kappa)}{\Delta\left|G_i^-\right|}>0\Leftrightarrow\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\Delta\phi_i-\Delta\varepsilon_i-\left[\delta-R\left(\Delta\phi_i+\phi_i(G)\right)\right]\kappa>0\Leftrightarrow$$

$$\Leftrightarrow\kappa<\left\{\left[(1-\bar{\gamma})R-1-\Delta r_{IB,i}\right]\Delta\phi_i-\Delta\varepsilon_i\right\}/\left[\delta-R\left(\Delta\phi_i+\phi_i(G)\right)\right]\equiv\kappa_s\left(\Delta\phi_i;\delta,R\right).$$

Similarly, there is an analogous threshold for vulnerable banks, which is given by

$$\frac{\Delta\pi_i^\star(\cdot,\theta_L;\kappa)}{\Delta\left|G_i^-\right|}>0\Leftrightarrow$$
$$\left[(1-\bar{\gamma})R-1-\Delta r_{IB,I}\right]\beta\Delta\phi_i-\beta\Delta\varepsilon_i-\left[\delta-R\beta\left(\Delta\phi_i+\phi_i(G)\right)\right]\kappa>0\Leftrightarrow$$

$$\kappa<\frac{\left[(1-\bar{\gamma})R-1-\Delta r_{IB,I}\right]\beta\Delta\phi_i-\beta\Delta\varepsilon_i}{\delta-R\beta\left(\Delta\phi_i+\phi_i(G)\right)}\equiv\kappa_v\left(\Delta\phi_i;\delta,R\right).$$

Comparing these two thresholds, yields

$$(1-\beta)\left\{\left[(1-\bar{\gamma})R-1\right]\Delta\phi_i-\Delta\varepsilon_i+R\left(\Delta\phi_i+\phi_i(G)\right)\kappa\right\}<0\Leftrightarrow$$

$$\Leftrightarrow\kappa<\left\{-\left[(1-\bar{\gamma})R-1\right]\Delta\phi_i+\Delta\varepsilon_i\right\}/R\left(\Delta\phi_i+\phi_i(G)\right)\equiv\bar{\kappa}.$$