(In)efficient repo markets*

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Abstract

Repo markets trade off the efficient allocation of liquidity in the financial sector with resilience to funding shocks. The repo trading and clearing mechanisms are crucial determinants of the allocation-resilience trade-off. Two common mechanisms, anonymous central-counterparty (CCP) and non-anonymous over-the-counter (OTC) markets, are inefficient and their welfare rankings depend on funding tightness. Through a collateral protection channel, OTC (CCP) markets worsen (improve) funding allocations for small funding shocks but force (in)efficient asset liquidation for intermediate funding shocks. CCP markets are more resilient to runs than OTC markets for large funding shocks, but absent novation and well-capitalized default fund CCP runs create systemic risk. Two innovations to repo market design improve welfare: a liquidity-contingent trading mechanism and a two-tiered guarantee fund in which collateral transfers insure against illiquidity while the default fund insures against insolvency.

JEL Classification: G01, G14, G21, G28

Keywords: repo market, funding run, financial stability, asymmetric information, central clearing, novation, guarantee fund, collateral

1 Introduction

Repo markets are an integral component of the financial plumbing of any modern economy (BIS, 2017). Repurchase agreements, or repos are the primary source of short-term funding for banks with outstanding repo volumes amounting to several trillion dollars both in the United States (Gorton and Metrick, 2012; Copeland et al., 2014; Krishnamurthy et al., 2014) and Europe (Mancini et al., 2016).[1] Repo markets are instrumental for the efficient allocation of liquidity in the financial sector, implementation and transmission of monetary policy (Bianchi and Bigio, 2020), and financial stability (Martin et al., 2014a,b). However, repo runs have been a recurrent phenomenon during the Great Financial Crisis (GFC) in 2008 (Brunnermeier, 2009), the repo blowup[2] in September 2019, and the Covid-19 pandemic in March 2020 (Duffie, 2020). Repo markets are particularly reliant on liquid collateral in crisis times (Infante and Saravay, 2020). In response to recent funding crises, observers have repeatedly called for reforms to the functioning of repo markets.

Repo markets serve two main roles, the efficient allocation of short-term funding in normal times and the resilience to funding shocks in crisis times. How different repo market architectures affect this tradeoff, and what is the optimal repo market design remain open questions that we address in this paper. Several repo market structures (co)exist in the U.S., Europe, and around the world. Existing markets differ in the trading rules affecting the information environment and price setting, the clearing mechanism affecting counterparty risk, and the collateral requirements affecting ease of access to funding. In this paper, we show how the trading and clearing mechanisms affect the efficiency-resilience tradeoff in repo markets, why some markets are more efficient but less resilient than others, and why collateral requirements matter more in some markets than others.

We identify a new collateral channel through which safe collateral matters more in anonymous than non-anonymous repo markets. Collateral plays a crucial role in repo markets, both in practice and the model, compared to other unsecured short-term funding markets

[1]Repurchase agreements are collateralized loans based on a simultaneous sale and forward agreement to repurchase the securities at the maturity date. A broad array of assets are financed through repos, the most commonly being U.S. Treasuries, federal agency and mortgage-backed securities, corporate bonds, and money market instruments.

[2]See, e.g., Tilford, C., J. Rennison, L. Noonan, C. Smith, and B. Greeley, "Repo: How the financial markets' plumbing got blocked" in *Financial Times*, November 26, 2019.

and secured long-term lending markets which are not subject to rollover concerns, for two reasons. Collateral improves funding allocations and averts runs. For small funding shocks, anonymous repo markets provide more efficient allocation of liquidity than non-anonymous repo markets only when sufficient high-quality collateral is available to protect the inefficient sale of assets by low-quality borrowers. For large funding shocks, liquid collateral increases resilience against runs more for anonymous than for non-anonymous markets.

Figure 1 illustrates the dichotomy modelled in the paper.[3] To capture pertinent differences in trading and clearing protocols, we compare anonymous to non-anonymous repo trading and bilateral to central clearing, with contract novation and alternative guarantee fund arrangements. Trading in over-the-counter (OTC) repo markets, such as the bilateral and tri-party U.S. customer repo segments, is non-anonymous and clearing is bilateral.[4] Bilaterally-cleared OTC trades are negotiated directly between cash-strapped banks as the dominant borrowers and money-market funds as the dominant cash lenders. By contrast, trading in centralized limit order book (COB) markets is anonymous. In many interdealer repo markets (e.g., GCF Repo and FICC DVP) trades are executed through centralized platforms or interdealer brokers (e.g., BrokerTec) that provide anonymity to both parties of the trade.[5]

Many repo markets with anonymous trading use a central clearing counterparty (CCP). In turn, CCP markets typically but not exclusively feature anonymous trading via a central order book (COB) or masked bilateral negotiation. In the U.S., COB markets with central clearing include GCF Repo and FICC DVP via, e.g., BrokerTec. COB markets with direct settlement include multilateral trading facilities (MTF) with ex-post name give-up. The majority of repo trading in Europe is executed anonymously and centrally cleared.[6] Central clearing comprises contract novation and a default fund. Through novation of consummated

[3]Our dichotomy is not meant to be exhaustive, but rather highlights several features of existing repo markets. For instance, we abstract from differences in settlement (bilateral and triparty) that are material in practice.
[4]U.S. customer repo segments can be split into bilateral and triparty based on the settlement protocol. Bilateral repo is used when market participants want to interact directly with each other or if specific collateral is requested. Triparty is the preferred segment for general collateral funding given the efficiency gains from delegated collateral management. Triparty agents are not CCPs because they do not novate contracts and do not assume credit risk. In our model, the triparty market is effectively the same as the bilateral market.
[5]GFC Repo is a small part of the overall U.S. repo market (Baklanova et al., 2017).
[6]Eurex, BrokerTec, and MTS are leading trading platforms. LCH.Clearnet is a major clearing house.

Trading \ Clearing	**direct**	**central**
non-anonymous	OTC repo market (bilateral & tri-party U.S. customer repo)	Clearinghouse (reform proposals, e.g., Duffie (2020))
anonymous	COB without novation (MTFs with ex-post name give-up)	CCP = COB + novation + default fund (GCF Repo & FICC DVP via e.g. BrokerTec, EUREX, LCH.Clearnet)

Figure 1: Anatomy of repo trading and clearing mechanisms

The figure documents features of different repo trading and clearing mechanisms. We compare non-anonymous trading in over-the-counter (OTC) repo markets to anonymous trading in central order book (COB) markets. Central clearing includes contract novation with or without a default fund. A central clearing counterparty (CCP) market combines anonymous trading with novation and default fund.

repo contracts the CCP becomes the legal counterparty to both borrower and lender. Novation effectively excludes low-quality borrowers from the COB market. Default funds to which all participants contribute provide capital insurance and protect cash lenders against borrower default, so that repo markets can absorb larger funding shocks. Other structures exist where market participants execute a trade with one another on a non-anonymous basis, e.g., on request-for-quote platforms (BrokerTec Quote, Tradeweb AiEX), and then have it centrally cleared. Recent reform proposals, e.g., Duffie (2020), propose to centrally clear bilaterally negotiated Treasury repos.

Our analysis shows that existing market designs are inefficient and their welfare rankings switches repeatedly depending on funding tightness. Anonymous COB trading and collateral yield a larger repayment capacity for the economy than non-anonymous OTC trading when funding shocks are small. Non-anonymous OTC markets however prevent inefficient liquidation of assets for intermediate funding shocks. Anonymous COB trading makes the market more resilient against runs than non-anonymous OTC trading. In OTC markets, narrow runs on single borrowers may occur. To prevent systemic runs in the anonymous market, a CCP has to novate repo contracts. Run resilience is increased through a default fund which makes participants in a CCP market jointly liable to repay lenders.

Several innovations to the trading and clearing mechanisms of repo markets improve welfare. For OTC markets, central clearing of bilaterally negotiated trades helps increase resilience against narrow runs and improve financial stability. For CCPs, a liquidity-contingent trading mechanism makes funding allocations more efficient. In particular, anonymous trading in CCP markets during normal times needs to switch to non-anonymous trading when funding becomes tight. This hybrid trading mechanism is similar to the downstairs/upstairs market system in equity markets (Burdett and O'Hara, 1987; Seppi, 1990; Grossman, 1992), except that the switch occurs depending on aggregate funding conditions. Still, none of these reforms achieve neither the first best nor the privately optimal solution.

A collateral transfer or upgrade mechanism is required to maximize welfare and financial stability. This can be implemented through a two-tiered guarantee fund. The CCP's default fund covers lenders' losses in case of insolvency and, in addition, the CCP's liquidity fund transfers collateral to low-quality borrowers in case of illiquidity. While the former is standard, a liquidity fund is a novel feature to avert fire sales. Alternative implementations are ex-ante agreed upon collateral swaps between borrower banks or ex-post collateral upgrades, as the ECB and Federal Reserve have implemented through emergency facilities (Carlson and Macchiavelli, 2020).

We derive these results in the following model setup. Borrowers (cash-strapped banks) have assets in the forms of a long-term technology (LTT) that they finance through short-term collateralized loans (Brunnermeier and Oehmke, 2013).[7] There are two sources of uncertainty: borrower's credit quality and lenders' funding condition. Borrowers differ in the quality of their LTT, high or low, which is private information. They roll over their loans at an intermediate stage after they learn their LTT quality. Borrowers own risk-free assets that they can use as collateral to mitigate credit rationing. To repay initial loans, borrowers use new loans, and collateral and LTT liquidation. Early liquidation is costly.

We establish first a pecking order in that collateral is liquidated before LTT. Short-term lenders (cash-rich banks, money-market funds) provide funding, but they are subject to funding shocks at the time when borrowers roll over their repos.Sources for funding shocks

[7]LTT captures assets on the borrower's balance sheet with maturity larger than that of repos. Typical maturities of repos are a few days.

are fund outflows, margin calls, and balance sheet constraints.[8] The funding shock is zero or $f > 0$. The pecking order prescribes the following liquidation preference and events triggering a run: The larger the realized funding shock f, the more collateral and eventually LTT have to be liquidated, as done for example by Lehman Brothers and Bear Stearns in 2008. Rational second-round lenders anticipate the borrower's solvency which is determined by the size of the funding shock and the cost of liquidating collateral and LTT. Lenders stop providing loans when the expected borrower solvency does not guarantee the repayment of their loans—a rational incentive-based run occurs.

Repo market structure determines the run type and, as a result, affects the tradeoff between funding allocation and the resilience to liquidity crises. A key feature of OTC markets is non-anonymity in trading. Knowing your counterparty diminishes adverse selection risk and allows lenders to condition loan terms on borrowers' credit quality and, if needed, ration repo credit. Through discriminatory repo pricing, the low quality borrower bears the cost of the funding shock. The benefit of this is, the high quality borrower obtains the funding needed and can fully rollover their initial loan without liquidating collateral or LTT. The cost however is, that the low quality borrower has to liquidate the LTT when there is still cheaper to liquidate collateral in the economy, albeit in the high quality borrower's hands. Ultimately, the low quality borrower is subject to a narrow run when the repayment capacity from LTT and collateral is depleted. This occurs for intermediate funding shocks.

By contrast, borrowers and lenders in anonymous repo markets agree on the loan terms through a COB without observing the counterparty's identity. The anonymity maintained in trading and clearing requires nondiscriminatory pricing of all repo loans and in this way provides insurance to low-quality borrowers at the rollover stage. The one-fits-all loan yields that in case of a funding shock, low- and high-quality borrowers have to liquidate the same amount of collateral and LTT. The implicit subsidy through the loan contract is welfare beneficial as long as the high quality borrower is only liquidating collateral. It is detrimental as soon as the high quality borrower has to liquidate LTT. While anonymous markets are resilient to narrow runs, they are susceptible to systemic runs on all borrowers for large funding shocks, leading to market breakdown.

[8] He et al. (2021) document that dealers' balance sheets were constrained during the Covid-19 pandemic.

Systemic runs can be averted by novation. The CCP novates the loan contract by becoming the legal counterparty to both the borrower and lender. Through novation, the CCP effectively excludes low-quality borrowers for large funding shocks, so that lenders continue to provide loans to high-quality borrowers which prevents adverse selection. The implication is that an anonymous COB market must be paired with a novation process involving a rigorous vetting procedure of borrowers by the CCP in order to prevent market breakdown.

The default fund covers the lenders' losses in case of a borrower's default.[9] Through the default fund, the resilience to funding runs increases as it allows to transfer profits from solvent to insolvent borrowers. The default fund is individually rational only if borrowers commit to their contribution before they know their credit quality. We compute the size of the default fund. Only a sufficiently equipped default fund is effective in instilling confidence in lenders to provide funding.

Collateral plays a dual role in the model. High-quality liquid collateral improves both efficiency and resilience independent of repo market structure. Collateral quality however impacts OTC and CCP markets differently. When the borrower's LTT is illiquid, an increase in collateral liquidity makes the CCP market more resilient than the OTC market, and vice versa. This prediction is consistent with the stylized fact that CCPs often impose stringent collateral requirements.

The convenience yield on collateral, or collateral premium stems from the usage of the risk-free asset as collateral. In the model, the convenience yield switches between two regimes depending on borrowers' credit quality, and the probability and size of funding shocks. As a result, the convenience yield can rise or fall with funding tightness. The latter dynamics are consistent with the fall in treasury convenience yield documented by He et al. (2021).

The most common market structures, non-anonymous bilaterally-cleared OTC market and CCP market with anonymous COB, novation and default fund, neither welfare dominate each other nor achieve first best for any funding shock. The resilience to funding runs depends crucially on the liquidity of the LTT. For a given size of funding shock, the CCP is more resilient against runs than the OTC market when the LTT is illiquid. This highlights the

[9]CCP participants make contributions to the default fund that are regularly updated based on exposure and activity. We focus on the life cycle of a single project for which CCP participants contribute once at the investment stage.

insurance effect of the CCP in crisis times when funding is scarce and assets are illiquid.

The ranking in terms of resilience echoes the empirical evidence from the GFC and the repo blowups in 2019/20. The halt of the repo market during the GFC occurred in the OTC market, whereas the repo blowups in 2019/20 occurred in the CCP based interdealer market. The outbreak of the GFC was characterized by both a funding crisis and a decline in asset liquidity which makes the OTC market more susceptible to runs. In contrast, during the 2019/20 blowups, funding dried up but asset liquidity was hardly affected indicating that the CCP market is more susceptible to runs than the OTC market.

We derive a privately optimal market solution that achieves first best. The optimal market solution entails two types of transfers from high- to low-quality borrowers—a collateral transfer for small and moderate funding shocks, and both collateral and profit transfers for large funding shocks. The collateral transfer ensures efficient resource allocation by preventing liquidation of the low-quality borrowers' LTT. The profit transfer increases the threshold up to which lenders are willing to fund low-quality borrowers, increasing market resilience. The optimal market solution shows that the two common market structures can be improved by combining existing market features. The CCP market needs to switch from an anonymous to a non-anonymous trading mechanism for large funding shocks. This liquidity-contingent switch in trading technology improves resource allocation over existing CCP markets. The resilience of bilateral OTC markets can be improved by adopting a central-clearing mechanism that requires participants to contribute to a default fund. To this extent the optimal market solution in our model offers insights to the ongoing policy debate in the U.S. about whether to move repo contracts, after they have been agreed OTC, on a central-clearing platform (Duffie, 2020). To achieve first best, an incentive compatible two-tiered guarantee fund is needed. The fund features two types of transfers, a collateral transfer for small funding shocks to prevent liquidation of the low-quality borrowers' LTT, and a profit transfer for large funding shocks to prevent inefficient defaults.

Literature. Our paper relates to several strands of literature. Martin et al. (2014a,b) and Heider et al. (2015) study the breakdown of different interbank markets. Martin et al. (2014a,b) show that non-anonymous triparty repo markets are subject to runs and bilateral repo markets suffer from drawn out losses of funding and eventual collapse. In their model runs occur due to coordination failure in a maturity-mismatch model with homogeneous borrower quality. Heider et al. (2015) study the adverse-selection problem of unsecured loans in anonymous markets. We study the difference between non-anonymous OTC and anonymous CCP markets in a dynamic model of collateralized lending with heterogeneous borrower quality and a rational incentive-based run mechanism. We vary the information environment and highlight how the tradeoff between market resilience and resource allocation depends on the degree of asymmetric information and funding tightness.

A growing literature discusses the role of CCPs in derivatives markets and their welfare implications. Duffie and Zhu (2011) show that in derivatives markets a single CCP, through multiple netting, can reduce counterparty risk. Biais et al. (2016, 2020) study optimal risk sharing in derivatives markets and show that novation in CCP markets and optimal margin requirements can provide insurance against counterparty risk. These papers focus on the role of derivatives markets in risk sharing. Our paper focuses on lending markets and their ability to allocate funding efficiently while providing financial stability. In addition, we highlight the different roles played by anonymity, collateral, novation and default fund.

Our paper also intersects with the optimal opacity literature (Bouvard et al., 2015; Dang et al., 2017; Goldstein and Leitner, 2018) and the maturity mismatch literature (Diamond and Dybvig, 1983; Postlewaite and Vives, 1987; Goldstein and Pauzner, 2005). In the optimal opacity literature, our model is closest to Dang et al. (2017) who assume that the economy's endowment is large enough to satisfy consumption needs and investment, ruling out runs. Transparent capital markets in Dang et al. (2017) are similar to our OTC markets in that lenders condition their loans on borrowers' type, while their opaque bank setting is similar to our CCP market as lenders provide one-fits-all loans to different borrowers. We complement their analysis by allowing for scarce funding such that the economy's endowment is insufficient to fully fund both consumption needs and investment. We show that anonymity in the CCP market in the presence of scarce funding has important welfare effects arising from the efficiency-resilience tradeoff.

Hirshleifer (1971) was the first to point out the benefit of asymmetric information when it comes to risk sharing. We show that the fundamental tradeoff brought about by asymmetric information also extends to resource allocation. In addition, and different from the previous literature (Bouvard et al., 2015; Goldstein and Leitner, 2018) utilising the Hirshleifer effect, we show, in the presence of collateral and asymmetric information, the welfare benefits and costs of asymmetric information switch repeatedly depending on aggregate (funding) risk. We highlight a novel collateral channel through which asymmetric information is beneficial even for small levels of risk.

In line with the literature building on Diamond and Dybvig (1983), we consider risk about borrowers' liability side.[10] We augment the maturity mismatch problem by considering risk about borrowers' asset side. Our study contributes to the work on endogenous bank runs (Postlewaite and Vives, 1987; Allen and Gale, 1998). Postlewaite and Vives (1987) introduced the notion of run due to self interest. In this literature, agents run even if others do not, unlike in panic-based runs (Chen, 1999; Goldstein and Pauzner, 2005). Following Postlewaite and Vives (1987), lenders are subject to an observable, stochastic funding shock at the rollover stage. We implement this idea to unite lender types (early and late) and aggregate state of the economy (sunspot) in order to derive unique equilibria with and without run. Our study differs along several dimensions from Allen and Gale (1998), but most notably we consider heterogeneous borrowers and asymmetric information about their stochastic production functions.

Finally, we contribute to the literature on collateral value (Oehmke, 2014; Parlatore, 2019; Gottardi et al., 2019). We show that collateral has a differential effect on market resilience depending on market structure. Our model is consistent with the different empirical patterns of collateral convenience yields between the GFC and Covid-19 pandemic (He et al., 2021). In addition, we derive equilibria featuring runs on borrowers due to a combination of liquidity, counterparty and collateral risk complementing the work by Infante and Vardoulakis (2021) and Kuong (2021).

The remainder of the paper is organized as follows. Section 2 describes the model and Section 3 derives a constrained social planner solution. Section 4 compares anonymous and non-anonymous repo markets. Section 5 analyses CCP market features. Section 6 explores how to implement an optimal repo market. Section 7 demonstrates the effect of collateral.

[10] Gorton and Winton (2003) provide an excellent survey of the maturity mismatch literature.

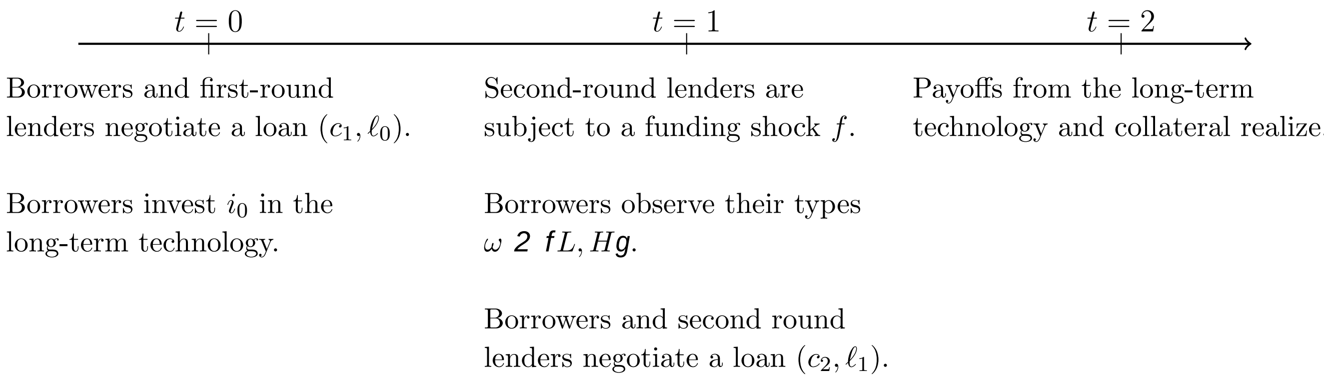

Figure 2: Timeline

Section 8 concludes. All proofs are contained in the Appendix.

2 Model

Consider an economy with two rounds of short-term lending at $t = 0, 1$, terminal date $t = 2$, two types of borrowers, and a continuum of lenders. All agents in the economy are risk neutral and there is no discounting. At $t = 0$, borrowers seek one-period loans to invest in a long-term technology (LTT). At $t = 1$, the economy is subject to a funding shock and borrowers and lenders take the rollover decision on maturing first-period loans. Second-period loans mature and payoffs from the LTT realize at $t = 2$. Figure 2 summarizes the sequence of events.

Agents and assets. There are two generations of a finite mass of $2m$ lenders with unit endowment of cash per lender. Lenders are present in the market for one period, entering at $t = \{0, 1\}$ and exiting at $t + 1$. When they exit, they consume both their initial endowment and investment return, c_{t+1}. Second-round lenders are subject to an exogenous funding shock f with a distribution that is known to all agents at $t = 0$.[11] With probability $(1 - \alpha)$

[11] This assumption renders the funding run in our model different from the global games approach in which lenders receive idiosyncratic signals about the prior probability of the funding shock.

the funding shock is $f = 0$ and with probability α the funding shock is $f > 0$.[12] The larger the funding shock, f, the larger the difference between the economy's funding endowment at the rollover stage, $t = 1$, and the investment stage, $t = 0$, i.e. $2(1 - f)m < 2m$. This implies $f \in [0, \frac{1}{2})$. The funding shock captures in a reduced form lenders' margin calls, fund outflows, or balance sheet constraints.

The LTT's quality is borrowers' private information and they learn it over time. At $t = 0$, agents know there will be a high-type R^H with probability β and a low-type borrower R^L with the probability $1 - \beta$. Asymmetric information is a key friction in interbank lending. For example, during the GFC market participants knew that their counterparties had toxic assets on their balance sheets, they just did not know who held how much.

We study the relevant case in which the two borrowers turn out to be of opposite type. If borrowers are of identical type, resource allocation does not matter. At the investment stage, $t = 0$, each borrower invests i_0 in the LTT yielding a gross return R^ω at $t = 2$ depending on type $\omega \in \{L, H\}$.

At $t = 1$, borrowers learn their type R^ω. Early liquidation of the LTT is costly and yields $\lambda < 1$ per unit of investment. At $t = 2$, payoffs from the long-term technology realize.

Assumption 1 *Aggregate funding risk f and idiosyncratic borrower risk R^ω realize simultaneously at the rollover stage, $t = 1$. At this stage, funding risk is publicly observable whereas borrower risk is private information.*

Repo loans are collateralized. Each borrower has a collateral endowment of $k_0 = m$ at $t = 0$. The value of collateral is given by κ_t per unit of collateral at $t = \{0, 1, 2\}$. We assume that $\kappa_1 \leq \kappa_0$ and $\kappa_2 = \kappa_0$, that is, there are collateral liquidation costs at $t = 1$ while the long-term return on collateral is normalized to zero.[13] Repo haircuts are given by the relative

[12] The Postlewaite and Vives (1987) critique of Diamond and Dybvig (1983) says a bank run is not part of the equilibrium which features the first-best solution. By assuming an observable stochastic funding shock on second-round lenders, we implement their idea (Postlewaite and Vives, 1987) to unite lender type (early and late) and aggregate state of the economy (sunspot) which allows us, as suggested by Postlewaite and Vives (1987), to derive unique equilibria with and without run respectively. We show under which conditions the equilibria with and without run, respectively, attain the first-best solution.

[13] We capture collateral liquidation costs in a reduced form with $\kappa_1 < \kappa_0$. Oehmke (2014) discusses the issues arising from liquidating collateral, justifying the assumption of collateral liquidation cost.

difference between collateral value and loan value, i.e., $\frac{\kappa_t k_t}{\ell_t} \quad 1$.[14]

Repayment conditions. Borrowers require funding to invest in their LTT. At $t = 0$, they enter a one-period loan contract in which they borrow ℓ_0 at a gross interest rate of $c_1 \quad 1$ from first-round lenders. Borrowers invest at most the entire loan $i_0 \quad \ell_0$.

At $t = 1$, borrowers need to roll over maturing loans. We adopt the following assumption to define the parameter space where resource allocation matters.

Assumption 2 *At least one borrower can fully roll over their initial loan from lenders' resources,* $2(1 \quad f)m \quad c_1\ell_0$.

To continue their long-term technology, borrowers can use a mix of new loans, proceeds from liquidation of collateral, and proceeds from liquidation of the LTT. Second-round lenders provide new loans ℓ_1 at gross loan rate c_2. Partial liquidation of collateral $w_1 \quad k_0$ yields $\kappa_1 w_1$. Partial liquidation of the LTT $z_1 \quad i_0$ generates λz_1. Both the proceeds from liquidating collateral and the LTT can be used to repay maturing loans. To roll over initial loans at $t = 1$, the repayment condition has to be satisfied:

$$c_1\ell_0 + \ell_1 + \kappa_1 w_1 + \lambda z_1 = 0. \tag{1}$$

The repayment condition (1) holds because early liquidation of collateral and LTT as well as new loans, ℓ_1, are costly.

Assumption 3 *The opportunity cost from liquidating the LTT is larger than the opportunity cost from liquidating collateral,* $\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1} \quad 1$.

Assumption 3 establishes a pecking order in which assets are liquidated. At the rollover stage, it is always cheaper to liquidate collateral than the LTT. While Assumption 3 encompasses negative net present value (NPV) projects, to help intuition consider positive NPV projects, i.e., $R^H > R^L \quad 1 > \lambda$.

[14] In a model with risk-neutral agents and scarce collateral, haircuts are naturally negative (Parlatore, 2019). If we take a broader view on collateral and consider the borrower liable for the loan not only with the asset valued at κ_t but also with the LTT, then the haircut is positive. For example, the haircut on the first-round loan is $\frac{E(R)i_0+\kappa_1 k_0}{\ell_0} \quad 1 > 0$, where $E(R)$ is the expected return of the LTT.

Borrowers default if they do not obtain a large enough loan ℓ_1 to roll over initial loans. The borrower's default value at $t = 1$ comprises the liquidation values of LTT and collateral, $\lambda i_0 + \kappa_1 k_0$. We focus on the case in which there is insufficient liquidation value from both LTT and collateral to repay first-round lenders,[15]

Assumption 4 *Collateral is scarce,* $c_1 \ell_0 \geq \lambda i_0 + \kappa_1 k_0$.

In default, borrowers are protected by limited liability, and therefore the liquidation value is zero. First-round lenders are then repaid the default value $c_1^D \leq c_1$, given by $c_1^D \ell_0 = \lambda i_0 + \kappa_1 k_0$.

For borrowers to continue their LTT at $t = 1$, the continuation value has to exceed the liquidation value:

$$R^\omega (i_0 - z_1) - c_2 \ell_1 + \kappa_2 (k_0 - w_1) \geq 0. \tag{2}$$

The continuation value is the left-hand side (LHS) of (2). The gross return R^ω of the LTT is scaled by $(i_0 - z_1)$. The latter is the amount that is still invested in the technology after liquidation. Borrowers have to repay $c_2 \ell_1$ to second-round lenders that require a gross return of $c_2 \geq 1$. The gross return from collateral after partial liquidation amounts to $\kappa_2 (k_0 - w_1)$. Note an important difference to the continuation value in Bouvard et al. (2015). While Bouvard et al. (2015) consider a fixed return, the return here is scalable $R^\omega (i_0 - z_1)$. We will show that this difference in production functions reverses some of the results of Bouvard et al. (2015). Alternatively, borrowers can default on the initial loan which causes liquidation of their assets and yields, by Assumption 4 and limited liability, a value of zero, which is the right-hand side (RHS) of (2). All proofs are provided in the Appendix.

3 Constrained social planner solution

We start by studying the first best solution with symmetric information and a social planner who is bound to repay first generation lenders. This provides a benchmark and illustrates the role of transfers between borrowers.

[15] This assumption can be relaxed without qualitatively affecting the main results by allowing LTT and collateral returns at $t = 1$ to be more than sufficient to repay initial loans.

At $t = 0$, first-round lenders provide equal shares of their cash endowment to each borrower, $\ell_0 = m$, if lenders' net profit is weakly positive, $c_1 \geq 1$.[16] With a positive expected return from the long-term technology, borrowers invest the entire loan amount in the LTT, $i_0 = \ell_0$. From a welfare perspective, it is optimal to give zero profit to first-round lenders, $c_1 = 1$, as it reduces the funding required at the rollover stage.[17]

At $t = 0$, the social planner maximizes ex-ante net welfare. Therefore, taking a loan and investing it in the LTT, $i_0 = \ell_0 = m$, must weakly exceed ex-ante welfare from liquidating collateral and investing the proceeds in the LTT. Note, liquidating collateral and investing in the LTT is always larger than net welfare from merely holding collateral to maturity.

At $t = 1$, the social planner conditions loan terms on borrower types, $(c_2^\omega, \ell_1^\omega)$ for $\omega \in \{L, H\}$, and on the realization of the funding shock f. In case of a funding shock, $f > 0$, the social planner maximizes welfare by rolling over the H-type loan. The funding available from second-round lenders to the L-type borrower is the residual:

$$\ell_1^H = c_1 \ell_0 = m, \quad \ell_1^L = 2m(1 - f) - \ell_1^H = m(1 - 2f). \tag{3}$$

The pecking order dictates that the social planner first liquidates the collateral of both borrowers, $2\kappa_0 k_0$, up to the point at which the funding shock exceeds the collateral endowment, $f > \kappa_1$. The social planner redistributes part of the H-type profit to second-round lenders of the L-type. In a risk neutral economy, the redistribution of profits has no direct impact on welfare. In case of no funding shock, $f = 0$, both borrowers obtain equal size loans, $\ell_{1,f=0}^\omega = m$, that allow them to roll over their loans without liquidating collateral or LTT.

Next, we derive the largest funding shock that an economy with a social planner can withstand. There are two cases depending on the relation between the return of collateral and the funding shock. First, if $0 < f \leq \kappa_1$, there is enough collateral in the economy to

[16] We are considering the first-best solution which enforces full repayment of first-round lenders. We use this benchmark because we want to highlight the problem of funding shortage at the rollover stage, $t = 1$, and how it can be mitigated through transfers. Welfare could be further maximized by letting first-round lenders default as this would effectively eliminate the maturity mismatch problem and allow borrowers to continue the LTT to maturity.

[17] For the remainder of the paper we assume that at $t = 0$, borrowers hold the bargaining power such that lenders individual rationality constraint is binding. This assumption is for tractability and can be relaxed. In fact, it can be shown that all the main results carry through if lenders at $t = 0$ make a positive profit.

make up for the missing funding from second-round lenders. First-round lenders are repaid with a mix of new loans and collateral, $-2c_1\ell_0 + \ell_1^H + \ell_1^L + 2\kappa_1 w_1 = 0$, which yields

$$w_1 = \frac{m}{\kappa_1} f. \tag{4}$$

The larger the funding shock, the more collateral has to be liquidated. The effect is amplified by less liquid collateral, that is, if κ_1 is smaller.

In the second case, borrowers' collateral is exhausted and the social planner has to liquidate the L-type LTT, that is, if $\kappa_1 < f \le \frac{1}{2}$. Then the repayment condition yields the amount of liquidation of the L-type LTT, $-2c_1\ell_0 + \ell_1^H + \ell_1^L + 2\kappa_1 k_0 + \lambda z_1^L = 0$, or

$$z_1^L = \frac{2m}{\lambda}(f - \kappa_1). \tag{5}$$

The larger the funding shock the more of the LTT has to be liquidated, while a larger return on collateral, κ_1, reduces the amount liquidated. The more illiquid the LTT, that is the smaller λ, the more of the LTT has to be liquidated.

We are now ready to state the maximum funding shock the social planner economy can withstand which is given when welfare is zero. This determines the funding shock at which all collateral is liquidated, part of the L-type LTT and the H-type's profit is used up. The following proposition summarizes the results.

Proposition 1 (first-best run threshold and welfare) *Given repayment of first-round lenders, the social planner maximizes welfare by imposing two types of transfers, the liquidation of the H-type collateral and the use of the H-type profit to repay second-round lenders of the L-type. The largest funding shock that the economy can withstand is*

$$f^{FB} = \frac{R^H + R^L - 2}{R^L - \lambda}\frac{\lambda}{2} + \frac{R^L}{R^L - \lambda}\kappa_1 - \frac{\lambda}{R^L - \lambda}\kappa_0. \tag{6}$$

Ex-post welfare conditional on the funding shock is

$$W^{FB} = \begin{cases} (R^H + R^L - 2)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m & \text{if } 0 \le f \le \kappa_1, \\ (R^H + R^L - 2)m + 2\kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m - 2f(\frac{R^L}{\lambda} - 1)m & \text{if } \kappa_1 < f \le f^{FB}. \end{cases} \tag{7}$$

For $0 \leq f \leq \kappa_1$ in expression (7), welfare decreases in the size of the funding shock but less so the smaller the difference between the collateral's liquidation value κ_1 and the collateral's value at maturity κ_2.

If $\kappa_1 < f \leq f^{FB}$ in expression (7), the intermediate collateral value, κ_1, helps to preserve the LTT and the positive value is reflected in the expression $\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1}$ which is strictly positive by the assumption on the pecking order. Ex-post welfare decreases in the funding shock and the more so the larger the foregone profit of liquidating the L-type LTT, $(\frac{R^L}{\lambda} - 1)$.

4 Repo Market Structure, Efficiency, and Resilience

In this section, we study the impact on resource allocation, resilience to funding shocks, and welfare of the trading mechanisms in OTC and COB markets, respectively. The different trading mechanisms impact the information environment at the rollover stage. In Section 5, we turn to the clearing mechanisms of a CCP, novation and default fund.

In the OTC market, there is no information asymmetry and, hence, lenders are able to condition loan terms on borrower type, $(c_2^\omega, \ell_1^\omega)$ with $\omega \in \{L, H\}$. In the COB market, there is asymmetric information about the borrower type.[18] In this case, we characterize Perfect Bayesian Equilibria in which agents contract on gross loan rate and loan amount (c_2, ℓ_1). We focus on the pooling equilibrium in which the two borrowers obtain the same loan (c_2^P, ℓ_1^P) as a distinguishing outcome of COB markets as it represents best the idea that lenders provide one-fits-all loans to an average borrower in anonymous centrally cleared markets.[19] We proceed by characterizing run thresholds, lending terms, and welfare for the OTC and COB markets in Sections 4.1 and 4.2. We distinguish two run types:

Definition 1 *A narrow run is an equilibrium in which second-round lenders refuse to provide*

[18] For our theoretical results to hold, the lender does not need to know exactly the quality of the borrower's long-term technology in OTC markets. Instead, the lender has to know more about the borrower type in OTC markets than in COB markets. That is, our model highlights the effects of an informational wedge between OTC and COB markets.

[19] In Appendix F, we show that for the relevant parameter space the pooling equilibrium welfare dominates the separating equilibrium. CCPs, which are usually profit maximizing entities, should therefore try to coordinate the market on the pooling equilibrium. The decision to have participants trade anonymously can be seen as an effort to coordinate on the pooling equilibrium. This maximizes welfare and therefore the CCP's ability to derive profit.

loans to the L-type for funding shocks $f \in \Phi$. A systemic run is an equilibrium in which second-round lenders refuse to provide loans to any type for funding shocks $f \in \Psi$.

4.1 OTC market: Loans, run threshold, and welfare

Lenders in the OTC market observe borrowers' identity and condition their loan terms on the borrowers' type, $(c_2^{\omega}, \ell_1^{\omega})$ for $\omega \in \{L, H\}$. Loan contracts, run threshold, and welfare are the ones of a constrained first-best solution. The constrained first-best solution deviates from the constrained social planner solution in Section 3, insofar as borrowers' and lenders' individual rationality constraints have to be satisfied.

The run threshold f^{OTC} is the largest funding shock up to which both borrower types are able to repay their loans $c_1\ell_0$ to first-round lenders. Beyond this threshold only the H-type continues to obtain funding from second-round lenders whereas L-type borrower is refused further loans. The L-type therefore defaults on the loans from first-round lenders and they obtain the L-type's liquidation value $c_1^D \ell_0$. By contrast, both types of borrowers are able to repay their initial loans when there is no funding shock. Below we derive the equilibrium threshold f^{OTC}.

First-round lenders provide equal shares of their cash endowment to each borrower, $\ell_0 = m$, so long as their net profit is weakly positive. The lenders' individual rationality (IR) constraint requires

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{OTC}, \\ \alpha(\beta c_{1,f>f^{OTC}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{OTC}} & \text{if } f > f^{OTC}. \end{cases} \tag{8}$$

The individual rationality constraint (8) is from a single lender's perspective and, therefore, the conditions are expressed per unit of loan. We differentiate between the gross loan rate c_1 for $f \leq f^{OTC}$ and the gross loan rate $c_{1,f>f^{OTC}}$ for $f > f^{OTC}$. With borrowers holding all bargaining power at $t = 0$, expression (8) holds with equality.[20] Furthermore, borrowers compute the expected profit by taking into account the distributions of funding shock and

[20] For the remainder of the paper we assume lender competition at $t = 0$ but this assumption can be relaxed and lenders can be allowed a positive profit.

LTT quality. Therefore, they finance the LTT with loans, $i_0 = \ell_0$, instead of liquidating collateral and investing it in the LTT if the expected return from the former is weakly larger than the return from the latter.[21]

At $t = 1$, borrowers' individual rationality constraint reflects the cash-flow as described in expression (2) conditional on borrower type and subject to the repayment condition of first-round lenders:[22]

$$\text{Borrower IR:} \qquad R^{\omega}(i_0 - z_1^{\omega}) - c_2^{\omega}\ell_1^{\omega} + \kappa_2(k_0 - w_1^{\omega}) \geq 0, \tag{9}$$

$$s.t. \qquad -c_1\ell_0 + \ell_1^{\omega} + w_1^{\omega}\kappa_1 + z_1^{\omega}\lambda = 0. \tag{10}$$

Last, the model is about scarcity of funding at the rollover stage. To capture this effect in the loan terms, we make the additional assumption that borrowers compete for funding by setting interest rates at $t = 1$ à la Bertrand.[23]

Assumption 5 *Lenders set interest rates at $t = 1$ by take-it-or-leave-it offers to perfectly competitive borrowers.*

Under Assumption 5, the loan contracts are

$$c_2^{OTC} = c_2^H = c_2^L = \frac{R^L(i_0 - z_1^L) + \kappa_2(k_0 - w_1^L)}{\ell_1^L}, \tag{11}$$

$$\ell_1^H = c_1\ell_0, \quad \ell_1^L = 2(1 - f)m - \ell_1^H. \tag{12}$$

Competition drives the L-type borrower's loan rate up to their break-even condition, $R^L(i_0 - z_1^L) - c_2^L\ell_1^L + \kappa_2(k_0 - w_1^L) = 0$, which yields (11). The H-type borrower can attract, by outbidding the L-type borrower by an infinitesimal amount, the funding needed to repay maturing loans, $\ell_1^H = c_1\ell_0$. By assumption, funding supply weakly exceeds the borrowing need of one borrower, $2(1 - f)m \geq c_1\ell_0$. Given the infinitesimally larger rate offered by the H-type borrower, lenders compete to fund the H-type borrower by underbidding each

[21] The explicit derivations of borrowers' individual rationality constraint are deferred to Appendix B.

[22] Since the return from liquidating both assets is weakly smaller than what is owed to first-round lenders, $\kappa_1 k_0 + \lambda i_0 \leq c_1\ell_0$, the outside option for borrowers, in expression (9), is zero due to limited liability.

[23] While borrower competition at $t = 1$ seems to be the natural assumption, the bargaining power can be reversed, so that lenders are competitive, without affecting the main results.

other until $c_2^H = c_2^L = c_2^{OTC}$. The L-type borrower hence obtains the residual funding, $\ell_1^L = 2(1 - f)m - \ell_1^H$.

For second-round lenders to be willing to provide loans, their individual rationality constraint has to be satisfied.

$$\text{Lender IR:} \qquad c_2^{OTC} \geq 1. \tag{13}$$

When lenders decide on providing a loan, they contemplate the loan rate provided by the L-type's break-even condition in (11). In particular, knowing the size of the funding shock, lenders know how much of collateral and LTT has been liquidated which, in turn, implies lenders anticipate how much the L-type borrower is able to repay at $t = 2$. Second-round lenders' loan provision depends on the size of the funding shock. The larger the funding shock, the more of the L-type borrower's collateral and LTT has to be liquidated reducing the capacity to repay the loan. For small realizations of the funding shock, $0 \leq f \leq \frac{\kappa_1}{2}$, the L-type has to partially liquidate collateral. For $f > \frac{\kappa_1}{2}$, the L-type's collateral is used up and they have to partially liquidate the LTT. The largest funding shock up to which second-round lenders provide loans to both types is given by their break even condition, $c_2^{OTC} = 1$, which yields f^{OTC}. First-round lenders do not require a risk premium and from expression (8), we obtain $c_1 = 1$. For large funding shocks $f > f^{OTC}$, lenders do not provide loans to the L-type borrower. The following proposition summarizes the OTC market equilibrium depending on the realization of the funding shock $f > 0$.[24]

Proposition 2 (OTC equilibrium) *A narrow run occurs in the OTC market if the funding shock exceeds the threshold*

$$f^{OTC} = \frac{R^L - 1}{R^L - \lambda}\frac{\lambda}{2} + \frac{R^L}{R^L - \lambda}\frac{\kappa_1}{2}. \tag{14}$$

The H-type borrower always rolls over their initial loan without liquidation of neither LTT, $z_1^H = 0$*, nor collateral,* $w_1^H = 0$*. The L-type borrower adopts the strategy:*

1. *For* $0 \leq f \leq \frac{\kappa_1}{2}$*, the L-type partially liquidates collateral,* $w_1^L = \frac{2f}{\kappa_1}m$*, and continues the LTT to maturity,* $z_1^L = 0$*.*

[24] Note $\frac{1}{2} \geq f^{OTC} > \frac{\kappa_1}{2}$ if $\kappa_1 + \lambda \leq 1$ which satisfies the initial assumption.

2. *For $\frac{\kappa_1}{2} < f \leq f^{OTC}$, the L-type liquidates the entire collateral, $w_1^L = k_0$, and partially liquidates the LTT, $z_1^L = \frac{2f - \kappa_1}{\lambda} m$.*

3. *For $f > f^{OTC}$, the L-type liquidates both collateral and LTT.*

A narrow run is therefore defined by $\Phi : (f^{OTC}, \frac{1}{2})$. Expression (14) illustrates that liquid collateral, $\kappa_1 > 0$, increases the run threshold. While the threshold decreases in the opportunity cost of liquidating the LTT, $R^L - \lambda$, it increases in the returns from the LTT both at the rollover stage, λ, and at maturity, R^L.

4.2 COB market: Loans, run threshold, and welfare

CCP markets operate through a COB which creates asymmetric information about borrower types. The COB allows borrowers to post loan demand specifying loan amount, rate, and collateral. The lender can lift the post but does not observe the borrower's identity in a COB which precludes the lender from assessing counterparty risk. We return to the other key features of a CCP market in Section 5.

We derive a Perfect Bayesian equilibrium and focus on the pooling equilibrium as a distinguishing outcome of the COB. In the pooling equilibrium borrowers obtain a loan contract independent of their type, (c_2^P, ℓ_1^P) for $\omega \in \{L, H\}$. The threshold f^{COB} is the largest funding shock up to which both borrowers are able to repay their loans $c_1 \ell_0$ to first-round lenders. Beyond this threshold lenders stop providing loans altogether, i.e., there is a systemic run, so that first-round lenders are only repaid borrowers' liquidation value $c_1^D \ell_0$.

At the investment stage, $t = 0$, first-round lenders provide equal shares of their cash endowment to each borrower, $\ell_0 = m$, so long as their net profit is weakly positive. These arguments yield the lenders' individual rationality constraint

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{COB}, \\ \alpha c_1^D + (1 - \alpha) c_{1, f > f^{COB}} & \text{if } f > f^{COB}. \end{cases} \tag{15}$$

With borrowers holding the bargaining power at $t = 0$, expression (15) is binding. Borrowers compute the expected profit at $t = 0$ taking into account the distributions of funding shock and LTT quality. Therefore, they finance the LTT with loans, $i_0 = \ell_0$, instead of liquidating own collateral and investing it in the LTT. We come back to the optimality of using loans instead of liquidating collateral when we discuss the collateral convenience yield in Section 7.2.

At the rollover stage, $t = 1$, in a pooling equilibrium, second-round lenders condition loan terms on the funding shock, f, only and not on borrower type. We define lenders' beliefs as

$$Pr(R^H j c_2) = \begin{cases} \beta & \text{if } c_2 = c_2^P, \\ 1 & \text{otherwise.} \end{cases} \tag{16}$$

On the equilibrium path, lenders cannot infer types from the loan contract and keep their prior beliefs. Off the equilibrium path, lenders believe to face the H-type borrower for any loan rate $c_2^{\emptyset}$. In Appendix C, we show that this specification of lenders' beliefs survives the Intuitive Criterion.

Borrowers' individual rationality constraint take into account the cost of the new loan and the liquidation of LTT and collateral. Furthermore, it is subject to the repayment condition of first-round lenders:

$$\text{Borrower IR:} \qquad R^{\omega}(i_0 \quad z_1^P) \quad c_2^P \ell_1^P + \kappa_2(k_0 \quad w_1^P) \quad 0 \tag{17}$$

$$s.t. \qquad c_1\ell_0 + \ell_1^P + \lambda z_1^P + \kappa_1 w_1^P = 0 \tag{18}$$

Furthermore, for borrowers not to deviate from the equilibrium path, the following incentive compatibility constraint (IC) has to be satisfied

$$\text{Borrower IC:} \quad R^{\omega}(i_0 \quad z_1^P) \quad c_2^P \ell_1^P + \kappa_2(k_0 \quad w_1^P) \quad R^{\omega}(i_0 \quad z_1^{\emptyset}) \quad c_2^{\emptyset}\ell_1^{\emptyset} + \kappa_2(k_0 \quad w_1^{\emptyset}). \tag{19}$$

The LHS of expression (19) represents the equilibrium payoff of borrower type ω and the RHS of expression (19) represents the off-equilibrium payoff. The latter is determined by lenders' beliefs as specified in expression (16). The off-equilibrium belief prescribes that lenders believe to face the H-type when observing a deviation ($c_2^0 = R^L + \kappa_2, \ell_1^0 = c_1\ell_0$).[25] The off-equilibrium repayment condition yields that neither LTT nor collateral have to be liquidated, i.e., $z_1^0 = 0$ and $w_1^0 = 0$.

At $t = 1$, second-round lenders require at least their initial investment back,

$$\text{Lender IR:} \qquad c_2^P \geq 1. \tag{20}$$

As long as lenders' individual rationality constraint (20) is satisfied, they provide their entire cash endowment as loans. Lenders take into account the size of the funding shock when deciding on providing a loan. Knowing the size of the funding shock, lenders anticipate how much collateral and LTT have been liquidated which, in turn, implies lenders know how much the L-type borrower is able to repay at $t = 2$. Since they cannot condition on borrower types, lenders offer a one-fits-all loan that in total amounts to half of the cash endowment per borrower, $\ell_1^P = (1 - f)m$, for any size funding shock up to the run threshold, $0 \leq f \leq f^{COB}$. Lenders' break-even condition pins down the run threshold f^{COB} when (20) holds with equality. The following proposition summarizes the COB market equilibrium depending on the realization of the funding shock $f > 0$.

Proposition 3 (COB equilibrium) *A systemic run occurs in the COB market if the funding shock exceeds the threshold*

$$f^{COB} = \frac{R^L - 1}{R^H - \lambda}\lambda + \frac{R^H}{R^H - \lambda}\kappa_1. \tag{21}$$

Borrowers adopt the strategy:

(i) For $0 \leq f \leq \kappa_1$, both borrower types partially liquidate collateral, $w_1^P = \frac{f}{\kappa_1}m$, and continue the LTT to maturity, $z_1^P = 0$.

(ii) For $\kappa_1 < f \leq f^{COB}$, both borrower types liquidate collateral entirely, $w_1 = k_0$, and partially liquidate the LTT, $z_1^P = \frac{f - \kappa_1}{\lambda}m$.

(iii) For $f > f^{COB}$, both borrower types liquidate both collateral and LTT.

[25] In Appendix C, we show that this off-equilibrium contract satisfies the Intuitive Criterion.

Borrowers' strategy depends on the size of the funding shock. In case (i) of Proposition 3 borrowers have to liquidate their collateral. Since both borrowers bear the funding shock, unlike in the OTC market, the economy's entire collateral is used up before any borrower has to start liquidating the LTT. This is welfare optimal due to the pecking of collateral and LTT. In case (ii) both borrowers liquidate all of their collateral and a part of their LTT. Liquidating the H-type LTT, instead of liquidating only the L-type LTT as in the OTC market, is costly from a welfare perspective. To determine the run threshold f^{COB} for $\kappa_1 < f$, lenders consider the loan rate c_2^P pinned down by the H-type's incentive compatibility constraint (19). It is the largest rate borrowers are willing to pay in a pooling equilibrium.[26] In case (iii), second-round lenders stop providing loans altogether, a systemic run.

The presence of liquid collateral, $\kappa_1 > 0$, increases the run threshold, f^{COB}. While the threshold decreases in the opportunity cost of liquidating the H-type's LTT, $R^H - \lambda$, it increases in the return from the L-type LTT both at the rollover stage, λ, and at maturity, R^L.

4.3 Comparison between OTC and COB market

To rank the OTC market and COB market relative to the first-best solution, we start by comparing run thresholds.

Proposition 4 *The run threshold in the COB market is larger than in the OTC market, $f^{COB} > f^{OTC}$, so long as $2R^L - R^H > \lambda$, $\kappa_1 \geq 0$, and $\kappa_0 \leq \frac{1}{2}$. The first-best solution can withstand strictly larger funding shocks, $f^{FB} > max\{f^{COB}, f^{OTC}\}$.*

The run threshold in the first best solution is largest since the social planner redistributes, for small funding shocks, collateral from liquid (H-type) to illiquid (L-type) borrower and, for large funding shocks, the return from risky assets from the solvent (H-type) to the insolvent (L-type) borrower.

The difference between the run thresholds in the COB market and the OTC market arises because in the former the L-type borrower is implicitly insured by the H-type borrower via

[26] Notwithstanding a degree of competition, both in the OTC and COB equilibrium borrowers make some profit at $t = 1$. It is always possible to allow for lender competition such that the loan rate is pinned down by lenders' IR.

the loan contract. The L-type borrower has to liquidate less of their LTT for a given funding shock in the COB market than in the OTC market. For any given funding shock, this is due to the larger loan in the COB market, ℓ_1^P, than in the OTC market, ℓ_1^L. Pooling H-type and L-type borrower makes the market more resilient against a funding run if the LTT is illiquid. Note this is not possible in Bouvard et al. (2015). We explain why after the next theorem. This result is in line with empirical evidence from the GFC where both funding and asset liquidity declined and OTC markets experienced repo runs (Copeland et al., 2014; Krishnamurthy et al., 2014; Pérignon et al., 2018) whereas CCP markets continued to function (Mancini et al., 2016). Conversely, during the repo blowup in September 2019 and the interruption of the repo market at the onset of the Covid-19 pandemic, asset quality barely changed but funding liquidity became scarce. Our model predicts, in line with empirical evidence (Duffie, 2020), that then CCP-based markets are more susceptible to runs.

Equipped with the equilibrium outcomes in OTC and COB markets and the respective run thresholds, we are now ready to state the first main result of the paper.

Theorem 1 *The welfare ranking between an anonymous COB and an non-anonymous OTC market switches repeatedly and depends on the size of the funding shock:*

$$W^{COB} \quad W^{OTC} = \begin{cases} 0 & \textit{if } 0 \quad f \quad \frac{\kappa_1}{2}, \\ (2f \quad \kappa_1)(\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1})m & \textit{if } \frac{\kappa_1}{2} < f \quad \kappa_1, \\ \kappa_1(\frac{R^H}{\lambda} \quad \frac{\kappa_2}{\kappa_1})m \quad f\frac{R^H \quad R^L}{\lambda}m & \textit{if } \kappa_1 < f \quad f^{OTC}, \\ (R^L \quad \lambda)m \quad f(\frac{R^H+R^L}{\lambda} \quad 2)m + \kappa_1(\frac{R^H+R^L \quad \lambda}{\lambda} \quad \frac{\kappa_2}{\kappa_1})m & \textit{if } f^{OTC} < f \quad f^{COB}, \\ \quad (R^H \quad \lambda + \kappa_0 \quad \kappa_1)m & \textit{if } f > f^{COB}. \end{cases}$$

Theorem 1 is illustrated in Figure 3. The welfare difference between COB and OTC market is identical to the difference between first-best solution and OTC market for $0 \quad f \quad \kappa_1$. The COB market implements the first-best solution, which effectively transfers collateral from H-type to L-type borrower, through the loan contract. In the COB market, at the rollover stage when funding is scarce, the H-type subsidizes the L-type by accepting a smaller loan amount in return for a smaller loan rate and, therefore, the H-type leaves relatively more funding to the L-type. This causes both the H-type and the L-type to liquidate

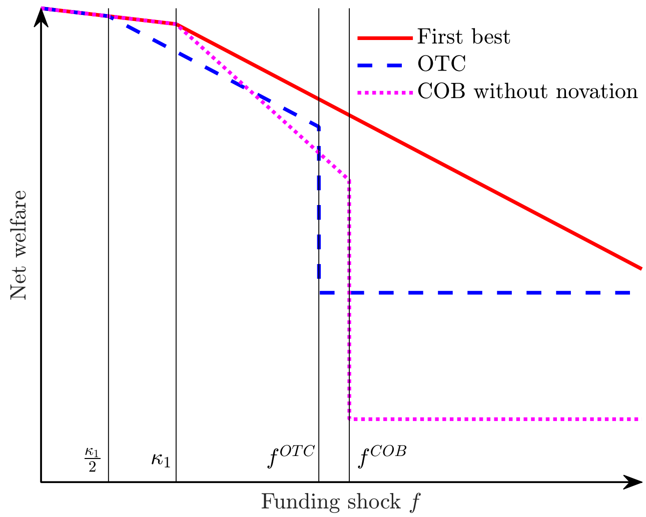

Figure 3: Welfare comparison: Systemic run in COB market vs. narrow run in OTC market

collateral equally before they have to start liquidating their LTT. An economy with a COB market implements an implicit collateral transfer and thus can withstand larger funding shocks before borrowers have to liquidate their LTT. In the OTC market, the cost of the funding shock is entirely born by the L-type. After their collateral endowment is used up, borrowers have to start liquidating their LTT. Since liquidating the LTT is more expensive than liquidating collateral, the welfare decrease is steeper in the OTC market than in the first-best-solution and the COB market. This welfare difference occurs after the L-type's collateral in the OTC market is used up, i.e. $\frac{\kappa_1}{2} < f \leq \kappa$.

For $\kappa_1 < f \leq f^{OTC}$, the welfare difference between COB and OTC market is ambiguous. In the COB market, the decrease in welfare is steeper than in the OTC market, since in the COB market both the H-type and the L-type have to liquidate their LTT while in the OTC market only the L-type liquidates the LTT, similar to the first-best solution. The fact that also the H-type has to liquidate its LTT is the effect of resource misallocation in the COB market. In sum, as long as in the COB market the insurance effect from collateral, $\kappa_1(\frac{R^H}{\lambda} - \frac{\kappa_2}{\kappa_1})m$, outweighs the resource misallocation effect, $f\frac{R^H - R^L}{\lambda}m$, welfare in the COB market dominates the OTC market, and vice versa. Notice, this result is absent in Bouvard et al. (2015) due to the fixed return from investment in their model. In our model, because investment is scalable welfare decreases not only because of liquidation cost $1 - \lambda$ but also because of foregone profits $R^{\omega} - 1$.

For $f^{OTC} < f \leq f^{COB}$, welfare is always larger in the COB market than in the OTC market, since by Proposition 4, the run on the L-type in the OTC market occurs for a smaller funding shock than the systemic run in the COB market. The double switch of the welfare ranking, for $0 < f$ f^{COB} is absent in Bouvard et al. (2015) since in their model disinvestment of the LTT reduces profits and welfare regardless of the LTT's return. Our model takes into account the heterogeneity in foregone profits from disinvestment.

For $f > f^{COB}$, the OTC market always yields larger welfare than the COB market since the former prevents a systemic run by allowing lenders to condition their loans on borrower type.

The role of idiosyncratic information is reminiscent of Hirshleifer (1971), who provides a model in which the knowledge of realizations of uncertainty prevents individuals from sharing risk efficiently through transactions.[27] Different from the previous literature utilising the Hirshleifer effect, we show, when aggregate (funding) risk and idiosyncratic risk interact, the risk sharing benefits from asymmetric information are

(i) positive even for small funding shocks (in normal times),

(ii) ambiguous for intermediate funding shocks unlike e.g. Bouvard et al. (2015) and

(iii) positive even for large funding shocks (the anonymous market is more resilient against a run than the non-anonymous market).

Our model is also able to address concerns of borrower connectedness.[28] The more borrowers are connected, the more similar they are in terms of their payoffs, i.e. the closer R^H and R^L. We can therefore study how the efficiency-resilience tradeoff in Theorem 1 is affected by borrowers' connectedness. Increasing connectedness at the same time means changing average borrower quality. We study, what we believe to be the more relevant case, that is when average borrower quality decreases. Then R^H approaches R^L from above. The more connected they are, i.e. the closer R^H to R^L, the smaller the insurance benefit from anonymity for intermediate and large funding shocks, $\kappa_1 < f$ f^{COB}. There are two policy implications coming out of this analysis. First, borrower risk should be diverse and second, a prerequisite for an anonymous market is sufficiently high average borrower quality.

[27]The Hirshleifer effect underlies the vast literature studying risk sharing arrangements among banks. The closest to our paper are Bouvard et al. (2015) and Goldstein and Leitner (2018).

[28]We thank Sophie Moinas for pointing this out to us.

5 Clearing Mechanism of CCP Markets

So far we have compared the trading mechanisms in OTC and COB markets. We now introduce different clearing mechanisms.

5.1 COB with novation

In a CCP market, after borrower and lender have agreed on the loan terms through the COB, the contract is novated by the CCP. This means that the CCP becomes the legal counterparty to both parties. CCPs usually have an extensive rulebook in place setting out the criteria under which it novates a repo contract. The rulebook is central to the CCPs risk management. It allows the CCP to exclude borrowers from the platform on a predefined set of rules. The effectiveness of the novation process is key to participants' confidence to arrange repos anonymously.

In terms of the model, novation alleviates the asymmetric information problem of the COB market in the following way. Observing both funding shock and borrower type, the CCP only novates the repo contract of solvent borrowers. In equilibrium, conditional on the funding shock, this implies, as long as $f \leq f^{COB}$ the CCP novates the contracts agreed upon through the COB of both borrower types. When the funding shock exceeds the run threshold, $f > f^{COB}$, the CCP only novates the contract of the solvent H-type borrower and not of the insolvent L-type borrower. This has implications on loan contracts both at the investment stage $t = 0$ and at the rollover stage at $t = 1$. We proceed by highlighting the changes with respect to the COB market in Section 4.2. It will become clear that novation only affects the equilibrium beyond the run threshold.

At the investment stage, first-round lenders require at least their initial investment back,

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{COB}, \\ \alpha(\beta c_{1,f>f^{COB}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{COB}} & \text{if } f > f^{COB}. \end{cases} \tag{22}$$

Unlike in the COB market, there is no systemic run in a COB market with novation. The second line of expression (22) takes into account that the H-type borrower is able to repay first-round lenders even after a large funding shock occurs, $f > f^{COB}$. First-round lenders therefore require a lower repo rate $c_{1,f>f^{COB}}$ which enlarges the parameter space, with respect to the parameter space for the COB market, for which a functioning lending market exists. Moreover, a lower repo rate implies less refinancing pressure at the rollover stage $t = 1$. If the realization of the funding shock is larger than the run threshold, $f > f^{COB}$, the COB market with novation exhibits the same solution as the OTC market. Second-round lenders know that the L-type borrower is effectively excluded from the market since the CCP only novates repos with the H-type borrower. There is, by assumption, enough funding to roll over one borrower, $2(1 \quad f)m \quad c_{1,f>f^{COB}}\ell_0$, and thus second-round lenders compete for the H-type borrower such that they break even, $c^H_{2,f>f^{COB}} = 1$. The loans extended to the H-type borrower allow them to continue the LTT without liquidation, $\ell^H_{1,f>f^{COB}} = c_{1,f>f^{COB}}\ell_0$. The run threshold and the equilibria below the run threshold remain the same as in Section 4.2.

Novation has an important effect on the COB market. At the cost of an individual run on the L-type borrower, it prevents a systemic run on both borrowers. The following proposition summarizes the result in terms of welfare.

Proposition 5 (COB market with novation) *A narrow run occurs in the COB market with novation if the funding shock exceeds the threshold f^{COB} de ned in (21). Novation improves welfare in the COB market:*

$$W^{COB,N} \quad W^{COB} = \begin{cases} 0 & \textit{if} \quad f \quad f^{COB}, \\ (R^H \quad \lambda + \kappa_0 \quad \kappa_1)m & \textit{if } f > f^{COB}. \end{cases}$$

Figure 4 illustrates Proposition 5. Welfare in the COB market with novation is identical to welfare in the COB market up to the run threshold f^{COB}. Beyond the run threshold, welfare in the OTC market and the COB market with novation are identical since both exhibit a run on the L-type borrower and allow the H-type borrower to continue the LTT to maturity without liquidation. Beyond the run threshold, novation helps improve welfare with respect to the COB market by preventing a systemic run.

Note that there is a role for novation even in the case of positive NPV projects. When heterogeneous borrowers compete for scarce funding, it is socially optimal to liquidate the

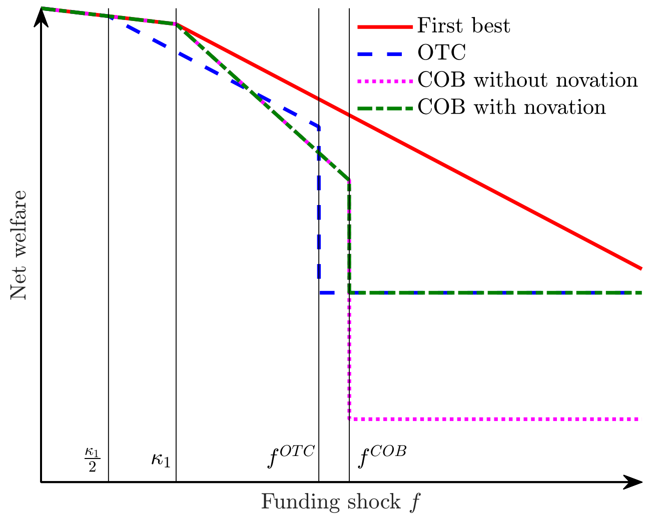

Figure 4: Welfare comparison: Narrow runs in COB vs. OTC market

least productive asset. And that is what novation implements. We come back to the role of novation when we discuss NPV projects and the skin-in-the-game effect of collateral in Section 7.3. With a negative NPV project, novation has the more obvious effect of excluding the negative NPV borrower.

5.2 CCP market: COB with novation and default fund

A default fund plays an important role in a CCP market. The default fund is used in case of a borrower's default. CCP participants contribute to it depending on the amount of business and risk they bring to the platform. Importantly, the contribution is determined before participants engage in repo trading. It is typically the last line of defence and only used after all of the defaulting borrower's resources are exhausted.

In terms of the model, borrowers commit to contributing to the default fund before they learn their type, just like in real CCP markets. Otherwise, the borrower turning out as H-type at the rollover stage would withdraw its contribution to the default fund. Notice that the contribution to the default fund determined at $t = 0$ is individually rational. As long as there are positive expected profits for borrowers at $t = 0$, they are willing to contribute to the default fund. The maximum contribution to the default fund is given by borrowers' ex-ante profit, yielding

$$\tau_{DF}^{CCP} = \frac{1}{\alpha\beta}\Bigg[\alpha\Big(\beta(R^H(i_0 - z_1^P) - c_2^P\ell_1^P) - \kappa_2 w_1^P\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P\ell_{1,f=0}^P\Big) - (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0\Bigg]. \tag{23}$$

To study the effect of the default fund on financial stability, we derive the threshold at which second-round lenders stop providing loans, f^{CCP}. Naturally, the threshold is beyond the point at which a run would occur without default fund, $f^{CCP} > f^{COB}$. When second round lenders provide one-fit-all loans at $t = 1$, they take into account not only counterparty risk but also the repayment capacity of the default fund. The largest funding shock a CCP with a default fund can withstand is given by the L-type borrower's maximum repayment capacity which consists of their own proceeds and the transfer from the default fund

$$R^L(i_0 - z_1^P) - c_{2,DF}^P\ell_1^P + \tau_{DF}^{CCP} = 0. \tag{24}$$

From expression (24) it is clear that the CCP with default fund can withstand a larger funding shock the larger the transfer τ_{DF}^{CCP}, since it increases the L-type's repayment capacity. Notice that the default fund, like in real world CCP markets, is only drawn upon after the defaulting borrower's resources, that is the proceeds from collateral and LTT, are exhausted. The following proposition summarizes the financial stability effect of a default fund.

Proposition 6 *A narrow run occurs in the CCP market if the funding shock exceeds the threshold*

$$f^{CCP} = \frac{(R^L - 1)\lambda + R^H\kappa_1}{R^H + R^L - 2\lambda} + \frac{(\lambda + \kappa_1)R^L - \lambda}{R^H + R^L - 2\lambda} + \frac{\lambda(\beta(R^H - R^L) - \kappa_0 R^L)}{\alpha\beta(R^H + R^L - 2\lambda)}. \tag{25}$$

The run threshold in the CCP market is larger than in the COB market without default fund, $f^{CCP} > f^{COB}$*.*

Like in the first-best solution, the default fund allows to transfer proceeds from the solvent to the insolvent borrower. Although the default fund enhances financial stability, the run threshold in a CCP market with a default fund is always smaller than the run threshold in the first-best solution, f^{FB}. Recall, in the first-best solution the social planner redistributes the H-type's realized profit. In the CCP market with default fund, the transfer can be at most the *ex-ante* profit of borrowers which is necessarily smaller than the realized profit of the H-type.

The default fund is desirable from a social planner viewpoint as it helps to continue, instead of liquidating, the L-type LTT, a positive NPV project. The socially optimal novation policy therefore considers the repayment capacity of both borrower and the CCP, through the default fund, as a whole. Only if both are exhausted should the CCP exclude the L-type borrower. Modeling a profit-maximizing CCP is beyond the scope of this paper. Such CCP may want to preclude insolvent borrowers from rolling over their loans, even though rollover is socially optimal.

In practice, OTC and CCP markets exist in parallel. Appendix F extends the model to allow for search cost in the OTC market. We derive theoretical predictions for the size of OTC market search cost so that markets indeed co-exist.

6 Implementing an Efficient Repo Market

Following the financial crisis of 2008 (Brunnermeier, 2009), the repo blowup of September 2019, and the Covid-19 pandemic of March 2020 (He et al., 2021), a discussion among policy makers, industry leaders, and academics has emerged as to whether OTC repos should be centrally cleared more often (Duffie, 2020). Our analysis contributes to this debate by exploring the costs and benefits of a centrally cleared market. We proceed by establishing the optimal market solution and then discuss how real world market features can help to implement the optimal market structure.

6.1 Optimal market solution

Recall from the first-best solution that the social planner implements two transfers from the H-type to the L-type, a collateral transfer at $t = 1$ and a profit transfer at $t = 2$. We derive the privately optimal market solution which improves upon existing markets but does not attain the first best solution. Regardless of clearing and trading mechanism, the privately optimal market solution implements the two types of transfers, albeit of different magnitudes.

At $t = 0$, borrowers commit to a transfer τ^{OPT} that amounts up to their expected net profit. Borrowers take into account that the transfer is due if they turn out to be of H-type, and the funding shock has depleted the L-type's repayment capacity consisting of (i) second round loan and collateral or (ii) second round loan, collateral and LTT. Naturally, for case (ii) to occur the funding shock is larger than in case (i). The transfer is split into two payments: A collateral transfer, w_1^H at $t = 1$ to repay first-round lenders once the L-type has run out of collateral, and a profit transfer τ^{OPT} at $t = 2$ to subsidize L-type's repayment of second-round lenders. By transferring the H-type's collateral, w_1^H, at $t = 1$, the privately optimal market solution achieves allocative efficiency identical to the first-best solution.[29] The profit transfer from the H-type to the L-type, τ^{OPT}, at $t = 2$, increases the latter's repayment capacity so that second round lenders, at $t = 1$ are willing to provide loans even to the L-type. As a result, the profit transfer increases the market's run resilience. Resilience is, of course, higher in the first-best solution than in the market solution, $f^{FB} > f^{OPT}$, because the privately optimal transfer at $t = 2$ does not attain the socially optimal transfer. While the profit transfer is already a feature of existing central clearing mechanisms, implemented through the default fund, the collateral transfer is an innovation that we discuss further below. We state now the second main result of the paper.

Theorem 2 (Privately optimal repo market) *The privately optimal market solution implements the first-best solution for* $0 < f \le f^{OPT} = \frac{R^L-1}{R^L-\lambda}\frac{\lambda}{2} + \frac{R^L\kappa_1(w_1^H+k_0)}{2(R^L-\lambda)m} + \frac{\tau^{OPT}\lambda}{2(R^L-\lambda)m}$*, where* $w_1^H = [0, k_0]$*, with ex-ante committed total transfer equal to*

$$\tau^{OPT} = \frac{m}{\alpha\beta}[\alpha\beta(R^H-1)+(1-\alpha)\beta(R^H-R^L)-(\beta R^H+(1-\beta)R^L-\alpha\beta(1-w_1^H))\kappa_0]. \quad (26)$$

The payouts of the total transfer occur through:

(i) collateral transfer at $t = 1$*:* $w_1^H = \frac{c_1\ell_0-\ell_1^L-\kappa_1 k_0}{\kappa_1}$ *for* $\kappa_1/2 < f \le \kappa_1$ *and*

[29] The collateral transfer at $t = 1$ reduces the profit transfer at $t = 2$. Although, in general, there is a trade-off between collateral transfer and profit transfer in terms of welfare, the trade-off is immaterial for the relevant parameter ranges in our model.

(ii) profit transfer at $t = 2$*:* τ^{OPT} *for* $f^{OPT}|_{\tau^{OPT}=0} < f \quad f^{OPT}$.

When the payout (i) occurs, the collateral of the L-type is used up, i.e., $w_1^L = k_0$, and the H-type's collateral is liquidated to prevent the liquidation of the L-type LTT. The maximum run threshold attainable in this case is $f^{OPT}|_{\tau^{OPT}=0} = \frac{R^L \quad 1}{R^L \quad \lambda}\frac{\lambda}{2} + \frac{R^L \kappa_1}{(R^L \quad \lambda)}$. The collateral transfer not only improves allocative efficiency but also increases run resilience compared to the OTC market, $f^{OPT}|_{\tau^{OPT}=0} > f^{OTC}$.[30] Interestingly, for $\kappa_1 < f$, the run threshold in the COB market may be smaller than the one in the privately optimal market with collateral transfer.[31] Both markets implement collateral transfers but in the COB market both H-type and L-type LTT are liquidated while in the privately optimal market only the L-type LTT is liquidated. This shows that there exist well designed, privately optimal transfers, which alleviate the Hirshleifer trade-off (Hirshleifer, 1971) between allocative efficiency and resilience.

The profit transfer in (ii) leaves allocative efficiency unaffected since the effective transfer takes place after the realization of the LTT. The profit transfer maximizes the run resilience in an individually rational market.

6.2 Repo market reforms

We start by describing how and to which extent the optimal market solution derived in Theorem 2 can be implemented with a combination of existing market features. We show that current reform proposals improve upon existing market structure. The optimal solution in Theorem 2 is however only attainable by adopting a novel market feature — a two-tiered guarantee fund.

Bilateral trading and central clearing: Centrally cleared OTC markets are an important segment of U.S. repo markets. Augmenting OTC markets with central clearing and a default fund that pays in case of a borrower's default is a general reform proposal which is

[30] Notice that $f^{OPT}|_{w_1^H=0,\,\tau^{OPT}=0} = f^{OTC}$, as the OTC market is the constrained first best solution without transfers.

[31] Observe $f^{OPT}|_{w_1^H=k_0,\,\tau^{OPT}=0} > f^{COB}$ is granted if $\kappa_1 > \frac{R^L \quad 1}{2(R^H \quad R^L)}(2R^L \quad R^H \quad \lambda)$.

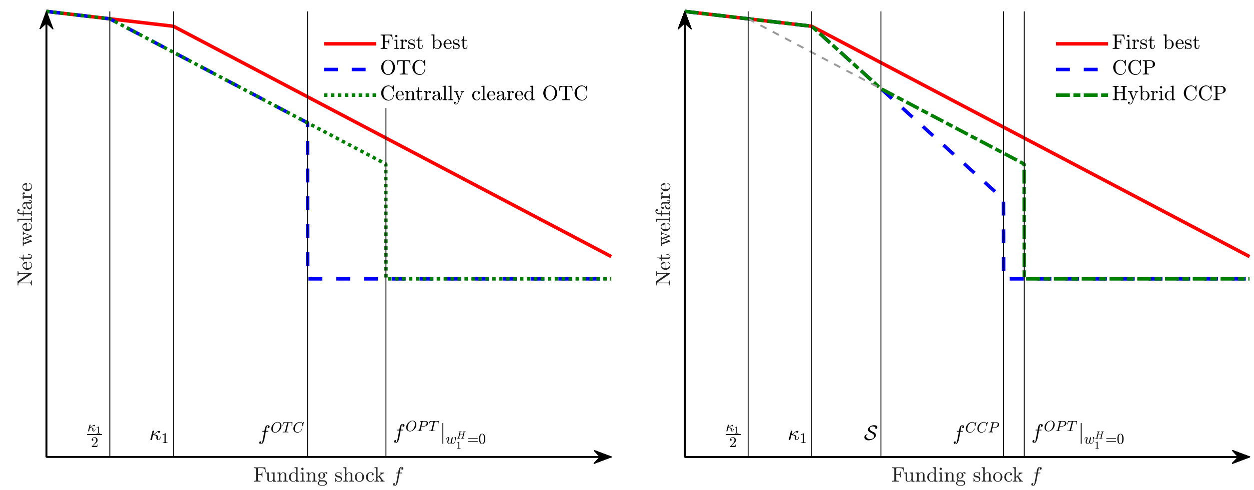

Figure 5: Welfare comparison: Centrally cleared OTC (left) and hybrid CCP market (right).

currently being discussed (Duffie, 2020). Central clearing improves the resilience of OTC markets and resembles the functioning of existing request-for-quote platforms.

A corollary of Theorem 2 is that, when non-anonymous markets are augmented with a default fund involving profit transfers, i.e., τ^{OPT} at $t = 2$, run resilience improves since $f^{OPT}|_{w_1^H=0} > f^{OTC}$. Figure 5 (left) illustrates that bilateral trading with central clearing improves run resilience, but the reform leaves allocative efficiency unchanged and suboptimal.

Hybrid trading mechanism: To improve upon existing CCP markets with novation and default fund, we propose a hybrid trading mechanism. The COB trading mechanism implements the collateral transfer through one-fits-all loans for $f \leq \kappa_1$. Therefore, as we show above, they achieve first-best welfare for small funding shocks. However, the COB inefficiently forces liquidation of part of the H-type's LTT for $f > \kappa_1$. To improve upon this inefficient resource allocation, the trading mechanism needs to switch from an anonymous COB to a non-anonymous trading mechanism for funding shocks $f \geq \mathcal{S}$. The switching point $\mathcal{S}$ is defined by the funding shock at which net welfare in the COB and OTC markets are equal in Theorem 1:

$$\mathcal{S} = \left(\frac{R^H}{\lambda} - \frac{\kappa_2}{\kappa_1}\right)\frac{\kappa_1\lambda}{R^H - R^L}. \tag{27}$$

The hybrid repo trading mechanism is similar to the downstairs/upstairs market system in equity markets (Burdett and O'Hara, 1987; Seppi, 1990; Grossman, 1992), except that the switch occurs depending on aggregate funding conditions in the market. The switch in the trading mechanism at S prevents liquidation of the H-type LTT. At the same time, the switch exacerbates the credit rationing for the L-type making them susceptible to narrow runs. To improve run resilience, the CCP needs to continue using the default fund.

The largest funding shock, f S, the hybrid market with a default fund can withstand is given by $f^{OPT}|_{w_1^H=0}$. Since the H-type is not required to liquidate neither LTT nor collateral in the hybrid market, as opposed to the anonymous COB trading in a CCP market, there is more profit to redistribute which makes the hybrid market more resilient than the CCP market, $f^{OPT}|_{w_1^H=0} > f^{CCP}$.

Figure 5 (right) illustrates that the hybrid trading mechanism improves upon existing CCP markets by allocating resource more efficiently for intermediate and large funding shocks, $S < f$ $f^{OPT}|_{w_1^H=0}$, but it does not attain the efficient resource allocation of the first-best solution.

Two-tiered guarantee fund: Both of the solutions above, centrally cleared OTC market and hybrid CCP market, can be further improved to the point that they achieve the privately optimal solution in Theorem 2 and resolve the allocation-resilience trade-off. Setting up a two-tiered guarantee fund is needed. Regardless of the trading mechanism, the two-tiered guarantee fund requires an initial contribution that mimics the two transfers, collateral and profit, derived in Theorem 2. The contribution is agreed upon before trading take place and updated on a regular basis depending on participants' net exposure.

The two-tiered guarantee fund works as follows. In the model, participants transfer both safe collateral and a fraction of the LTT into two separate escrow accounts. Collateral is used to support illiquid but solvent borrowers, so that the H-type's collateral is liquidated before the L-type's LTT, but after the L-type's collateral. This means that if a borrower runs out of collateral, the borrower is subsidized by other borrowers' collateral within the predetermined contribution agreed upon at the time of joining the platform.

The mechanism resembles a collateral upgrade, as implemented by the ECB and the Federal Reserve through emergency facilities (Carlson and Macchiavelli, 2020), in which the borrowers effectively increase their collateral endowment. The risky asset escrow is used to bail out defaulting borrowers. This captures the profit transfer described in the privately optimal repo market solution in Theorem 2. It helps to instill confidence in lenders to continue to provide funding as they incorporate in their lending decision that the other participants on the platform guarantee, to a certain extent, borrowers' repayment. This transfer therefore increases the market's resilience against runs.

As an alternative to the two-tiered guarantee fund, the transfer scheme in Theorem 2 can be implemented by requiring borrowers to write both a credit default swap and a collateral swap. The swap contracts grant payments, amounting to τ^{OPT}, from the H-type borrower to the L-type borrower who is subject to credit rationing. Specifically, borrowers write two types of swaps at $t = 0$. The collateral swap is triggered if the L-type borrower runs out of collateral and transfers the H-type's collateral to the L-type. This prevents inefficient liquidation of the L-type's LTT at $t = 1$. The credit default swap is triggered if the L-type is insolvent at $t = 2$. In this case the H-type effectively repays part of the L-type's lenders. Second-round lenders take into account this transfer and provide funding to the L-type at $t = 1$ even for large funding shocks enhancing the resilience of the market.

7 Collateral, Market Structure, and Financial Fragility

7.1 Collateral quality and run resilience

This section studies how collateral quality impacts market resilience. A marginal increase in collateral value affects run thresholds in the CCP and OTC markets differently for riskiness of the LTT and collateral amount. Specifically, when the LTT is sufficiently illiquid, the CCP market benefits the most from an increase in collateral value. To our knowledge, we are the first to point out the heterogeneous effect of collateral quality, depending on market structure. The following proposition summarizes this result.

Proposition 7 *The CCP market's resilience to a run is more sensitive to collateral value than the OTC market's resilience, $\frac{\partial f^{CCP}}{\partial \kappa_1} > \frac{\partial f^{OTC}}{\partial \kappa_1}$, when the LTT is illiquid, $\lambda < \frac{R^L(R^H \; R^L)}{2R^H}$, and vice versa.*

The proposition states that collateral value is more relevant for borrowers in a CCP market at times when the LTT is illiquid. Because the run threshold in the OTC market is lower than the run threshold in the CCP market, $f^{OTC} < f^{CCP}$, one might expect that a marginal increase in collateral value would benefit borrowers in the OTC market the most. That is actually ***not*** the case when the LTT is illiquid, $\lambda < \frac{R^L(R^H \quad R^L)}{2R^H}$. The reason is that in the CCP market the H-type is forced to partially liquidate the LTT, which is the most valuable asset in the economy, and its liquidation is particularly costly when λ is low. Consequently, a marginal increase in collateral value prevents the liquidation of the H-type LTT, benefiting the CCP market.

7.2 Collateral convenience yield

This section investigates when an asset is indeed used as collateral instead of being sold on the spot market to finance long-term investment. The usage of the asset as collateral gives rise to an endogenous convenience yield in excess of the assets' face value. In line with previous literature (Parlatore, 2019; Gottardi et al., 2019), we define the convenience yield of collateral, or collateral premium **cp**, as the value created from financing the investment with collateralized loans instead of liquidating the collateral asset. Specifically, the collateral premium at $t = 0$ is the difference between two borrowers' expected payoffs: the payoff from using the asset as collateral to obtain a loan to invest in the LTT, and the payoff from investing the proceeds of the asset sale in the LTT.

We show that the convenience yield depends not only on funding market conditions but also on market structure, namely whether repo trading occurs in the CCP or OTC market. The convenience yield is non-monotone in the funding shock in both markets. Our theoretical predictions for the critical ranges of the funding shock, i.e., $\kappa_1 < f \quad f^{COB}$ and $\frac{\kappa_1}{2} < f \quad f^{OTC}$, echo the empirical results from Auh and Landoni (2017) in so far as the collateral premium decreases with an increase in collateral quality, κ_1. In other words, it becomes less profitable to use the asset as collateral instead of selling it. That is, in addition to the liquidity of collateral and counterparty risk (Parlatore, 2019), we show that the convenience yield of the collateral asset depends on the market structure and funding risk.

To speak to the empirical evidence on the convenience yield from the United States (He et al., 2021), we focus on the OTC market as this seems to be the predominant market structure. In the OTC market, focusing on the range $\frac{\kappa_1}{2} < f \quad f^{OTC}$ where an increase in f is particularly costly since it requires liquidating LTT, the convenience yield on collateral can be either increasing or decreasing in the size of the funding shock. We obtain the following result:

Proposition 8 *In the OTC market, for $\frac{\kappa_1}{2} < f \quad f^{OTC}$ and $\alpha > R^H \quad R^L$, the convenience yield on collateral $\mathbf{cp}^{OTC}$ increases (decreases) in f if $\beta < (>) \frac{R^L}{\alpha + R^L \quad R^H}$.*

The model predicts that when the economy is at the brink of a funding crisis (α is large), the collateral premium in the OTC market increases in the size of the funding shock if average borrower quality is sufficiently low (β is low). Conversely, the collateral premium decreases in the size of the funding shock if average borrower quality is sufficiently high. The proposition highlights the protective role of collateral in a funding crisis. When idiosyncratic borrower risk is high, collateral becomes more valuable to borrowers as it protects their LTT investment.

These predictions are in line with empirical evidence from the GFC when average borrower quality was low due to large positions in asset-backed securities on banks' balance sheets. The model predicts a resulting rise in the convenience yield as the funding shock hits. During the Covid-19 pandemic, by contrast, banks were better capitalized and had higher creditworthiness than during the financial crisis. The model then predicts that the convenience yield should decline during a liquidity crisis such as the Covid-19 pandemic. This prediction is consistent with the empirical evidence in He et al. (2021).

7.3 Collateral scarcity and negative NPV projects

Market participants have voiced concerns that in anonymous CCP based markets low-quality borrowers can hide amongst high-quality borrowers.[32] To investigate this issue, we introduce negative NPV projects and study the role of collateral scarcity and pecking order.

We demonstrate that only socially optimal rollover takes place in CCP markets with an anonymous COB. Collateral has a skin-in-the-game effect. Assume that the LTT of the

[32] See, e.g., Jenkins, P., and P. Stafford, "Banks warn of risk at clearing houses" in *Financial Times*, July 7, 2013, or Jenkins, P., "How much of a systemic risk is clearing?" in *Financial Times*, January 8, 2018.

L-type has negative NPV, $R^L < 1$. There are two cases: the L-type LTT yields a negative NPV but still larger than the return from early liquidation, $1 > R^L > \lambda$. Alternatively, the L-type LTT yields a return even smaller than early liquidation $1 > \lambda > R^L$. In the first case, continuation of the L-type LTT at $t = 1$ is desirable from a welfare viewpoint, whereas in the second case liquidation improves welfare.

First, we focus on the case in which rollover is socially optimal, $1 > R^L > \lambda$. We have to show that in this case there is rollover when $\kappa_1 < f \quad f^{COB}$. Notice, if borrower and lender are willing to agree on a repo when collateral is depleted, they are certainly willing to do so for smaller funding shocks $f \quad \kappa_1$. For there to be rollover, we thus require a non-empty range for f such that $f^{COB} \quad \kappa_1$, which yields

$$R^L + \kappa_1 \quad 1. \tag{28}$$

That is, when the return from the LTT yields a negative NPV, liquid collateral (high κ_1), helps to reduce the liquidation of the LTT at the intermediate stage so that second round lenders continue to provide loans. The admissible value of collateral is however bound from above by Assumption 4. From collateral scarcity at $t = 1$, i.e., $c_1 \ell_0 \quad \lambda i_0 + \kappa_1 k_0$, we obtain

$$1 \quad \kappa_1 + \lambda, \tag{29}$$

with $c_1 = 1$, $\ell_0 = i_0 = k_0$. Combining conditions (28) and (29),

$$1 \quad \lambda \quad \kappa_1 \quad 1 \quad R^L, \tag{30}$$

yields $R^L > \lambda$. That is, in a COB market with scarce collateral rollover is socially optimal.

Next, we show that it is privately optimal for the L-type not to rollover the LTT when it is socially inefficient to do so ($\lambda > R^L$). Assumption 3 establishes the pecking order between LTT and collateral. In particular, the opportunity cost from liquidating the L-type LTT is larger than the opportunity cost from liquidating collateral, $\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1} \quad 1$. When the L-type's LTT return drops below the liquidation value, $\lambda > R^L$, the first inequality is reversed. The L-type borrower therefore liquidates first the LTT before liquidating collateral in order to protect the total asset value. Notice, for the funding shock levels (below the run threshold) studied in this section, novation plays no role. It remains however key to preventing complete market failure for funding shocks exceeding the run threshold. To summarise, in an economy with scarce collateral, the anonymous COB market implements socially optimal rollover via the collateral's skin in the game effect.

Infante and Vardoulakis (2021) and Kuong (2021) also obtain run results in the presence of collateral but the mechanisms differ. Infante and Vardoulakis (2021) show, when borrowers internalize the risk of losing their collateral in case their lender defaults, borrowers are prompted to withdraw it, causing a collateral run on lenders. Kuong (2021) shows in a global games model with moral hazard how, notwithstanding collateral, runs can occur. In our model, the run is on borrowers and collateral aligns private with social incentives.

8 Conclusion

Well-functioning repo markets are integral to an efficient banking system, effective monetary policy transmission, and overall financial market resilience and stability. Repo market design trades off the efficient allocation of short-term funding in normal times and the resilience to funding shocks in crisis times. In a dynamic model of short-term repo funding with uncertainty about borrowers' credit quality and lenders' funding condition, we study how repo trading and clearing mechanisms affect the allocation-resilience tradeoff.

Two common repo market designs have emerged in practice: non-anonymous bilaterally-cleared over-the-counter (OTC) markets and anonymous centralized order books with default fund and novation to a central counterparty (CCP). We show that none of them achieve first best. Non-anonymous trading in OTC markets allocates funding efficiently, but credit rationing causes narrow runs on low-quality borrowers when funding is scarce. Anonymous trading in CCP markets provides two types of insurance, against illiquidity and insolvency but CCPs allocate funding inefficiently through insufficient repo loans to high-quality borrowers. Novation and a well-capitalized default fund render CCPs resilient against systemic runs that cause market breakdown.

Repo market reforms improve funding allocations and market resilience: Central clearing of bilateral OTC trading, and a CCP market with hybrid trading protocol where anonymous trading switches to non-anonymous trading contingent on aggregate funding conditions. The optimal market structure achieves first best and can be implemented through a two-tiered guarantee fund with transfers contingent on both borrower illiquidity and default.

The model explains several stylized facts on recent funding crises and the behavior of collateral convenience yields. During the Great Financial Crisis funding was scarce and assets were illiquid, whereas during the Covid-19 outbreak asset remained fairly liquid. In our model, repo market resilience depends on both funding liquidity and asset liquidity. CCP markets are more resilient than OTC markets when there is both low funding and low asset liquidity. In turn, OTC markets are more resilient when funding is scarce while asset liquidity is high. These predictions reconcile the halt of OTC repo markets in 2008 with the 2019/20 repo blowups in CCP markets.

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Internet Appendix

This Internet Appendix contains all proofs and derivations relevant for the results in the paper "(In)efficient repo markets".

A First best

At $t = 0$, the social planner maximizes ex-ante net welfare. For borrowers to take a loan and invest in the LTT, $i_0 = \ell_0 = m$, instead of liquidating collateral and investing the proceeds in the LTT, the following ex-ante welfare comparison has to be satisfied

$$\alpha\big[(R^H i_0 - \ell_1^H) + (R^L(i_0 - z_1^L) - \ell_1^L) - 2\kappa_0 k_0\big] + (1-\alpha)\big[(R^H i_0 - \ell_{1,f=0}^H) + (R^L i_0 - \ell_{1,f=0}^L)\big] \geq (R^H + R^L - 2)k_0\kappa_0 \quad \text{(IA1)}$$

The outside option $(R^H + R^L - 2)k_0\kappa_0$ on the RHS of inequality (IA1) obtains from liquidating the collateral endowment of borrowers and investing it in the LTT. Investing the proceeds from collateral liquidation is independent of the funding shock as the financing is independent of the state of the economy. The outside option is strictly larger than net welfare from merely holding collateral to maturity. Ex-ante welfare on the LHS of inequality (IA1) is independent of the transfers between borrowers and lenders, $c_2^\omega \ell_1^\omega$, since agents are risk neutral. Recall that we consider the case that one borrower turns out to be H-type and the other L-type and, therefore, there is uncertainty with respect to types from an individual agent's point of view but not from a total welfare perspective.

B OTC

B.1 Small funding shock $f \leq f^{OTC}$

If $f = 0$, both borrowers obtain sufficiently large loans to repay first-round lenders $\ell_{1,f=0}^L = \ell_{1,f=0}^H = m$. Moreover borrower competition yields

$$R^L i_0 - c_{2,f=0}^{OTC}\ell_{1,f=0}^L + \kappa_2 k_0 = 0 \quad \text{(IA2)}$$

$c_{2,f=0}^{OTC} = R^L + \kappa_2 > 1$.

Consider next the case in which $c_1\ell_0 \leq \ell_1^L + \kappa_1 k_0$, i.e. $0 < f \leq \frac{\kappa_1}{2}$. Then

$$-c_1\ell_0 + \ell_1^L + w_1^L\kappa_1 = 0 \quad \text{(IA3)}$$

$$-c_1\ell_0 + \ell_1^H = 0 \quad \text{(IA4)}$$

such that $\ell_1^L = 2(1-f)m - \ell_1^H$, $w_1^L = \frac{2f}{\kappa_1}m$ and $z_1^L = 0$.

It is indeed more profitable to take a loan than to liquidate collateral if the L-type's participation constraint is satisfied

$$R^L i_0 - c_2^L\ell_1^L + \kappa_2(k_0 - w_1^L) \geq 0 \quad \text{(IA5)}$$

$$\frac{R^L + \kappa_2 - 2f\frac{\kappa_2}{\kappa_1}}{1 - 2f} \geq c_2^L. \quad \text{(IA6)}$$

With competition for funds among borrowers, $c_2^H = c_2^L = c_2^{OTC} = \frac{R^L+\kappa_2 - 2f\frac{\kappa_2}{\kappa_1}}{1-2f}$. Since the H-type can marginally outbid the L-type borrower lenders provide funding to the H-type up to their capacity $\ell_1^H = c_1\ell_0$, and thus $w_1^H = 0$ and $z_1^H = 0$. The H-type participation constraint (they prefer continuing the LTT than to liquidate it and repay the missing part with collateral) is hence:

$$R^H i_0 \quad c_2^{OTC} \ell_1^H + \kappa_2 k_0 \quad 0 \tag{IA7}$$

This condition is satisfied if $\frac{R^H \quad R^L}{\kappa_1(R^H+\kappa_2) \quad \kappa_2} \frac{\kappa_1}{2} \quad f$ and $\kappa_1 > \frac{\kappa_2}{\kappa_2+R^H}$. Or simply $\kappa_1 \quad \frac{\kappa_2}{\kappa_2+R^H}$.
Second-round lenders require at least their initial investment back:

$$c_2^{OTC} \quad 1 \tag{IA8}$$

$$\frac{R^L + \kappa_2 \quad 1}{\kappa_2 \quad \kappa_1} \frac{\kappa_1}{2} \quad f \tag{IA9}$$

Note since $\frac{R^L+\kappa_2 \quad 1}{\kappa_2 \quad \kappa_1} > 1$, lenders' participation is always satisfied.
To summarize the equilibrium at $t = 1$ exists, if $0 < 2f \quad \kappa_1 < \frac{\kappa_2}{R^H+\kappa_2}$ or $\frac{R^H \quad R^L}{\kappa_1(R^H+\kappa_2) \quad \kappa_2} \frac{\kappa_1}{2} \quad f$ and $1 \quad \frac{R^L}{R^H+\kappa_2} \quad \kappa_1 > \frac{\kappa_2}{\kappa_2+R^H}$.

Consider next the case in which $c_1 \ell_0 > \ell_1^L + \kappa_1 k_0$, i.e. $\frac{\kappa_1}{2} < f \quad f^{OTC}$. Then

$$c_1 \ell_0 + \ell_1^L + k_0 \kappa_1 + z_1^L \lambda = 0 \tag{IA10}$$

$$c_1 \ell_0 + \ell_1^H = 0 \tag{IA11}$$

so that $\ell_1^L = 2(1 \quad f)m \quad \ell_1^H$ and $z_1^L = \frac{2f \quad \kappa_1}{\lambda} m$.
It is indeed more profitable to take a loan than to liquidate collateral if the L-type's participation constraint is satisfied

$$R^L(i_0 \quad z_1^L) \quad c_2^L \ell_1^L \quad 0 \tag{IA12}$$

$$\frac{R^L(1 \quad \frac{2f \quad \kappa_1}{\lambda})}{1 \quad 2f} \quad c_2^L. \tag{IA13}$$

Call $c_2^{OTC} = \frac{R^L(1 \quad \frac{2f \quad \kappa_1}{\lambda})}{1 \quad 2f}$.
The H-type's participation constraint is satisfied

$$R^H i_0 \quad c_2^{OTC} \ell_1^H + \kappa_2 k_0 \quad 0 \tag{IA14}$$

Observe that $\frac{\partial c_2^{OTC}}{\partial f} < 0$. With $f = \kappa_1/2$, the H-type's profit is $(R^H + \kappa_2 \quad \frac{R^L}{1 \quad \kappa_1})m$ which is weakly positive if $1 \quad \frac{R^L}{R^H+\kappa_2} \quad \kappa_1$.
Moving backward to $t = 0$. Consider the case when $\frac{\kappa_1}{2} < f \quad f^{OTC}$.The case $0 < f \quad \frac{\kappa_1}{2}$ is satisfied by continuity. Suppose $i_0 = \ell_0 = m$ and $c_1 = 1$. To finance the investment with loans instead of liquidating own collateral:

$$\alpha\Big(\beta(R^H i_0 \quad c_2^{OTC} \ell_1^H) \quad (1 \quad \beta)\kappa_2 k_0\Big) + (1 \quad \alpha)\Big(\beta(R^H i_0 \quad c_{2,f=0}^{OTC} \ell_1^H) \quad (1 \quad \beta)\kappa_2 k_0\Big)$$
$$(\beta R^H + (1 \quad \beta)R^L \quad 1)k_0 \kappa_0 \tag{IA15}$$

$$\frac{\beta(R^H \quad R^L(\alpha \frac{1 \quad \frac{2f \quad \kappa_1}{\lambda}}{1 \quad 2f} + 1 \quad \alpha))}{\beta R^H + (1 \quad \beta)R^L \quad 1 + (1 \quad \beta) + (1 \quad \alpha)\beta} \quad \kappa_0, \tag{IA16}$$

with $\kappa_0 = \kappa_2$. The numerator is positive if $\frac{R^H \quad R^L}{\frac{R^L(1 \quad \frac{2f \quad \kappa_1}{\lambda})}{1 \quad 2f} \quad 1} \quad \alpha$ and $\frac{R^L(1 \quad \frac{2f \quad \kappa_1}{\lambda})}{1 \quad 2f} \quad 1 > 0$ since $f \quad f^{OTC}$.

B.2 Large funding shock $f > f^{OTC}$

For $f = 0$, $\ell_1^H = c_{1,f>f^{OTC}}\ell_0$ and $\ell_1^L = 2m \quad c_{1,f>f^{OTC}}\ell_0$. The L-type borrower breaks even when

$$R^L(i_0 \quad z_1^L) \quad c_2^L \ell_1^L + \kappa_2(k_0 \quad w_1^L) \quad 0 \tag{IA17}$$

$$\text{s.t.} \quad c_{1,f>f^{OTC}}\ell_0 + \lambda z_1^L + w_1^L \kappa_1 + \ell_1^L = 0 \tag{IA18}$$

Suppose that loan and collateral are sufficient to repay first-round lenders, $z_1^L = 0$ and $w_1^L = 2\frac{c_{1,f>f^{OTC}} \quad 1}{\kappa_1}m$ and suppose that $i_0 = \ell_0 = m$.

The loan rate is given by the L-type's break even condition.

$$c_2^L = \frac{R^L i_0 + \kappa_2(k_0 \quad w_1^L)}{\ell_1^L} \tag{IA19}$$

$$= \frac{R^L + \kappa_2(1 \quad 2\frac{c_{1,f>f^{OTC}} \quad 1}{\kappa_1})}{2 \quad c_{1,f>f^{OTC}}} \tag{IA20}$$

Due to borrower competition for funding, $c_2^L = c_{2,f=0}^{OTC}$.

For the H-type borrower's profit to be non negative,

$$R^H i_0 \quad c_{2,f=0}^{OTC}\ell_1^H + \kappa_2 k_0 \quad 0 \tag{IA21}$$

$$\text{s.t.} \quad c_{1,f>f^{OTC}}\ell_0 + \ell_1^H = 0. \tag{IA22}$$

Observe that if $\kappa_1 < \frac{\kappa_2}{2(R^L+\kappa_2)}$, $\frac{\partial(c_2^{OTC}\ell_1^H)}{\partial c_{1,f>f^{OTC}}} j_{c_{1,f>f^{OTC}}=1} < 0$ and therefore it suffices to show that with $c_{1,f>f^{OTC}} = 1$, the H-type borrower is willing to participate since $R^H \quad R^L \quad \kappa_2 \quad 0$.

For $f > f^{OTC}$, due to lender competition for the H-type borrower, $c_{2,f>f^{OTC}}^H = 1$ and $\ell_1^H = c_{1,f>f^{OTC}}\ell_0$. Assume that $c_{1,f>f^{OTC}}\ell_0 \quad 2(1 \quad f)m$.

At $t = 0$, first-round lenders of the L-type are repaid the liquidation value of the L-type borrower

$$c_1^D \ell_0 + \lambda i_0 + \kappa_1 k_0 = 0 \tag{IA23}$$

$$c_1^D = \lambda + \kappa_1. \tag{IA24}$$

Competitive lenders at $t = 0$ require

$$\alpha(\beta c_{1,f>f^{OTC}} + (1 \quad \beta)c_1^D) + (1 \quad \alpha)c_{1,f>f^{OTC}} = 1 \tag{IA25}$$

$$c_{1,f>f^{OTC}} = \frac{1 \quad \alpha(1 \quad \beta)c_1^D}{\alpha\beta + (1 \quad \alpha)} \tag{IA26}$$

Borrowers finance the investment with loans instead of liquidating own collateral if

$$\alpha\Big(\beta(R^H i_0 \quad c_2^{OTC}\ell_1^H) \quad (1 \quad \beta)\kappa_2 w_1^L\Big) + (1 \quad \alpha)\Big(\beta(R^H i_0 \quad c_{2,f=0}^{OTC}\ell_1^H) \quad (1 \quad \beta)\kappa_2 k_0\Big)$$
$$(\beta R^H + (1 \quad \beta)R^L \quad 1)k_0\kappa_0 \tag{IA27}$$

$$\frac{\beta(R^H \quad (\alpha + (1 \quad \alpha)\frac{R^L+\kappa_2(1 \quad 2\frac{c_{1,f>f^{OTC}} \quad 1}{\kappa_1})}{2 \quad c_{1,f>f^{OTC}}})c_{1,f>f^{OTC}})}{\beta R^H + (1 \quad \beta)R^L \quad 1 + (1 \quad \beta)(\alpha 2\frac{c_{1,f>f^{OTC}} \quad 1}{\kappa_1} + (1 \quad \alpha))} \quad \kappa_0. \tag{IA28}$$

B.3 Welfare

We consider ex-post welfare for the case in which a funding shock realizes.

If $0 < f \leq \frac{\kappa_1}{2}$, then ex-post welfare yields

$$\begin{aligned}
&R^H i_0 - c_2^{OTC}\ell_1^H + R^L i_0 - c_2^{OTC}\ell_1^L - \kappa_2 w_1^L + c_2^{OTC}(\ell_1^H + \ell_1^L) - \ell_1^H - \ell_1^L + 2c_1\ell_0 - 2\ell_0 && \text{(IA29)}\\
=&R^H i_0 + R^L i_0 - \kappa_2 w_1^L - \ell_1^H - \ell_1^L && \text{(IA30)}\\
=&(R^H + R^L - 2)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m. && \text{(IA31)}
\end{aligned}$$

If $\frac{\kappa_1}{2} < f \leq f^{OTC}$, then ex-post welfare yields

$$\begin{aligned}
&R^H i_0 - c_2^{OTC}\ell_1^H + R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L - \kappa_2 k_0 + c_2^{OTC}(\ell_1^H + \ell_1^L) - \ell_1^H - \ell_1^L + 2c_1\ell_0 - 2\ell_0 && \text{(IA32)}\\
=&R^H i_0 + R^L(i_0 - z_1^L) - \kappa_2 w_1^L - \ell_1^H - \ell_1^L && \text{(IA33)}\\
=&(R^H + R^L - 2)m - 2f(\frac{R^L}{\lambda} - 1)m + \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m. && \text{(IA34)}
\end{aligned}$$

If $f > f^{OTC}$ ex-post welfare yields

$$R^H i_0 - c^H_{2,f>f^{OTC}}\ell^H_{1,f>f^{OTC}} + c^H_{2,f>f^{OTC}}\ell^H_{1,f>f^{OTC}} - \ell^H_{1,f>f^{OTC}} + c_{1,f>f^{OTC}}\ell_0 + \lambda i_0 + \kappa_1 k_0 - \kappa_2 k_0 - 2\ell_0 \quad \text{(IA35)}$$

$$=(R^H + \lambda + \kappa_1 - \kappa_2 - 2)m \quad \text{(IA36)}$$

C CCP

C.1 COB market

Suppose that $i_0 = \ell_0 = m$ and $c_1 = 1$.

Consider first the case in which $f \leq \kappa_1$ and thus $z_1^P = 0$ since $k_0\kappa_1 + \ell_1^P \geq c_1\ell_0$. Then $w_1^P = \frac{f}{\kappa_1}m$.

The H-type borrower's participation constraint is slack and the L-type borrower's participation constraint is binding:

$$\begin{aligned}
R^L i_0 - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P) = 0 && \text{(IA37)}\\
\frac{R^L + \kappa_2(1 - \frac{f}{\kappa_1})}{1 - f} = c_2^P && \text{(IA38)}
\end{aligned}$$

With $(c_2^0 = R^L + \kappa_2, \ell_1^0 = c_1\ell_0)$, incentive compatibility for borrowers is satisfied:

$$R^\omega(i_0 - z_1^P) - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P) \geq R^\omega(i_0 - z_1^0) - c_2^0\ell_1^0 + \kappa_2(k_0 - k_1^0) \quad \text{(IA39)}$$

Lenders are willing to provide funding if

$$\begin{aligned}
c_2^P \geq 1 && \text{(IA40)}\\
\frac{R^L - 1}{\kappa_2 - \kappa_1}\kappa_1 + \frac{\kappa_2\kappa_1}{\kappa_2 - \kappa_1} \geq f. && \text{(IA41)}
\end{aligned}$$

Note, $\frac{R^L - 1}{\kappa_2 - \kappa_1}\kappa_1 + \frac{\kappa_2\kappa_1}{\kappa_2 - \kappa_1} > \kappa_1$.

If $\kappa_1 < f \leq f^{COB}$, $w_1^P = k_0$ and thus $z_1^P = \frac{c_1\ell_0 - \ell_1^P - \kappa_1 k_0}{\lambda}$.

The H-type borrower's participation constraint is slack and the L-type borrower's participation constraint is:

$$\begin{aligned}
R^L(i_0 - z_1^P) - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P) \geq 0 && \text{(IA42)}\\
\frac{R^L(1 - \frac{f - \kappa_1}{\lambda})}{1 - f} \geq c_2^P && \text{(IA43)}
\end{aligned}$$

The incentive compatibility of the H-type is the binding one and we obtain:

$$R^{\omega}(i_0 \quad z_1^P) \quad c_2^P \ell_1^P + \kappa_2(k_0 \quad w_1^P) \quad R^{\omega}(i_0 \quad z_1^0) \quad c_2^0 \ell_1^0 + \kappa_2(k_0 \quad k_1^0) \tag{IA44}$$

$$\frac{R^L \quad R^H \frac{f \quad \kappa_1}{\lambda}}{1 \quad f} \quad c_2^P \tag{IA45}$$

Observe that $\frac{R^L(1 \quad \frac{f \quad \kappa_1}{\lambda})}{1 \quad f} > \frac{R^L \quad R^H \frac{f \quad \kappa_1}{\lambda}}{1 \quad f}$. Then with $c_2^P = \frac{R^L \quad R^H \frac{f \quad \kappa_1}{\lambda}}{1 \quad f}$, lenders are willing to provide funding if

$$\frac{R^L \quad R^H \frac{f \quad \kappa_1}{\lambda}}{1 \quad f} \quad 1 \tag{IA46}$$

$$\frac{R^L \quad 1}{R^H \quad \lambda}\lambda + \frac{R^H \kappa_1}{R^H \quad \lambda} \quad f \tag{IA47}$$

Define $f^{COB} = \frac{R^L \quad 1}{R^H \quad \lambda}\lambda + \frac{R^H \kappa_1}{R^H \quad \lambda}$.

At $t = 1$ if $f = 0$, it is straightforward to show that $c_{2,f=0}^P = R^L + \kappa_2$, $\ell_{1,f=0}^P = m$, $k_{1,f=0}^P = 0$.

At $t = 0$, regardless whether lenders end up facing the H-type or L-type borrower, they are always repaid their investment, $c_1 = 1$.

Borrowers are willing to take a loan instead of investing the collateral value, in case $\kappa_1 < f \quad f^{COB}$, if

$$\alpha\Big((\beta R^H + (1 \quad \beta)R^L)(i_0 \quad z_1^P) \quad c_2^P \ell_1^P \quad \kappa_2 w_1^P\Big) + (1 \quad \alpha)\Big((\beta R^H + (1 \quad \beta)R^L)i_0 \quad c_{2,f=0}^P \ell_{1,f=0}^P\Big)$$
$$(\beta R^H + (1 \quad \beta)R^L \quad 1)\kappa_0 k_0 \tag{IA48}$$

$$\frac{(R^H \quad R^L)(\beta + \alpha(1 \quad \beta)\frac{f \quad \kappa_1}{\lambda})}{\beta R^H + (1 \quad \beta)R^L} \quad \kappa_0 \tag{IA49}$$

Observe that (IA49) also provides a lower bound on the size of the funding shock:

$$f \quad k_1 + \frac{(\beta R^H + (1 \quad \beta)R^L)\kappa_0 \quad \beta(R^H \quad R^L)}{\alpha(1 \quad \beta)(R^H \quad R^L)}\lambda \tag{IA50}$$

The intuition for why the individual rationality constraint delivers a lower bound on on the funding shock is that the interest rate decreases faster than the loan amount in the funding shock. We consider the range of funding shocks, $\kappa_1 < f \quad f^{COB}$. Then with $(\beta R^H + (1 \quad \beta)R^L)\kappa_0 \quad \beta(R^H \quad R^L) < 0$, i.e. $\kappa_0 \quad \frac{\beta(R^H \quad R^L)}{\beta R^H + (1 \quad \beta)R^L}$, condition (IA50) is always satisfied.

C.2 Welfare

We consider ex-post welfare in the case of a funding shock.

Consider first $\kappa_1 \quad f > 0$, then ex-post welfare is

$$(R^H + R^L)i_0 \quad 2c_2^P \ell_1^P \quad 2\kappa_2 w_1^P + 2c_2^P \ell_1^P \quad 2(1 \quad f)m + 2c_1 \ell_0 \quad 2\ell_0 \tag{IA51}$$

$$=(R^H + R^L \quad 2)m \quad 2f(\frac{\kappa_2}{\kappa_1} \quad 1)m \tag{IA52}$$

Next consider the case in which $\kappa_1 < f < f^{COB}$.

Ex-post welfare is

$$(R^H + R^L)(i_0 \quad z_1^P) \quad 2c_2^P \ell_1^P \quad 2\kappa_2 w_1^P + 2c_2^P \ell_1^P \quad 2(1 \quad f)m + 2c_1\ell_0 \quad 2\ell_0 \tag{IA53}$$

$$=(R^H + R^L \quad 2)m \quad f(\frac{R^H + R^L}{\lambda} \quad 2)m + (\frac{R^H + R^L}{\lambda}\kappa_1 \quad 2\kappa_2)m \tag{IA54}$$

If $f > f^{COB}$, ex post welfare is the liquidation value of collateral and LTT net of their investment cost $2(\lambda + \kappa_1 \quad \kappa_0 \quad 1)m$.

C.3 COB with novation

Suppose $i_0 = \ell_0 = m$. If $f > f^{COB}$, assuming novation, there is no market failure. Then, due to lender competition for the H-type borrower, $c^H_{2,f>f^{COB}} = 1$ and $\ell^H_{1,f>f^{COB}} = c_{1,f>f^{COB}}\ell_0$. Assume that $c_{1,f>f^{COB}}\ell_0 \quad 2(1 \quad f)m$.

First-round lenders of the L-type are repaid the liquidation value of the L-type borrower

$$c_1^D \ell_0 + \lambda i_0 + \kappa_1 k_0 = 0 \tag{IA55}$$

$$c_1^D = \lambda + \kappa_1. \tag{IA56}$$

If $f = 0$, $\ell^P_{1,f>f^{COB}} = m$. Suppose that there is no liquidation of the LTT and thus the missing part to repay first-round lenders comes from liquidating collateral, $w_1^P = \frac{c_{1,f>f^{COB}}\ell_0 \quad \ell^P_{1,f>f^{COB}}}{\kappa_1}$.

The H-type borrower's participation constraint is slack and the L-type borrower's participation constraint is binding:

$$R^L i_0 \quad c^P_{2,f>f^{COB}}\ell^P_{1,f>f^{COB}} + \kappa_2(k_0 \quad k^P_{1,f>f^{COB}}) \quad 0 \tag{IA57}$$

$$R^L + \kappa_2(1 \quad \frac{c_{1,f>f^{COB}} \quad 1}{\kappa_1}) \quad c^P_{2,f>f^{COB}} \tag{IA58}$$

Incentive compatibility is the same for either type with $c_2^0 = \frac{R^L+\kappa_2}{c_{1,f>f^{COB}}}$, $\ell_1^0 = c_{1,f>f^{COB}}\ell_0$:

$$R^\omega i_0 \quad c^P_{2,f>f^{COB}}\ell^P_{1,f>f^{COB}} + \kappa_2(k_0 \quad k^P_{1,f>f^{COB}}) \quad R^\omega i_0 \quad c_2^0\ell_1^0 + \kappa_2 k_0 \tag{IA59}$$

$$R^L + \kappa_2(1 \quad \frac{c_{1,f>f^{COB}} \quad 1}{\kappa_1}) \quad c^P_{2,f>f^{COB}}. \tag{IA60}$$

Therefore $c^P_{2,f>f^{COB}} = R^L + \kappa_2(1 \quad \frac{c_{1,f>f^{COB}} \quad 1}{\kappa_1})$.

For second-round lenders to provide loans

$$R^L + \kappa_2(1 \quad \frac{c_{1,f>f^{COB}} \quad 1}{\kappa_1}) \quad 1 \tag{IA61}$$

$$\kappa_2(1 \quad \frac{c_{1,f>f^{COB}} \quad 1}{\kappa_1}) \quad 1 \quad R^L \tag{IA62}$$

Observe the RHS is negative and the LHS, with $1 \quad \frac{c_{1,f>f^{COB}} \quad 1}{\kappa_1} > 0$, positive.

At $t = 0$, competitive lenders require

$$\alpha(\beta c_{1,f>f^{COB}} + (1 \quad \beta)c_1^D) + (1 \quad \alpha)c_{1,f>f^{COB}} = 1 \tag{IA63}$$

$$c_{1,f>f^{COB}} = \frac{1 \quad \alpha(1 \quad \beta)c_1^D}{\alpha\beta + (1 \quad \alpha)}. \tag{IA64}$$

Recall the assumption $c_{1,f>f^{COB}} \quad 2(1 \quad f)$. The assumption is satisfied if $c_1^D \quad 1$.

Borrowers are willing to take a loan instead of investing the collateral value if

$$\alpha\left(\beta(R^H i_0 - c^H_{2,f>f^{COB}}\ell^H_{1,f>f^{COB}}) - (1-\beta)\kappa_2 k_0\right) \tag{IA65}$$

$$+ (1-\alpha)\left((\beta R^H + (1-\beta)R^L)i_0 - c^P_{2,f>f^{COB}}\ell^P_{1,f>f^{COB}} - \kappa_2 k^P_{1,f>f^{COB}}\right)$$

$$-(\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA66}$$

$$\frac{\beta(R^H - (\alpha c_{1,f>f^{COB}} + (1-\alpha)R^L))}{\beta R^H + (1-\beta)R^L - 1 + (1-\alpha) + \alpha(1-\beta)} - \kappa_0 \tag{IA67}$$

Welfare: If $f^{COB} < f$, ex-post welfare is

$$R^H i_0 - c^H_{2,f>f^{COB}}\ell^H_{1,f>f^{COB}} - \kappa_2 k_0 + c^H_{2,f>f^{COB}}\ell^H_{1,f>f^{COB}} - \ell^H_{1,f>f^{COB}} + c_{1,f>f^{COB}}\ell_0 + c^D_1 \ell_0 - 2\ell_0 \tag{IA68}$$

$$=(R^H + \lambda + \kappa_1 - \kappa_2 - 2)m \tag{IA69}$$

C.4 Intuitive Criterion: pooling equilibrium

Recall, to construct the pooling equilibrium we have considered the following specification of beliefs:

$$Pr(R^H|c_2) = \begin{cases} \beta & \text{if } c_2 = c^P_2, \\ 1 & \text{otherwise .} \end{cases} \tag{IA70}$$

Consider $\kappa_1 < f - f^{COB}$. Then $w^P_1 = k_0$ and thus $z^P_1 = \frac{c_1\ell_0 - \ell^P_1 - \kappa_1 k_0}{\lambda}$. The equilibrium payoffs are

$$u(L) = (R^H - R^L)\frac{f - \kappa_1}{\lambda}m$$
$$u(H) = (R^H - R^L)m.$$

Equilibrium dominance: The response which maximizes the borrower's payoff is $\ell_1 = m$ and thus $w_1 = 0$.

$$max_{\ell_1 \in BR\ell_1} \quad R^\omega(i_0 - z_1) - c'_2\ell_1 = R^\omega m - c'_2 m + \kappa_2 m$$

Consider first the L-type borrower:

$$(R^H - R^L)\frac{f - \kappa_1}{\lambda}m > R^L m - c'_2 m + \kappa_2 m$$
$$c'_2 > R^L + \kappa_2 - (R^H - R^L)\frac{f - \kappa_1}{\lambda}.$$

All messages $c'_2 > R^L + \kappa_2 - (R^H - R^L)\frac{f-\kappa_1}{\lambda}$ are equilibrium dominated for the L-type.

Similarly for the H-type:

$$(R^H - R^L)m > R^H m - c'_2 m + \kappa_2 m$$
$$c'_2 > R^L + \kappa_2.$$

All messages $c'_2 > R^L + \kappa_2$ are equilibrium dominated for the H-type.

We can therefore summarize that

- $c'_2 \in [0, R^L + \kappa_2 - (R^H - R^L)\frac{f-\kappa_1}{\lambda})$ is not equilibrium dominated for neither the H-type nor the L-type,
- $c'_2 \in (R^L + \kappa_2 - (R^H - R^L)\frac{f-\kappa_1}{\lambda}, R^L + \kappa_2]$ is equilibrium dominated for the L-type only, and

- $c_2' \in (R^L + \kappa_2, \infty)$ is equilibrium dominated for both types.

We conclude that for $c_2' \in (R^L + \kappa_2 - (R^H - R^L)\frac{f-\kappa_1}{\lambda}, R^L + \kappa_2]$ the Intuitive Criterion prescribes that $Pr(L|c_2') = 0$. For the other ranges of c_2', the Intuitive Criterion is silent about which off-equilibrium belief to specify. In particular, our specified off-equilibrium belief $Pr(H|c_2') = 1$ survives the Intuitive Criterion.

D Optimal market solution

D.1 Privately optimal transfers

Consider the OTC market with $\ell_1^H = c_1\ell_0$ and $\ell_1^L = 2(1-f)m - c_1\ell_0$. At $t = 1$ if $f > \kappa_1/2$, then the H-type can at most transfer collateral w_1^H at $t = 1$ and τ at $t = 2$:

$$R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau \geq 0 \tag{IA71}$$

$$s.t. \quad c_1\ell_0 + \ell_1^H = 0 \tag{IA72}$$

The L-type borrower's participation is then given by

$$R^L(i_0 - z_1^L) - c_2^L\ell_1^L + \kappa_2(k_0 - w_1^L) + \tau = 0 \tag{IA73}$$

$$s.t. \quad c_1\ell_0 + \ell_1^L + \kappa_1(w_1^L + w_1^H) + \lambda z_1^L = 0 \tag{IA74}$$

This yields

$$c_2^L = \frac{R^L(i_0 - z_1^L) + \kappa_2(k_0 - w_1^L) + \tau}{\ell_1^L} \tag{IA75}$$

$$z_1^L = \frac{c_1\ell_0 - \ell_1^L - \kappa_1(w_1^L + w_1^H)}{\lambda} \tag{IA76}$$

Note that the market rate is given by

$$R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \kappa_2(k_0 - w_1^L) = 0 \tag{IA77}$$

$$s.t. \quad c_1\ell_0 + \ell_1^L + \kappa_1 w_1^L + \lambda z_1^L = 0 \tag{IA78}$$

if $f \leq f^{OTC}$ and $c_2^{OTC} = 1$ if $f > f^{OTC}$.

Consider now the equilibrium when the realization of the funding shock is $f = 0$. Then $\ell_1^H = \ell_{1,f=0}^L = m$. Then the market rate is

$$R^L i_0 - c_{2,f=0}^{OTC}\ell_{1,f=0}^L + \kappa_2 k_0 = 0 \tag{IA79}$$

$$s.t. \quad c_1\ell_0 + \ell_{1,f=0}^L = 0 \tag{IA80}$$

At $t = 0$ expected borrower profit is

$$\alpha\Big[\beta\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau - \kappa_0 k_0\big) - (1-\beta)\kappa_0 m\Big]$$

$$+(1-\alpha)\Big[\beta\big(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H + (\kappa_2 - \kappa_0)k_0\big) - (1-\beta)\kappa_0 m\Big] - (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA81}$$

To derive the transfer in case of default, consider $f > f^{OTC}$ such that $c_2^{OTC} = 1$. Then from expression

(IA81), we obtain the maximum commitment borrowers are willing to make to the default fund:

$$
\begin{aligned}
\tau^{OPT} &= \frac{1}{\alpha\beta}\Bigg[\alpha\Big(\beta((R^H \quad 1)m \quad \kappa_0 w_1^H) \quad (1 \quad \beta)\kappa_0 m\Big) \\
&\qquad + (1 \quad \alpha)\Big(\beta\big(R^H \quad R^L \quad \kappa_2\big) \quad (1 \quad \beta)\kappa_0\Big)m \quad (\beta R^H + (1 \quad \beta)R^L \quad 1)\kappa_0 m\Bigg] \\
&= \frac{1}{\alpha\beta}\Bigg[\alpha\beta(R^H \quad 1) + (1 \quad \alpha)\beta(R^H \quad R^L) \quad (\beta R^H + (1 \quad \beta)R^L)\kappa_0 + \alpha\beta(1 \quad w_1^H)\kappa_0\Bigg]m
\end{aligned}
\tag{IA82}
$$

The transfer decreases in the liquidation of the H-type's collateral, w_1^H. There is hence a trade-off for the policy maker between increasing the repayment capacity of the L-type borrower at $t = 1$ and $t = 2$. We show below that it is socially optimal to liquidate the H-type's collateral at $t = 1$, i.e. $w_1^H = k_0$. With $w_1^H = k_0$, $\tau^{OPT} > 0$ if $\frac{\beta(R^H \quad (\alpha+(1 \quad \alpha)R^L))}{\beta R^H+(1 \quad \beta)R^L} \quad \kappa_0$. This condition guarantees that borrowers make ex-ante non-negative profits which can be committed to a default fund paid out at $t = 2$. This expected profit already takes into account a collateral transfer from the H-type to the L-type at $t = 1$.

D.2 Socially optimal collateral transfer

Next, we show that it is indeed optimal to liquidate the H-type's entire collateral, i.e. $w_1^H = k_0$. Therefore, consider ex-ante welfare

$$
\begin{aligned}
&\alpha\Big[\big(R^H i_0 \quad c_2^{OTC}\ell_1^H + \kappa_2(k_0 \quad w_1^H) \quad \tau^{OPT} \quad \kappa_0 k_0 + c_2^{OTC}\ell_1^H \quad \ell_1^H + c_1\ell_0 \quad \ell_0\big) \\
&\quad + \big(R^L(i_0 \quad z_1^L) \quad c_2^{OTC}\ell_1^L + \tau^{OPT} \quad \kappa_0 k_0 + c_2^{OTC}\ell_1^L \quad \ell_1^L + c_1\ell_0 \quad \ell_0\big)\Big] \\
&+(1 \quad \alpha)\Big[\big(R^H i_0 \quad c_{2,f=0}^{OTC}\ell_1^H + (\kappa_2 \quad \kappa_0)k_0 + c_{2,f=0}^{OTC}\ell_1^H \quad \ell_1^H + c_1\ell_0 \quad \ell_0\big) \\
&\quad + \big(R^L i_0 \quad c_{2,f=0}^{OTC}\ell_{1,f=0}^L(\kappa_2 \quad \kappa_0)k_0 + c_{2,f=0}^{OTC}\ell_{1,f=0}^L \quad \ell_{1,f=0}^L + c_1\ell_0 \quad \ell_0\big)\Big]
\end{aligned}
\tag{IA83}
$$

$$
\begin{aligned}
&= \alpha\Big[\big(R^H i_0 \quad \kappa_2 w_1^H \quad \ell_1^H\big) + \big(R^L(i_0 \quad z_1^L) \quad \kappa_0 k_0 \quad \ell_1^L\big)\Big] \\
&\quad +(1 \quad \alpha)\Big[\big(R^H i_0 \quad \ell_1^H\big) + \big(R^L i_0 \quad \ell_{1,f=0}^L\big)\Big]
\end{aligned}
\tag{IA84}
$$

$$
= (R^H + R^L \quad 2)m \quad \alpha\Big(2fm(\frac{R^L}{\lambda} \quad 1) \quad \kappa_1(\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1})(w_1^H + m)\Big)
\tag{IA85}
$$

with $z_1^L = \frac{c_1\ell_0 \quad \ell_1^L \quad \kappa_1(w_1^L+w_1^H)}{\lambda}$. Observe, expected welfare is increasing in the H-type's liquidation of collateral, w_1^H, due to the pecking order, $\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1} > 0$.

Furthermore, we have to show that the H-type lender is able to make the transfer, at $t = 2$

$$
R^H i_0 \quad c_2^{OTC}\ell_1^H \quad \tau^{OPT} \quad 0
\tag{IA86}
$$

if $\kappa_0 \quad \frac{(1 \quad \alpha)\beta(R^H \quad R^L)}{\beta R^H+(1 \quad \beta)R^L}$. Recall the upper bound on κ_0 required for $\tau^{OPT} \quad 0$. It is straightforward to show that there exists indeed a non-empty range for κ_0.

D.3 Run threshold

$R^L(i_0 \quad z_1^L) \quad c_2^L\ell_1^L + \kappa_2(k_0 \quad w_1^L) + \tau^{OPT} = 0.$

Finally, we provide the condition up to which the L-type is able to repay second round lenders. Recall from expression (IA82) that τ^{OPT} is independent of f if $w_1^H = \text{f}0, m\text{g}$.

$$R^L(i_0 \quad z_1^L) \quad c_2^L \ell_1^L + \kappa_2(k_0 \quad w_1^L) + \tau^{OPT} = 0 \tag{IA87}$$

$$\frac{R^L \quad 1}{R^L \quad \lambda}\frac{\lambda}{2} + \frac{R^L \kappa_1 (w_1^H + w_1^L)}{2(R^L \quad \lambda)m} + \frac{\tau^{OPT}\lambda}{2(R^L \quad \lambda)m} \quad f \tag{IA88}$$

Call $f^{OPT} = \frac{R^L \quad 1}{R^L \quad \lambda}\frac{\lambda}{2} + \frac{R^L \kappa_1 (w_1^H + w_1^L)}{2(R^L \quad \lambda)m} + \frac{\tau^{OPT}\lambda}{2(R^L \quad \lambda)m}$.

D.4 Ex-post welfare

This is to show that the above mechanism implements the first-best solution up to f^{OPT}.

If $\frac{\kappa_1}{2} < f \quad \kappa_1$, ex-post welfare is given by

$$\begin{aligned}
&\big(R^H i_0 \quad c_2^{OTC}\ell_1^H + \kappa_2(k_0 \quad w_1^H) \quad \tau^{OPT} \quad \kappa_0 k_0 + c_2^{OTC}\ell_1^H \quad \ell_1^H + c_1\ell_0 \quad \ell_0\big) \\
&\quad + \big(R^L(i_0 \quad z_1^L) \quad c_2^{OTC}\ell_1^L + \tau^{OPT} \quad \kappa_0 k_0 + c_2^{OTC}\ell_1^L \quad \ell_1^L + c_1\ell_0 \quad \ell_0\big) \\
=&\big(R^H i_0 \quad \kappa_2 w_1^H \quad \ell_1^H\big) + \big(R^L(i_0 \quad z_1^L) \quad \kappa_0 k_0 \quad \ell_1^L\big) \\
s.t. \quad & c_1\ell_0 + \kappa_1(w_1^H + k_0) + \ell_1^L = 0.
\end{aligned} \tag{IA89}$$

With $w_1^H = \frac{c_1\ell_0 \quad \kappa_1 k_0 \quad \ell_1^L}{\kappa_1}$, ex-post welfare is

$$(R^H + R^L \quad 2)m \quad 2f(\frac{\kappa_2}{\kappa_1} \quad 1)m. \tag{IA90}$$

If $\kappa_1 < f \quad f^{OPT}$, ex-post welfare is given by

$$\begin{aligned}
&\big(R^H i_0 \quad c_2^{OTC}\ell_1^H + \kappa_2(k_0 \quad w_1^H) \quad \tau^{OPT} \quad \kappa_0 k_0 + c_2^{OTC}\ell_1^H \quad \ell_1^H + c_1\ell_0 \quad \ell_0\big) \\
&\quad + \big(R^L(i_0 \quad z_1^L) \quad c_2^{OTC}\ell_1^L + \tau^{OPT} \quad \kappa_0 k_0 + c_2^{OTC}\ell_1^L \quad \ell_1^L + c_1\ell_0 \quad \ell_0\big) \\
=&\big(R^H i_0 \quad \kappa_2 k_0 \quad \ell_1^H\big) + \big(R^L(i_0 \quad z_1^L) \quad \kappa_0 k_0 \quad \ell_1^L\big) \\
s.t. \quad & c_1\ell_0 + 2\kappa_1 k_0 + \ell_1^L + \lambda z_1^L = 0.
\end{aligned} \tag{IA91}$$

With $z_1^L = \frac{c_1\ell_0 \quad 2\kappa_1 k_0 \quad \ell_1^L}{\lambda}$, ex-post welfare is

$$(R^H + R^L \quad 2)m \quad 2f(\frac{R^L}{\lambda} \quad 1)m + 2\kappa_1(\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1})m. \tag{IA92}$$

D.5 Run threshold comparison

Recall the first-best run threshold $f^{FB} = \frac{R^H + R^L \quad 2}{R^L \quad \lambda} \quad \frac{\lambda}{2} + \frac{R^L}{R^L \quad \lambda} \quad \kappa_1 \quad \frac{\lambda}{R^L \quad \lambda} \quad \kappa_0$.

Observe that $f^{FB} > f^{OPT}$ with $R^H < 2$, $\alpha < \frac{(1 \quad \beta)R^L}{\beta(2 \quad R^H)}$ and $\kappa_0 > \frac{\beta(1 \quad \alpha)(R^H \quad R^L)}{\alpha\beta(R^H \quad 2)+(1 \quad \beta)R^L}$.

Finally, for most admissible parameter values, $f^{OPT} > \frac{1}{2}$, in particular for $\frac{\beta\lambda(R^H \quad R^L)+\alpha\beta(R^L(2(\kappa_1+\lambda) \quad 1) \quad \lambda)}{(\beta R^H+(1 \quad \beta)R^L)\lambda} > \kappa_0$.

D.6 OTC and default fund

Suppose there is no transfer of collateral, $w_1^H = 0$.

Then, for $\frac{\kappa_1}{2} < f < \frac{1}{2}$, $z_1^L = \frac{c_1\ell_0 \quad \kappa_1 k_0 \quad \ell_1^L}{\lambda}$, and ex-post welfare is given

$$(R^H + R^L \quad 2)m + \kappa_1(\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1}) \quad 2f(\frac{R^L}{\lambda} \quad 1)m. \tag{IA93}$$

Observe that

$$W^{OPT} \quad W^{OPT}_{w_1^H=0} = \begin{cases} (\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1})(\kappa_1 + 2f) & \text{if } \frac{\kappa_1}{2} < f \quad \kappa_1 \\ (\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1})\kappa_1 & \text{if } \kappa_1 < f \quad f^{OPT} \end{cases} \tag{IA94}$$

D.7 Hybrid mechanism

The run threshold in the hybrid market is indeed larger than in the CCP market since

$$\begin{aligned} f^{OPT} j_{w_1^H=0} > & f^{CCP} \\ \kappa_0 > & \frac{1}{\alpha\beta\kappa_1 R_L(R_H + R_L \quad 2\lambda)} \\ & \Big[\alpha\beta\Big(2\kappa_1 R_L(R_H + R_L) \quad \kappa_0\lambda(R_H + R_L \quad 2\lambda) + 2\lambda((R_L \quad 1 \quad \kappa_1)R_L \quad R_H(R_L \quad 1 + \kappa_1))\Big) \\ & + \lambda(R_H \quad R_L)\Big(\kappa_0 R_L + \beta(\quad R_H + R_L + \kappa_0(R_H + R_L \quad 2\lambda))\Big)\Big], \end{aligned}$$

where the R.H.S is strictly smaller than 1.

E Convenience yield

E.1 OTC market

In case of the OTC market, borrowers finance the investment with loans instead of liquidating own collateral

- for $0 < f \quad \frac{\kappa_1}{2}$, if

$$\begin{aligned} & \alpha\Big(\beta(R^H i_0 \quad c_2^{OTC}\ell_1^H) \quad (1 \quad \beta)\kappa_2 w_1^L\Big) + (1 \quad \alpha)\Big(\beta(R^H i_0 \quad c_{2,f=0}^{OTC}\ell_1^H) \quad (1 \quad \beta)\kappa_2 k_0\Big) \\ & (\beta R^H + (1 \quad \beta)R^L \quad 1)k_0\kappa_0 \end{aligned} \tag{IA95}$$

$$\frac{\beta(R^H \quad R^L(\alpha\frac{1}{1 \quad 2f} + 1 \quad \alpha))}{\beta R^H + (1 \quad \beta)R^L \quad 1 + \alpha(\beta\frac{\kappa_1 \quad 2f}{1 \quad 2f} + (1 \quad \beta)2f)\frac{1}{\kappa_1} + (1 \quad \alpha)} \quad \kappa_0, \tag{IA96}$$

- for $\frac{\kappa_1}{2} < f \quad f^{OTC}$, if

$$\begin{aligned} & \alpha\Big(\beta(R^H i_0 \quad c_2^{OTC}\ell_1^H) \quad (1 \quad \beta)\kappa_2 k_0\Big) + (1 \quad \alpha)\Big(\beta(R^H i_0 \quad c_{2,f=0}^{OTC}\ell_1^H) \quad (1 \quad \beta)\kappa_2 k_0\Big) \\ & (\beta R^H + (1 \quad \beta)R^L \quad 1)k_0\kappa_0 \end{aligned} \tag{IA97}$$

$$\frac{\beta(R^H \quad R^L(\alpha\frac{1 \quad \frac{2f \quad \kappa_1}{\lambda}}{1 \quad 2f} + 1 \quad \alpha))}{\beta R^H + (1 \quad \beta)R^L \quad 1 + (1 \quad \beta) + (1 \quad \alpha)\beta} \quad \kappa_0, \tag{IA98}$$

- $f > f^{OTC}$ if

$$\begin{aligned} & \alpha\Big(\beta(R^H i_0 \quad c_2^{OTC}\ell_1^H) \quad (1 \quad \beta)\kappa_2 w_1^L\Big) + (1 \quad \alpha)\Big(\beta(R^H i_0 \quad c_{2,f=0}^{OTC}\ell_1^H) \quad (1 \quad \beta)\kappa_2 k_0\Big) \\ & (\beta R^H + (1 \quad \beta)R^L \quad 1)k_0\kappa_0 \end{aligned} \tag{IA99}$$

$$\frac{\beta(R^H \quad (\alpha + (1 \quad \alpha)\frac{R^L + \kappa_2(1 \quad 2\frac{c_{1,f>f^{OTC}} \quad 1}{\kappa_1})}{2 \quad c_{1,f>f^{OTC}}})c_{1,f>f^{OTC}})}{\beta R^H + (1 \quad \beta)R^L \quad 1 + (1 \quad \beta)(\alpha 2\frac{c_{1,f>f^{OTC}} \quad 1}{\kappa_1} + (1 \quad \alpha))} \quad \kappa_0. \tag{IA100}$$

The collateral premium in the OTC market is therefore defined by

$$\mathbf{cp}^{OTC} = \begin{cases} \frac{\beta(R^H \;\; R^L(\alpha\frac{1}{1\;\;2f}+1\;\;\alpha))}{\beta R^H+(1\;\;\beta)R^L\;\;1+\alpha(\beta\frac{\kappa_1\;\;2f}{1\;\;2f}+(1\;\;\beta)2f)\frac{1}{\kappa_1}+(1\;\;\alpha)} \;\; \kappa_0, & \text{if } 0 < f \;\; \frac{\kappa_1}{2}, \\ \frac{\beta(R^H\;\;R^L(\alpha\frac{1\;\;\frac{2f\;\;\kappa_1}{\lambda}}{1\;\;2f}+1\;\;\alpha))}{\beta R^H+(1\;\;\beta)R^L\;\;\alpha\beta} \;\; \kappa_0, & \text{if } \frac{\kappa_1}{2} < f \;\; f^{OTC}, \\ \frac{\beta(R^H\;\;(\alpha+(1\;\;\alpha)\frac{R^L+\kappa_2(1\;\;2\frac{c_{1,f>f^{OTC}}\;\;1}{\kappa_1})}{2\;\;c_{1,f>f^{OTC}}})c_{1,f>f^{OTC}})}{\beta R^H+(1\;\;\beta)R^L\;\;1+(1\;\;\beta)(\alpha 2\frac{c_{1,f>f^{OTC}}\;\;1}{\kappa_1}+(1\;\;\alpha))} \;\; \kappa_0, & \text{if } f > f^{OTC}. \end{cases} \tag{IA101}$$

The ranking of collateral premia requires the parametrization for the collateral shadow values. We use the following parameters: $R^H = 1.55$, $R^L = 1.05$, $\lambda = 0.7$, $\kappa_1 = 0.09$, $\kappa_0 = 0.1$, $\kappa_2 = \kappa_0$, $\beta = 0.3$, $\alpha = 0.2$. Then, the largest collateral premium is obtained for $f > f^{OTC}$ whereas the ranking of the collateral premia for $0 < f \;\; \frac{\kappa_1}{2}$ and $\frac{\kappa_1}{2} < f \;\; f^{OTC}$ is ambiguous.

E.2 CCP market

In case of COB trading in the CCP market, borrowers finance the investment with loans instead of liquidating own collateral

- for $0 < f \;\; \kappa_1$, if

$$\alpha\Big((\beta R^H + (1 \;\; \beta)R^L)i_0 \;\; c_2^P\ell_1^P \;\; \kappa_2 w_1^P\Big) + (1 \;\; \alpha)\Big((\beta R^H + (1 \;\; \beta)R^L)i_0 \;\; c_{2,f=0}^P\ell_{1,f=0}^P\Big)$$
$$(\beta R^H + (1 \;\; \beta)R^L \;\; 1)\kappa_0 k_0 \tag{IA102}$$
$$\frac{\beta(R^H \;\; R^L)}{\beta R^H + (1 \;\; \beta)R^L + (1 \;\; \alpha)} \;\; \kappa_0 \tag{IA103}$$

- for $\kappa_1 < f \;\; f^{COB}$, if

$$\alpha\Big((\beta R^H + (1 \;\; \beta)R^L)(i_0 \;\; z_1^P) \;\; c_2^P\ell_1^P \;\; \kappa_2 k_0\Big) + (1 \;\; \alpha)\Big((\beta R^H + (1 \;\; \beta)R^L)i_0 \;\; c_{2,f=0}^P\ell_{1,f=0}^P\Big)$$
$$(\beta R^H + (1 \;\; \beta)R^L \;\; 1)\kappa_0 k_0 \tag{IA104}$$
$$\frac{(R^H \;\; R^L)(\beta + \alpha(1 \;\; \beta)\frac{f\;\;\kappa_1}{\lambda})}{\beta R^H + (1 \;\; \beta)R^L} \;\; \kappa_0 \tag{IA105}$$

- for $f^{COB} < f$, if

$$\alpha\Big(\;\; \kappa_2 k_0\Big) + (1 \;\; \alpha)\Big((\beta R^H + (1 \;\; \beta)R^L)i_0 \;\; c_{2,f=0}^P\ell_{1,f=0}^P \;\; k_2 w_{1,f=0}^P\Big)$$
$$(\beta R^H + (1 \;\; \beta)R^L \;\; 1)\kappa_0 k_0 \tag{IA106}$$
$$\frac{(1 \;\; \alpha)\beta(R^H \;\; R^L)}{\beta R^H + (1 \;\; \beta)R^L} \;\; \kappa_0 \tag{IA107}$$

Observe, $\frac{(1\;\;\alpha)\beta(R^H\;\;R^L)}{\beta R^H+(1\;\;\beta)R^L} < \frac{\beta(R^H\;\;R^L)}{\beta R^H+(1\;\;\beta)R^L+(1\;\;\alpha)} < \frac{(R^H\;\;R^L)(\beta+\alpha(1\;\;\beta)\frac{f\;\;\kappa_1}{\lambda})}{\beta R^H+(1\;\;\beta)R^L}$, where the first inequality is satisfied if $\frac{(1\;\;\alpha)^2}{\alpha} < \beta R^H + (1 \;\; \beta)R^L$ and the second inequality is always satisfied. The collateral premium in the CCP market is therefore defined by

$$\mathbf{cp}^{COB} = \begin{cases} \frac{\beta(R^H\;\;R^L)}{\beta R^H+(1\;\;\beta)R^L+(1\;\;\alpha)} \;\; \kappa_0, & \text{if } 0 < f \;\; \kappa_1, \\ \frac{(R^H\;\;R^L)(\beta+\alpha(1\;\;\beta)\frac{f\;\;\kappa_1}{\lambda})}{\beta R^H+(1\;\;\beta)R^L} \;\; \kappa_0, & \text{if } \kappa_1 < f \;\; f^{COB}, \\ \frac{(1\;\;\alpha)\beta(R^H\;\;R^L)}{\beta R^H+(1\;\;\beta)R^L} \;\; \kappa_0, & \text{if } f > f^{COB}. \end{cases} \tag{IA108}$$

F Equilibrium selection and market co-existence

The equilibrium in Lemma 3 exhibits a one-fits-all loan for any type of borrower whereas in the separating equilibrium, in Appendix G, borrowers can signal their types through the loan contract and, consequently, lenders provide different loan contracts to different types. In Appendices C.4 and G.2, we show that the Intuitive Criterion does not lead to equilibrium selection. We can, however, rank the equilibria in terms of welfare. If borrowers were to choose between separating and pooling equilibria at $t = 1$, they would prefer the pooling equilibrium for any $f \quad f^{COB}$. The H-type borrower makes identical profits in both separating and pooling equilibrium while the L-type borrower is strictly better off in the pooling equilibrium. The pooling equilibrium also yields weakly larger ex-ante welfare than the separating equilibrium for most parameter values. We provide the proof in the following subsection.

F.1 Welfare dominance

Ex-ante welfare in the separating and pooling equilibrium differ and are non-monotonic. To develop some intuition for the difference, observe that welfare in the separating equilibrium is identical to welfare in the constrained first-best solution. While separation is costly for borrowers in the separating equilibrium (in particular the H-type has to pay a higher loan rate than in the constrained first best), it increases lenders profit to the same extent and thus welfare is unaffected. Indeed loan rates are mere transfers and hence the difference in loan rates between constrained first best and separating equilibrium are welfare neutral.

From Appendix B we know the welfare realizations at $t = 1$ for any level of funding shock. Furthermore, from Proposition 1, we can deduct that expected welfare

- is identical between separating and pooling equilibrium if the funding shock distribution is $0 < f \quad \frac{\kappa_1}{2}$ with probability α and $f = 0$ with probability $1 \quad \alpha$,
- is larger in the pooling equilibrium than in the separating equilibrium if the funding shock distribution is $\frac{\kappa_1}{2} < f \quad \kappa_1$ with probability α and $f = 0$ with probability $1 \quad \alpha$,
- is larger in the pooling equilibrium than in the separating equilibrium if the funding shock distribution is $\kappa_1 < f \quad f^{Sep}$ with probability α and $f = 0$ with probability $1 \quad \alpha$ (proof below) and
- is larger in the pooling equilibrium than in the separating equilibrium if the funding shock distribution is $f^{Sep} < f \quad f^{COB}$ with probability α and $f = 0$ with probability $1 \quad \alpha$.

We focus on the funding shocks $0 < f \quad f^{COB}$ because beyond this threshold novation and the default fund impact on the welfare comparison.

The proof for the ex-ante welfare comparison for $\kappa_1 < f \quad f^{Sep}$ is as follows:

$$W^{Sep} = \alpha\Big(R^H i_0 \quad c_2^{S,H}\ell_1^{S,H} + R^L(i_0 \quad z_1^{S,L}) \quad c_2^{S,L}\ell_1^{S,L} \quad \kappa_2 w_1^{S,L} + c_2^{S,H}\ell_1^{S,H} + c_2^{S,L}\ell_1^{S,L} \quad \ell_1^{S,H} \quad \ell_1^{S,L}$$
$$+2c_1\ell_0 \quad 2\ell_0\Big) + (1 \quad \alpha)\Big(R^H i_0 \quad c_{2,f=0}^{S,H}\ell_{1,f=0}^{S,H} + R^L i_0 \quad c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L}$$
$$+c_{2,f=0}^{S,H}\ell_{1,f=0}^{S,H} + c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L} \quad \ell_{1,f=0}^{S,H} \quad \ell_{1,f=0}^{S,L} + 2c_1\ell_0 \quad 2\ell_0\Big) \tag{IA109}$$

$$= (R^H + R^L \quad 2)m \quad \alpha(2f(\frac{R^L}{\lambda} \quad 1) \quad \kappa_1(\frac{R^L}{\lambda} \quad \frac{\kappa_0}{\kappa_0})) \tag{IA110}$$

Ex-ante welfare in the pooling equilibrium is:

$$W^{Pool} = \alpha\Big((R^H + R^L)(i_0 \quad z_1^P) \quad 2c_2^P\ell_1^P + 2\kappa_2(k_0 \quad w_1^P) \quad 2k_0\kappa_0 + 2c_2^P\ell_1^P \quad 2\ell_1^P + 2c_1\ell_0 \quad 2\ell_0\Big)$$
$$+(1 \quad \alpha)\Big((R^H + R^L)i_0 \quad 2c_{2,f=0}^P\ell_{1,f=0}^P + 2c_{2,f=0}^P\ell_{1,f=0}^P \quad 2\ell_{1,f=0}^P + 2c_1\ell_0 \quad 2\ell_0\Big) \tag{IA111}$$

$$= (R^H + R^L \quad 2)m \quad \alpha(f(\frac{R^H + R^L \quad 2\lambda}{\lambda} \quad 1) \quad \kappa_1(\frac{R^H + R^L}{\lambda} \quad 2\frac{\kappa_0}{\kappa_0})) \tag{IA112}$$

The difference in expected welfare between pooling and separating equilibrium, $W^{Pool} - W^{Sep} > 0$, is positive if $\kappa_1 > \frac{R^H - R^L}{R^H} f$. Since we are considering the parameter space $\kappa_1 < f - f^{Sep}$, we have to check that there exists a non-empty range for κ_1 which is the case since $\frac{R^H - R^L}{R^H} f < f$.

F.2 Market coexistence

We study the occurrence of different market structures by comparing borrowers' ex-ante profits. We define a level of the LTT's illiquidity, $\bar{\lambda}$, at which borrowers are ex-ante indifferent between the two markets. Different market structures co-exist depending on the nature of borrowers' LTT. The following proposition summarizes the results.

Proposition 9 *Borrowers with illiquid LTT, $\lambda < \bar{\lambda}$, prefer the CCP over the OTC market, while borrowers with liquid LTT, $\lambda > \bar{\lambda}$, prefer the OTC market over the CCP, in the parameter space most relevant for resource allocation and market resilience, i.e. $\kappa_1 < f - f^{OTC}$.*

For our main analysis to go through we require that markets co-exist for the same parameter values. There are two ways to achieve that borrowers are ex-ante indifferent between the two markets. We can assume that $\lambda = \bar{\lambda}$ or there is a cost, τ not explicitly modeled which closes the gap $\lambda - \tau = \bar{\lambda}$. Suppose $\lambda > \bar{\lambda}$, such that borrowers prefer the OTC market. The difference, $\lambda - \bar{\lambda}$, delivers therefore a theoretical prediction of e.g. search cost in the OTC market.

Proof For this analysis we focus on the parameter range which is most relevant for both resource allocation and market resilience, i.e. $\kappa_1 < f - f^{OTC}$.

Consider borrowers' ex- ante profit in case of COB trading in the CCP market

$$\begin{aligned} E(\Pi^{COB}) =& \alpha\Big((\beta R^H + (1-\beta)R^L)(i_0 - z_1^P) - c_2^P \ell_1^P - \kappa_2 k_0\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P\Big) \\ =& \beta(R^H - R^L) - \kappa_0 + \alpha(1-\beta)(R^H - R^L)\frac{f - \kappa_1}{\lambda}. \end{aligned} \tag{IA113}$$

And borrower's ex-ante profit in the OTC market is

$$\begin{aligned} E(\Pi^{OTC}) =& \alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big) + (1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big) \\ =& \beta(R^H - R^L) - \kappa_0 + \alpha\beta(\kappa_0 - R^L \frac{2f - \frac{2f-\kappa_1}{\lambda}}{1-2f}). \end{aligned} \tag{IA114}$$

Define $\bar{\lambda}$ by

$$\begin{aligned} E(\Pi^{CCP}) - E(\Pi^{OTC}) &= 0 \\ \bar{\lambda} &= \frac{(1-\beta)(R^H - R^L)(f - \kappa_1) + \beta R^L \frac{2f-\kappa_1}{1-2f}}{\beta(\kappa_0 - \frac{2f}{1-2f}R^L)} \end{aligned} \tag{IA115}$$

Then, with $\frac{\kappa_0}{R^L + \kappa_0} > \kappa_1$, borrowers choose to borrow from the CCP (OTC) market if $\lambda < (>)\bar{\lambda}$.

G Separating equilibrium

We specify beliefs as follows:

$$Pr(R^H | c_2) = \begin{cases} 1 & \text{if } c_2 = c_2^{S,H}, \\ 0 & \text{if } c_2 = c_2^{S,L}, \\ 1 & \text{otherwise .} \end{cases} \tag{IA116}$$

We first solve the roll over decision $(c_2^{S,\omega}, \ell_1^{S,\omega})$ and then move backward to the investment decision. At $t = 1$, a borrower of types ω rolls over if the participation constraint is satisfied (the outside option is liquidation $(\lambda + \kappa_1)m \quad c_1\ell_0 \quad 0)$,

$$R^{\omega}(i_0 \quad z_1^{S,\omega}) \quad c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 \quad w_1^{S,\omega}) \quad 0, \tag{IA117}$$

the repayment condition is met,

$$c_1\ell_0 + \lambda z_1^{S,\omega} + \ell_1^{S,\omega} + \kappa_1 w_1^{S,\omega} = 0, \tag{IA118}$$

borrowers incentive compatibility constraint is satisfied so that borrowers do not mimic each other,

$$R^{\omega}(i_0 \quad z_1^{S,\omega}) \quad c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 \quad w_1^{S,\omega}) \quad R^{\omega}(i_0 \quad z_1^{S, \quad \omega}) \quad c_2^{S, \quad \omega}\ell_1^{S, \quad \omega} + \kappa_2(k_0 \quad w_1^{S, \quad \omega}), \tag{IA119}$$

and borrowers do not choose anything but the equilibrium quantities provided that lenders believe they face the H-type off-equilibrium,

$$R^{\omega}(i_0 \quad z_1^{S,\omega}) \quad c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 \quad w_1^{S,\omega}) \quad R^{\omega}(i_0 \quad z_1^{\emptyset}) \quad c_2^{\emptyset}\ell_1^{\emptyset} + \kappa_2(k_0 \quad k_1^{\emptyset}). \tag{IA120}$$

Second-round lenders are willing to provide a loan if

$$c_2^{S,\omega} \quad 1. \tag{IA121}$$

Small funding shock $f \quad f^{Sep}$: At $t = 1$, if $f = 0$, $\ell_{1,f=0}^{S,H} = \ell_{1,f=0}^{S,L} = c_1\ell_0$, $z_{1,f=0}^{S,H} = z_{1,f=0}^{S,L} = 0$, $k_{1,f=0}^{S,H} = k_{1,f=0}^{S,L} = 0$. Then with borrower competition for funding,

$$R^L(i_0 \quad z_{1,f=0}^{S,L}) \quad c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L} + \kappa_2(k_0 \quad w_{1,f=0}^{S,L}) = 0 \tag{IA122}$$

$$c_{2,f=0}^{S,L} = \frac{R^L i_0 + \kappa_2 k_0}{\ell_{1,f=0}^{S,L}} \tag{IA123}$$

and $c_{2,f=0}^{S,L} = c_{2,f=0}^{S,H}$.

With $\ell_0 = i_0 = m$ and $c_1 = 1$ both incentive compatibility constraints in expression IA119 and IA120 are satisfied provided $c_2^{\emptyset} = R^L + \kappa_2$, $\ell_1^{\emptyset} = c_1\ell_0$ and $k_1^{\emptyset} = 0$.

At $t = 1$, if $0 < f \quad \frac{\kappa_1}{2}$, we construct an equilibrium with $\ell_1^{S,H} = c_1\ell_0$, $\ell_1^{S,L} = 2(1 \quad f)m \quad \ell_1^{S,H}$, $w_1^{S,H} = 0$, $w_1^{S,L} = \frac{c_1\ell_0 \quad \ell_1^{S,L}}{\kappa_1}$, $z_1^{S,L} = 0$, $z_1^{S,H} = 0$. The solutions for loan quantities $\ell_1^{S,\omega}$ and gross loan rates $c_2^{S,\omega}$ have to satisfy the conditions of the above program. With borrower competition for scarce funding at $t = 1$, the L-type borrower's participation constraint is binding:

$$R^L i_0 \quad c_2^{S,L}\ell_1^{S,L} + \kappa_2(k_0 \quad w_1^{S,L}) = 0 \tag{IA124}$$

$$c_2^{S,L} = \frac{R^L i_0 + \kappa_2(k_0 \quad w_1^{S,L})}{\ell_1^{S,L}} \tag{IA125}$$

Since the H-type borrower's profit from deviating to the L-type borrower's contract is strictly positive, the H-type borrower's incentive compatibility constraint, from expression (IA119), is binding and their participation constraint, in expression (IA117), is slack. For the H-type not to mimic the L-type and vice versa for the L-type not to mimic the H-type, the H-type borrower's gross loan rate has to satisfy the following condition

$$\frac{\kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \quad c_2^{S,H} \quad \frac{\kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \tag{IA126}$$

Since upper and lower bound are identical, the gross loan rate is uniquely identified by $c_2^{S,H} = \frac{\kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} =$

$\frac{R^L i_0 + \kappa_2 k_0}{\ell_1^{S,H}}$ with $c_2^{S,L}$.

Suppose $c_2^{S,H} > c_2^{S,L}$ (with $i_0 = \ell_0 = m$ and $c_1 = 1$, this is satisfied if $\kappa_1 < \frac{\kappa_2}{R^L + \kappa_2}$.), then lenders earn a higher gross return per unit of loan from the H-type borrower than from the L-type borrower. Lenders thus compete for the H-type borrower's loans up to the H-type borrower's borrowing capacity, $\ell_1^{S,H} = c_1 \ell_0$. The L-type borrower is thus the residual borrower, $\ell_1^{S,L} = 2(1 \quad f)m \quad \ell_1^{S,H}$.

With $c_2^{\emptyset} = R^L + \kappa_2$, $\ell_1^{\emptyset} = c_1 \ell_0$ and $k_1^{\emptyset} = 0$ it is straightforward to show that condition IA120 is satisfied for both types.

At $t = 1$, if $\frac{\kappa_1}{2} < f \quad f^{Sep}$, we construct an equilibrium with $\ell_1^{S,H} = c_1 \ell_0$, $\ell_1^{S,L} = 2(1 \quad f)m \quad \ell_1^{S,H}$, $w_1^{S,H} = 0$, $w_1^{S,L} = k_0$, $z_1^{S,L} = \frac{c_1 \ell_0 \quad \ell_1^{S,L} \quad \kappa_1 w_1^{S,L}}{\lambda}$, $z_1^{S,H} = 0$. The solutions for loan quantities $\ell_1^{S,\omega}$ and gross loan rates $c_2^{S,\omega}$ have to satisfy the conditions of the above program. With borrower competition for scarce funding at $t = 1$, the L-type borrower's participation constraint is binding:

$$R^L (i_0 \quad z_1^{S,L}) \quad c_2^{S,L} \ell_1^{S,L} = 0 \tag{IA127}$$

$$c_2^{S,L} = \frac{R^L (i_0 \quad z_1^{S,L})}{\ell_1^{S,L}} \tag{IA128}$$

Since the H-type borrower's profit from deviating to the L-type borrower's contract is strictly positive, the H-type borrower's incentive compatibility constraint, from expression (IA119), is binding and their participation constraint, in expression (IA117), is slack. For the H-type not to mimic the L-type and vice versa for the L-type not to mimic the H-type, the H-type borrower's gross loan rate has to satisfy the following condition

$$\frac{R^H z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L} \ell_1^{S,L}}{\ell_1^{S,H}} \quad c_2^{S,H} \quad \frac{R^L z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L} \ell_1^{S,L}}{\ell_1^{S,H}} \tag{IA129}$$

The LHS, the incentive compatibility constraint of the H-type borrower, delivers the upper bound on the gross loan rate and the RHS, the incentive compatibility constraint of the L-type borrower, provides the lower bound. Notice, the set for c_2^H is non-empty since $R^H > R^L$. Suppose $\frac{R^L z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L} \ell_1^{S,L}}{\ell_1^{S,H}} > c_2^{S,L}$. With $i_0 = \ell_0 = m$ and $c_1 = 1$, for $\frac{\kappa_1}{2} < f \quad f^{Sep}$ this is satisfied if $\kappa_2 > \frac{\kappa_1}{1 \quad \kappa_1}$. Then lenders earn a higher gross return per unit of loan from the H-type borrower than from the L-type borrower. Lenders thus compete for the H-type borrower's loans up to the H-type borrower's borrowing capacity, $\ell_1^{S,H} = c_1 \ell_0$. Due to lenders' competition for the H-type loan, the rate, $c_2^{S,H}$, is the smallest rate still constituting a separating equilibrium, i.e. the lower bound of condition IA129, $c_2^{S,H} = \frac{R^L z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L} \ell_1^{S,L}}{\ell_1^{S,H}} = \frac{R^L i_0 + \kappa_2 k_0}{c_1 \ell_0}$.

With $c_2^{\emptyset} = R^L + \kappa_2$, $\ell_1^{\emptyset} = c_1 \ell_0$ and $k_1^{\emptyset} = 0$ it is straightforward to show that condition IA120 is satisfied for both types.

At $t = 0$, consider the case for $f > 0$ in which $\frac{\kappa_1}{2} < f \quad f^{Sep}$. As first-round lenders are repaid regardless of the borrower type and liquidity shock they are willing to provide loans if

$$c_1 \quad 1. \tag{IA130}$$

With lender competition, $c_1 = 1$. Then lender provide their funds to the borrowers and since borrowers are ex-ante indistinguishable, each borrower obtains a loan $\ell_0 = m$.

Borrowers decide to invest in the long-term technology if

$$\beta \Big(\alpha (R^H i_0 \quad c_2^{S,H} \ell_1^{S,H}) + (1 \quad \alpha)(R^H i_0 \quad c_{2,f=0}^{S,H} \ell_{1,f=0}^{S,H}) \Big) \quad \alpha (1 \quad \beta) \kappa_0 m$$

$$(\beta R^H + (1 \quad \beta) R^L \quad 1) \kappa_0 m \tag{IA131}$$

$$\frac{\beta (R^H \quad R^L \quad \kappa_2)}{\beta R^H + (1 \quad \beta) R^L + \alpha (1 \quad \beta) \quad 1} \quad \kappa_0 \tag{IA132}$$

with $i_0 = \ell_0 = m$ and $\kappa_0 = \kappa_2$.

After having characterised the equilibrium quantities in the separating equilibrium, we provide conditions for its existence. For the separating equilibrium to exist, $c_2^{S,L} \quad 1$, i.e. $f < f^{Sep} = \frac{R^L \quad 1}{R^L \quad \lambda}\frac{\lambda}{2} + \frac{R^L \kappa_1}{2(R^L \quad \lambda)} \quad f$. It is clear that $f^{Sep} = f^{OTC}$.

Large funding shock $f > f^{Sep}$: If $f > 0$, due to lender competition for the H-type borrower, $c^H_{2,f>f^{Sep}} = 1$ and $\ell^H_{1,f>f^{Sep}} = c_{1,f>f^{Sep}}\ell_0$. Assume that $c_{1,f>f^{Sep}}\ell_0 \quad 2(1 \quad f)m$. First-round lenders of the L-type are repaid the liquidation value of the L-type borrower

$$c_1^D \ell_0 + \lambda i_0 + \kappa_1 k_0 = 0 \tag{IA133}$$

$$c_1^D = \lambda + \kappa_1. \tag{IA134}$$

If $f = 0$, we construct an equilibrium with $\ell^H_{1,f=0} = c_{1,f>f^{Sep}}\ell_0$, $\ell^L_{1,f=0} = 2m \quad \ell^H_{1,f=0}$, $w^H_{1,f=0} = 0$, $w^L_{1,f=0} = \frac{c_{1,f>f^{Sep}}\ell_0 \quad \ell_{1,f=0}}{\kappa_1}$, $z^L_{1,f=0} = 0$, $z^H_{1,f=0} = 0$.

Borrowers compete for funding at $t = 1$ up to the point at which the L-type borrower breaks even:

$$R^L i_0 \quad c^L_{2,f=0}\ell^L_{1,f=0} + \kappa_2(k_0 \quad w^L_{1,f=0}) = 0 \tag{IA135}$$

$$c^L_{2,f=0} = \frac{R^L i_0 + \kappa_2(k_0 \quad w^L_{1,f=0})}{\ell^L_{1,f=0}} \tag{IA136}$$

For the H-type not to mimic the L-type and vice versa for the L-type not to mimic the H-type, the H-type borrower's gross loan rate has to satisfy the following condition

$$\frac{\kappa_2 w^L_{1,f=0} + c^L_{2,f=0}\ell^L_{1,f=0}}{\ell^H_{1,f=0}} \quad c^H_{2,f=0} \quad \frac{\kappa_2 w^L_{1,f=0} + c^L_{2,f=0}\ell^L_{1,f=0}}{\ell^H_{1,f=0}} \tag{IA137}$$

The latter condition is satisfied if $c^H_{2,f=0} = \frac{R^L i_0 + \kappa_2 k_0}{\ell^H_{1,f=0}}$.

With $c_2^{\emptyset} = \frac{R^L + \kappa_2}{c_{1,f>f^{Sep}}\ell_0}m$, $\ell_1^{\emptyset} = c_{1,f>f^{Sep}}\ell_0$ and $w_1^{\emptyset} = 0$ it is straightforward to show that condition IA120 is satisfied for both types.

At $t = 0$, competitive lenders require

$$\alpha(\beta c_{1,f>f^{Sep}} + (1 \quad \beta)c_1^D) + (1 \quad \alpha)c_{1,f>f^{Sep}} = 1 \tag{IA138}$$

$$c_{1,f>f^{Sep}} = \frac{1 \quad \alpha(1 \quad \beta)c_1^D}{\alpha\beta + (1 \quad \alpha)} \tag{IA139}$$

Borrowers decide to invest in the long-term technology if

$$\beta\Big(\alpha(R^H i_0 \quad c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}}) + (1 \quad \alpha)(R^H i_0 \quad c^{S,H}_{2,f=0}\ell^{S,H}_{1,f=0})\Big) \quad (1 \quad \beta)\kappa_2 m$$
$$(\beta R^H + (1 \quad \beta)R^L \quad 1)\kappa_0 m \tag{IA140}$$

$$\frac{\beta(R^H \quad \alpha c_{1,f>f^{Sep}} \quad (1 \quad \alpha)R^L)}{\beta R^H + (1 \quad \beta)R^L \quad 1 + (1 \quad \beta) + \beta(1 \quad \alpha)} \quad \kappa_0. \tag{IA141}$$

with $i_0 = \ell_0 = m$ and $\kappa_2 = \kappa_0$.

G.1 Welfare

We consider ex-post welfare for the case in which a funding shock realizes.

If $0 < f \quad \frac{\kappa_1}{2}$, then ex-post welfare yields

$$R^H i_0 \quad c_2^{S,H}\ell_1^{S,H} + R^L i_0 \quad c_2^{S,L}\ell_1^{S,L} \quad \kappa_2 w_1^{S,L} + c_2^{S,H}\ell_1^{S,H} + c_2^{S,L}\ell_1^{S,L} \quad \ell_1^{S,H} \quad \ell_1^{S,L} + 2c_1\ell_0 \quad 2\ell_0 \tag{IA142}$$

$$=R^H i_0 + R^L i_0 \quad \kappa_2 w_1^{S,L} \quad \ell_1^{S,H} \quad \ell_1^{S,L} \tag{IA143}$$

$$=(R^H + R^L \quad 2)m \quad 2f(\frac{\kappa_2}{\kappa_1} \quad 1)m. \tag{IA144}$$

If $\frac{\kappa_1}{2} < f \quad f^{Sep}$, then ex-post welfare yields

$$R^H i_0 \quad c_2^{S,H}\ell_1^{S,H} + R^L(i_0 \quad z_1^{S,L}) \quad c_2^{S,L}\ell_1^{S,L} \quad \kappa_2 w_1^{S,L} + c_2^{S,H}\ell_1^{S,H} + c_2^{S,L}\ell_1^{S,L} \quad \ell_1^{S,H} \quad \ell_1^{S,L} + 2c_1\ell_0 \quad 2\ell_0 \tag{IA145}$$

$$=R^H i_0 + R^L(i_0 \quad z_1^{S,L}) \quad \kappa_2 w_1^{S,L} \quad \ell_1^{S,H} \quad \ell_1^{S,L} \tag{IA146}$$

$$=(R^H + R^L \quad 2)m \quad 2f(\frac{R^L}{\lambda} \quad 1)m + \kappa_1(\frac{R^L}{\lambda} \quad \frac{\kappa_2}{\kappa_1})m. \tag{IA147}$$

If $f > f^{Sep}$ ex-post welfare yields

$$R^H i_0 \quad c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}} + c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}} \quad \ell^H_{1,f>f^{Sep}} + c_{1,f>f^{Sep}}\ell_0 + \lambda i_0 + \kappa_1 k_0 \quad \kappa_2 k_0 \quad 2\ell_0 \tag{IA148}$$

$$=(R^H + \lambda + \kappa_1 \quad \kappa_2 \quad 2)m \tag{IA149}$$

G.2 Intuitive criterion: separating equilibrium

Recall, to construct the separating equilibrium we have considered the following specification of beliefs:

$$Pr(R^H j c_2) = \begin{cases} 1 & \text{if } c_2 = c_2^{S,H}, \\ 0 & \text{if } c_2 = c_2^{S,L}, \\ 1 & \text{otherwise }. \end{cases} \tag{IA150}$$

Equilibrium dominance: The response which maximizes the borrower's payoff is $\ell_1 = m$ and thus $w_1 = 0$.

$$max_{\ell_1 2 BR\ell} \quad R^{\omega}(i_0 \quad z_1) \quad c_2^{\ell}\ell_1 = R^{\omega}m \quad c_2^{\ell}m + \kappa_2 m$$

Consider first the L-type borrower:

$$\begin{aligned} 0 >& R^L m \quad c_2^{\ell}m + \kappa_2 m \\ c_2^{\ell} >& R^L + \kappa_2. \end{aligned}$$

All messages $c_2^{\ell} > R^L + \kappa_2$ are equilibrium dominated for the L-type.

Similarly for the H-type:

$$\begin{aligned} (R^H \quad R^L)m >& R^H m \quad c_2^{\ell}m + \kappa_2 m \\ c_2^{\ell} >& R^L + \kappa_2. \end{aligned}$$

All messages $c_2^{\ell} > R^L + \kappa_2$ are equilibrium dominated for the H-type.

We can therefore summarize that

- c_2^{ℓ} 2 $[0, R^L + \kappa_2]$ is not equilibrium dominated for neither the H-type nor the L-type,
- c_2^{ℓ} 2 $(R^L + \kappa_2,$ 1 $)$ is equilibrium dominated for both types.

For any $c_2^{\prime}$, the Intuitive Criterion is silent about which off-equilibrium belief to specify. In particular, our specified off-equilibrium belief $Pr(H|c_2^{\prime}) = 1$ survives the Intuitive Criterion.