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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 tradeoff. The 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. CCP (OTC) markets inefficiently liquidate high (low) quality assets for large (small) funding shocks. Two innovations to repo market design contribute to maximize welfare: a liquidity-contingent trading mechanism and a two-tiered guarantee fund.

JEL Classification: G01, G14, G21, G28

Keywords: repo market, funding run, Financial Stability, asymmetric information, Central clearing, novation, guarantee fund, Collateral

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(In)efficient repo markets*

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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 tradeoff. The 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. CCP (OTC) markets inefficiently liquidate high (low) quality assets for large (small) funding shocks. Two innovations to repo market design contribute to maximize welfare: a liquidity-contingent trading mechanism and a two-tiered guarantee fund.

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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 implementation and transmission of monetary policy (Bianchi and Bigio, 2020) and financial stability (Martin et al., 2014a,b), and they were at the heart of 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). In response to the funding crises, observers have repeatedly called for reforms to the functioning of repo markets.

Repo markets serve two conflicting objectives, the efficient allocation of short-term funding in normal times and the resilience to funding shocks in crisis times. In this paper we show that the trading and clearing mechanisms are crucial determinants of this tradeoff. Existing repo markets are different in the trading rules affecting the information environment and price setting, the clearing mechanism affecting counterparty risk, and collateral requirements affecting ease of access to funding. To capture these differences, we compare anonymous to non-anonymous repo trading and bilateral to central clearing with novation and alternative guarantee funds. We find that existing market designs are inefficient and their welfare rankings depend on funding tightness. An optimal repo market reform achieves first best, resolving the allocation-resilience tradeoff, and we show how to implement it through innovations in the repo trading and clearing mechanism.

Trading in over-the-counter (OTC) repo markets is non-anonymous. OTC markets efficiently allocate funding to high-quality borrowers. But they are prone to narrow runs on low-quality borrowers through a credit rationing channel. By contrast, trading in most repo markets with a central clearing counterparty (CCP) is anonymous. Anonymous trading cre-

[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.

ates asymmetric information about the borrowers' credit risk. CCP markets thereby provide insurance against narrow runs. But they allocate insufficient funding to high-quality borrowers and are prone to systemic runs leading to market breakdown. As a result, the welfare ranking of OTC and CCP markets switches repeatedly and depends non-monotonically on the magnitude of funding shocks.

We show that existing repo markets can be improved by changing the trading protocol and the clearing mechanism. For OTC markets, central clearing of bilaterally negotiated trades helps to avert 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 in the market. Still, none of these reforms achieve first best. 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).

Several repo market structures coexist around the world with a variety of alternative trading and clearing mechanisms in place in different market segments. The customer repo market in the U.S. is non-anonymous, with bilaterally-cleared OTC trades negotiated between cash borrowers and money-market funds as the dominant cash lenders.[3] In contrast, interdealer repo markets (i.e., GCF Repo and FICC DVP) are anonymous and centrally cleared as almost all trades are executed through centralized platforms or interdealer bro-

[3]Two variants exist based on differences in settlement—bilateral and triparty. 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. The triparty market is effectively the same as the bilateral market for the purpose of our study.

kers (e.g., BrokerTec) that provide anonymity to both parties of the trade.[4] Similarly, the vast majority of repo trading in Europe is executed anonymously and centrally cleared by a central counterparty (CCP).[5] CCP markets generally feature anonymous trading via a centralized order book (COB) or masked bilateral negotiation. Through novation of consummated repo contracts the CCP becomes the legal counterparty to both borrower and lender. The default fund to which all participants contribute protects lenders against borrower default. Other structures exist where two 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.

Prior research has documented that during the GFC lending to low-quality borrowers halted in the non-anonymous OTC segment (Copeland et al., 2014; Krishnamurthy et al., 2014). The empirical evidence for CCP markets is mixed. Mancini et al. (2016) document for a European CCP market that lending activity was uninterrupted during the GFC. The repo blowup in September 2019 and the interruption of the repo market at the onset of the Covid-19 pandemic (Duffie, 2020) took place in the CCP based interdealer segment.

This empirical evidence raises a number of issues: Which repo market features make funding markets resilient to funding shocks and at the same time allocate funding efficiently? Which market reforms improve financial stability? What is the role of collateral played in different repo markets? Why do convenience yields on collateral spike or collapse with tighter funding conditions? To address these questions, we develop a model that captures the most salient features of repo markets. The model shows how different repo trading and clearing mechanisms affect funding allocations, financial stability and welfare, repo rates, and convenience yields on collateral.

The model setup is as follows. Borrowers (cash-strapped banks) have access to a long-term technology (LTT) that they finance through short-term collateralized loans (Brunnermeier and Oehmke, 2013).[6] 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,

[4]GFC Repo is a small part of the overall U.S. repo market (Baklanova et al., 2017).

[5]Eurex, BrokerTec, and MTS are leading trading platforms and LCH.Clearnet is a major clearing house in Europe.

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

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 a pecking order according to which 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.[7] The funding shock is zero or $f > 0$. 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.

Two types of runs occur in the model: A narrow run on low-quality borrowers when funding tightness exceeds an endogenous threshold, or a systemic run on all borrowers that leads to market breakdown. 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 that we focus on is non-anonymous 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, OTC markets allocate financing efficiently so long as funding shocks remain modest. However, OTC markets are susceptible to narrow runs on low-quality borrowers at the repo rollover stage for intermediate funding shocks.

By contrast, borrowers and lenders in anonymous CCP 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 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

[7] Sources for funding shocks are fund outflows, margin calls, and balance sheet constraints. He et al. (2020) document that dealers' balance sheets were constrained during the Covid-19 pandemic.

amount of collateral and 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.

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.[8] 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 two important roles in repo markets. High-quality liquid collateral improves both efficiency and resilience independent of repo market structure. Collateral quality however impacts differently OTC and CCP markets. 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 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. (2020).

The two common market structures, non-anonymous bilaterally-cleared OTC market or CCP market with anonymous COB, novation and default fund, neither welfare dominate

[8] 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.

each other nor achieve first best for all levels of funding shocks. 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 insurance effect of the CCP in crisis times when funding is scarce and assets are illiquid.

The ranking of market 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, in line with our model, 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 moderate 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, novation, default fund, and collateral.

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 tradeoff between efficient resource allocation and financial stability.

In line with the literature building on Diamond and Dybvig (1983), we consider risk about borrowers' liability side.[9] 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., 2020). 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 (2020) and Kuong (2020).

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

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

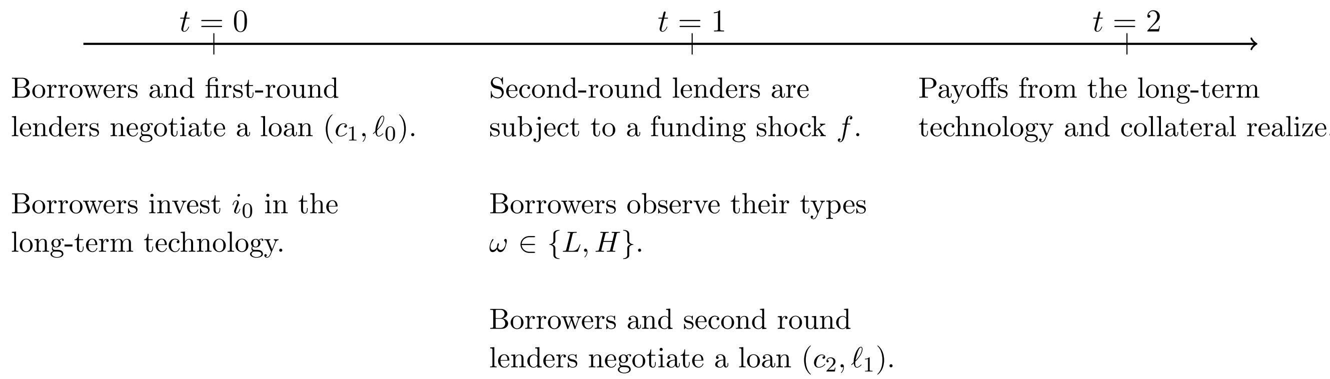

Figure 1: Timeline

2 Model and First Best

We model an economy in which heterogeneous borrowers require short-term funding from risk-neutral lenders to fund their long-term activity, such as trading or investment banking. Cash-strapped banks are the borrowers in the repo market and cash-rich banks, money-market funds, and other institutional investors are the lenders. We focus on the maturity transformation of long-term borrowers with short-term lenders which is a key role of repo markets.[10] In contrast to the existing banking literature, we focus on how repo market design and the information environment affect short-term lending. Borrowers differ in the quality of their long-term technology which creates an adverse selection problem.[11] Lenders are subject to funding shocks at the repo rollover stage.

2.1 Model description

Consider a risk-neutral 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. At $t = 0$, borrowers seek one-period loans to invest in their long-term technology (LTT). At $t = 1$, borrowers and lenders take the rollover decision on maturing first-period loans. Second-period loans mature and payoffs from the LTT realize at $t = 2$. There is no discounting. Figure 1 summarizes the sequence of events.

[10] Brunnermeier and Oehmke (2013) provide a rationale for why banks borrow short-term to invest long-term.
[11] While CCPs typically have a vetting process in place before admitting participants, there is still substantial heterogeneity among those who are admitted.

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 $t = 0$.[12] With probability $(1 - \alpha)$ the funding shock is $f = 0$ and with probability α the funding shock is $f \in (0, 1)$.[13] If $f = 0$, no funding shock hits second-round lenders and they simply replace the initial endowment. If $f > 0$, a funding crisis occurs as there is less funding available at $t = 1$ than $t = 0$, so that the total cash endowment drops to $2(1 - f)m < 2m$. The funding shock captures in a reduced form the lenders' margin calls, fund outflows, or balance sheet constraints. Different levels of funding shocks and funding shock variance characterize either different economies at a given point in time (cross-sectional interpretation), or they characterize an economy at different points in time (time-series interpretation).

We introduce asymmetric information in the model by assuming that there are two types of borrowers. At $t = 0$, each borrower invests i_0 in a LTT that yields a gross return R^ω at $t = 2$ depending on type $\omega \in \{L, H\}$. The LTT return is R^H with probability β and R^L with probability $1 - \beta$. For the most part of the analysis we consider positive net present value (NPV) projects, i.e., $R^H > R^L \geq 1$. We relax this assumption in Section 6.3. Early liquidation is costly. If the LTT is liquidated before $t = 2$, the return is below the initial investment, $\lambda < 1$.

Borrowers learn about the quality of the LTT over time. At $t = 0$, agents know there will be a high-type and a low-type borrower, but they do not know of which type they turn out. 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.[14] At $t = 1$, borrowers

[12]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.

[13]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.

[14]From a welfare perspective there would be no difference if one or the other borrower obtains a larger loan.

learn their type. At $t = 2$, payoffs from the long-term technology realize.

Repo loans are collateralized. Each borrower has a collateral endowment of $k_0 = m$ at $t = 0$. The exogenous value of collateral is 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.[15] Repo haircuts are given by the collateral value over loan value minus one, i.e., $\frac{\kappa_t k_t}{\ell_t} - 1$.[16]

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 $c_1 \geq 1$ from first-round lenders. Borrowers invest at most the entire loan $i_0 \leq \ell_0$. We adopt the following assumption to define the parameter space where resource allocation matters.

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

At $t = 1$, borrowers need to roll over maturing loans. 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 yields $\kappa_1 w_1$. Partial liquidation of the LTT $z_1 \leq i_0$ 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 2 *The opportunity cost from liquidating the LTT is larger than the opportunity cost from liquidating collateral,* $\frac{R^L}{\lambda} \geq \frac{\kappa_2}{\kappa_1} \geq 1$.

[15] We capture collateral liquidation costs in a reduced form with $\kappa_1 < 1$. Oehmke (2014) discusses the issues arising from liquidating collateral, justifying the assumption of collateral liquidation cost.

[16] 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 $\frac{E(R)i_0+\kappa_1 k_0}{\ell_0} - 1 > 0$, where $E(R)$ is the expected return of the LTT.

Assumption 2 establishes a pecking order in which assets are liquidated. It is always cheaper to liquidate collateral than the LTT. Moreover, early liquidation of the LTT and collateral is costly for two reasons. It decreases the value of the initial investment by $1-\lambda$ and $\kappa_0-\kappa_1$ per unit of the respective asset, and it carries an opportunity cost from foregone profits $R^\omega-1$ and $\kappa_2-\kappa_0$.

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:[17]

Assumption 3 *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:

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

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 $\kappa_2(k_0-w_1)$. Alternatively, borrowers can default on the initial loan which causes liquidation of their assets and yields, by Assumption 3 and limited liability, a value of zero, which is the right-hand side (RHS) of (2).

2.2 First best: Symmetric information and social planner

We start by considering the benchmark with no asymmetric information to illustrate the role of transfers between borrowers. An important feature of the first-best solution is that

[17]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.

the social planner can redistribute profits between borrowers to maximize welfare.

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, $c_1 \geq 1$.[18] Because the expected return of the long-term technology is positive, 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. 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.[19]

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. This outside option is strictly larger than net welfare from merely holding collateral to maturity. A detailed derivation is provided in Appendix A.

At $t = 1$, borrower types are revealed and the funding shock realizes. The social planner can condition 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, $0 < f \leq \frac{1}{2}$, 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 promises the profits of the H-type as transfer to the second-round lenders of the L-type. The redistribution of profits has no direct impact on welfare since it is merely a transfer between risk neutral agents. In case of no funding shock, $f = 0$,

[18] 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.

[19] This assumption can be relaxed and it can be shown that all the main results carry through if lenders at $t = 0$ make a positive profit.

both borrowers obtain equal size loans, $\ell^{\omega}_{1,f=0} = m$, that allow them to roll over their loans without liquidating collateral or LTT.

In the next step, we derive the largest funding shock that an economy with a social planner can withstand. We do so by deriving ex-post net welfare in the case of a funding shock. 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 make up for the missing funding from second-round lenders. First-round lenders are repaid with a mix of new loans and collateral, $-2c_1\ell_0 + \ell^H_1 + \ell^L_1 + 2\kappa_1 w_1 = 0$, which yields

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

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. Ex-post net welfare is then given by the sum of borrowers' net return from the LTT and collateral

$$\begin{aligned} W^{FB} &= R^H i_0 - \ell^H_1 + R^L i_0 - \ell^L_1 + 2\kappa_2(k_0 - w_1) - 2\kappa_0 k_0 \\ &= (R^H + R^L - 2)m + 2(\kappa_2 - \kappa_0)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m. \end{aligned} \tag{5}$$

Since $\kappa_0 = \kappa_2$, the collateral has zero return. Ex-post net 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.

The second case is when the borrowers' collateral is exhausted and the social planner has to liquidate the L-type LTT, that is, if $\kappa_1 < f \leq \frac{1}{2}$. Then the repayment condition yields the amount of liquidation of the L-type LTT, $-2c_1\ell_0 + \ell^H_1 + \ell^L_1 + 2\kappa_1 k_0 + \lambda z^L_1 = 0$, or

$$z^L_1 = \frac{2m}{\lambda} \times (f - \kappa_1). \tag{6}$$

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. Ex-post welfare in this case is the net return of borrowers' LTTs net of the cost from liquidating collateral and the L-type's LTT

$$
\begin{aligned}
W^{FB} &= R^H i_0 - \ell_1^H + R^L(i_0 - z_1^L) - \ell_1^L - 2\kappa_0 k_0 \\
&= (R^H + R^L - 2)m + 2\kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m - 2f(\frac{R^L}{\lambda} - 1)m. \qquad (7)
\end{aligned}
$$

Collateral 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 difference between the L-type LTT's return at maturity and its early liquidation value, $R^L > \lambda$.

We are now ready to state the maximum funding shock the social planner economy can withstand which is given by net welfare, in expression (7), being 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*

$$
f^{FB} = \frac{R^H + R^L - 2}{R^L - \lambda}\frac{\lambda}{2} + \frac{R^L}{R^L - \lambda}\kappa_1 - \frac{\lambda}{R^L - \lambda}\kappa_0. \qquad (8)
$$

Ex-post welfare conditional on the funding shock is

$$
W^{FB} = \begin{cases} (R^H + R^L - 2)m + 2(\kappa_2 - \kappa_0)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m & \text{if } 0 \leq f \leq \kappa_1, \\ (R^H + R^L - 2)m + 2\kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m - 2f(\frac{R^L}{\lambda} - 1)m & \text{if } \kappa_1 < f \leq f^{FB}. \end{cases} \qquad (9)
$$

3 Repo Market Structure, Efficiency, and Resilience

In this section, we study the impact on resource allocation, resilience to funding shocks, and welfare of the market clearing mechanisms in OTC and COB markets, respectively.[20] The different market clearing mechanisms impact the information environment at the rollover

[20]The two market structures, OTC and CCP, exist in parallel. In Appendix E we provide conditions for which markets indeed co-exist.

stage. In Section 4, we return to further distinguishing features 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.[21] 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. We provide further support for the choice of the pooling equilibrium, as opposed to the separating equilibrium, in Appendix E. We proceed by characterizing run thresholds (which define the funding shock sets Φ and Ψ), lending terms, and welfare for the OTC and COB markets in Sections 3.1 and 3.2. We distinguish two run types:

Definition 1 *A narrow run is an equilibrium in which second-round lenders refuse to provide 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 $f \in \Psi$.*

3.1 OTC market: Loans, run threshold, and welfare

Lenders in the bilateral 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 unconstrained first-best solution, derived in Section 2.2, 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

[21] 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.

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

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{OTC}, \\ \alpha(\beta c_{1,f>f^{OTC}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{OTC}} & \text{if } f > f^{OTC}. \end{cases} \tag{10}$$

The individual rationality constraint (10) is from a single lender's perspective and, therefore, the conditions are expressed per unit of loan since each lender has one unit of endowment. 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 (10) holds with equality.[22] Furthermore, borrowers compute the expected profit by 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 collateral and investing it in the LTT if the expected return from the former is weakly larger than the return from the latter.[23]

At $t = 1$, borrowers' individual rationality constraint reflects the cash-flow as described in expression (2) conditional on borrower type and is subject to the repayment condition of first-round lenders:[24]

$$\text{Borrower IR:} \qquad R^\omega(i_0 - z_1^\omega) - c_2^\omega \ell_1^\omega + \kappa_2(k_0 - w_1^\omega) \geq 0, \tag{11}$$

$$s.t. \quad -c_1\ell_0 + \ell_1^\omega + w_1^\omega \kappa_1 + z_1^\omega \lambda = 0. \tag{12}$$

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

[22]If first-round lenders make positive profit, borrowers' funding need, $t = 1$, increases at and rollover risk exacerbates. There exists an upper bound on $c_1 > 1$ up to which the equilibrium in the OTC market exists.
[23]The explicit derivations of borrowers' individual rationality constraint are deferred to Appendix B.
[24]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 (11), is zero due to limited liability.

by setting interest rates at $t = 1$ à la Bertrand.[25]

Assumption 4 *Lenders set interest rates at $t = 1$ by take-it-or-leave-it offers to perfectly competitive borrowers.*

Under Assumption 4, the loan contracts are

$$c_2^{OTC} = c_2^H = c_2^L = \frac{R^L(i_0 - z_1^L) + \kappa_2(k_0 - w_1^L)}{\ell_1^L}, \tag{13}$$

$$\ell_1^H = c_1\ell_0, \quad \ell_1^L = 2(1-f)m - \ell_1^H. \tag{14}$$

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 (13). 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 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.

$$\text{Lender IR:} \qquad c_2^{OTC} \geq 1. \tag{15}$$

When lenders decide on providing a loan, they contemplate the loan rate provided by the L-type's break-even condition in (13). 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

[25]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.

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 (10), we obtain $c_1 = 1$. For large funding shocks $f > f^{OTC}$, lenders do not provide loans to the L-type borrower. The following lemma summarizes the OTC market equilibrium depending on the realization of the funding shock $f > 0$.[26]

Lemma 1 (OTC equilibrium) *A narrow run occurs in the OTC market if the funding shock exceeds the threshold*

$$f^{OTC} = \frac{R^L - 1}{R^L - \lambda}\frac{\lambda}{2} + \frac{R^L}{R^L - \lambda}\frac{\kappa_1}{2}. \tag{16}$$

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, $z_1^L = 0$.*

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.*

Detailed proofs are provided in Appendix B.

Expression (16) illustrates that liquid collateral, $\kappa_1 > 0$, increases the run threshold. While the threshold decreases in the liquidation cost of the LTT, $R^L - \lambda$, it increases in the returns from the LTT both at the rollover stage, λ, and at maturity, R^L. As a preparatory step for the comparison of welfare in the OTC market to welfare in the first-best solution, we state the following lemma.

Lemma 2 (Ranking first best and OTC thresholds) *The run threshold in the first-best solution is larger than in the OTC market, $f^{FB} > f^{OTC}$, so long as Assumption 2 and $R^H \geq 1 + \kappa_0$ hold.*

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

The transfers imposed by the social planner in the first-best solution ensure repayment of lenders and maximize the threshold up to which both borrowers can continue their projects to maturity. Beyond this threshold, the social planner should not operate a repo market. The OTC market achieves the constrained first-best solution in which there are no such transfers and, therefore, the threshold at which the L-type borrower defaults is strictly smaller than the first-best threshold.

We now compare ex-post net welfare in the OTC market to the first-best solution in expression (9). Welfare in the OTC market, conditional on the funding shock, is derived in Appendix B. The comparison allows to quantify the welfare losses from individual rationality in the OTC market vis-à-vis the first-best solution.[27]

Proposition 2 (Welfare comparison first best vs. OTC) *Depending on the relationship between collateral return, κ_1, LTT return, R^L and λ, and the funding shock, f, welfare in the OTC market is lower than first best by*

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

Proposition 2 is illustrated in Figure 2. For $0 \leq f \leq \frac{\kappa_1}{2}$, welfare in the OTC market is identical to first-best welfare since liquidation of the L-type's collateral prevents liquidation of the LTT in both cases. For $\frac{\kappa_1}{2} < f \leq \kappa_1$, in the OTC market the L-type's collateral is used up and LTT needs to be liquidated. By contrast, in the first best the social planner first liquidates the H-type's collateral and uses it to repay first-round lenders of the L-type. From the pecking order of collateral and LTT, $\frac{R^L}{\lambda} > \frac{\kappa_2}{\kappa_1}$, it is clear that liquidating first the H-type's collateral is less welfare detrimental than liquidating the L-type's LTT. For $\kappa_1 < f \leq f^{OTC}$, the welfare difference is constant since both the social planner in the first-best solution and the L-type in the OTC market liquidate the L-type's LTT. For $f^{OTC} < f \leq f^{FB}$, the L-type borrower defaults and only the H-type borrower continues its LTT to maturity in the OTC

[27]Note, $f^{OTC} > \kappa_1$ if $2\lambda > R^L$.

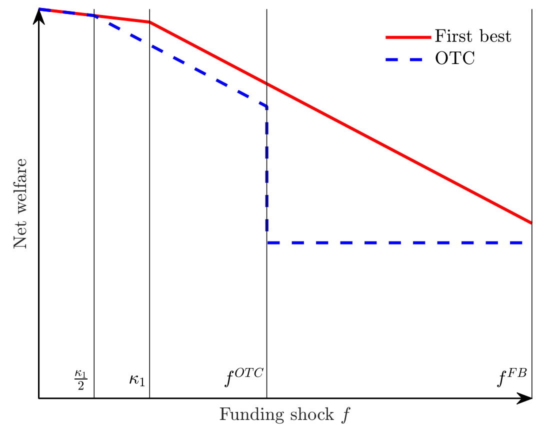

Figure 2: Welfare comparison: First best vs. OTC market

market, while the social planner uses the H-type's profit as transfer to the L-type's lenders so that they continue funding the L-type. The welfare difference is decreasing in $f > f^{OTC}$ as the L-type requires larger subsidies the larger the funding shock.

3.2 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, novation and default fund, in Sections 4.1 and 4.2.

Starting with the COB, we derive a Perfect Bayesian equilibrium. We 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 $\omega \in \{L, H\}$.[28] The threshold f^{CCP} 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 $c_1^D\ell_0$.

First-round lenders provide equal shares of their cash endowment to each borrower, $\ell_0 =$

[28]The separating equilibrium is derived in Appendix D. It exhibits the same allocation of funding as the constrained first-best solution, i.e., full rollover for the H-type borrower and only partial rollover for the L-type borrower. Loan rates differ from the constrained first best to satisfy incentive compatibility.

m, so long as their net profit is weakly positive. These considerations yield the lenders' individual rationality constraint

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{CCP}, \\ \alpha c_1^D + (1-\alpha) c_{1,f>f^{CCP}} & \text{if } f > f^{CCP}. \end{cases} \tag{17}$$

We assume borrowers hold the bargaining power at $t = 0$, such that expression (17) holds with equality.[29] 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, $i_0 \leq \ell_0$, instead of liquidating own collateral and investing it in the LTT if the expected return from the former is weakly larger than the return from the latter. The outside option is the expected net return from liquidating collateral and investing the proceeds in the LTT.[30] Then, borrowers invest the entire loan into the LTT, $i_0 = \ell_0$.

In a pooling equilibrium, second-round lenders at $t = 1$ condition loan terms on the funding shock, f. In contrast to the OTC market, lenders do not observe borrower type and cannot condition their loan offers on $\omega \in \{L, H\}$, that is, (c_2^P, ℓ_1^P) is independent of ω. We define lenders' beliefs as

$$Pr(R^H | c_2) = \begin{cases} \beta & \text{if } c_2 = c_2^P, \\ 1 & \text{otherwise.} \end{cases} \tag{18}$$

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'. In Appendix C, we show that this specification of lenders' beliefs survives the Intuitive Criterion.

Faced with a pooling contract, borrowers' individual rationality constraint is subject to

[29] If first-round lenders make positive profits borrowers' funding need increases and rollover risk exacerbates. There exists an upper bound on $c_1 > 1$ up to which the equilibrium in the COB exists.

[30] For the formal derivation of borrowers' IR at $t = 0$ refer to Appendix C.

the repayment condition of first-round lenders:

$$\text{Borrower IR:} \qquad R^{\omega}(i_0 - z_1^P) - c_2^P \ell_1^P + \kappa_2(k_0 - w_1^P) \geq 0 \tag{19}$$

$$s.t. \quad -c_1\ell_0 + \ell_1^P + \lambda z_1^P + \kappa_1 w_1^P = 0 \tag{20}$$

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

$$\text{Borrower IC:} \quad R^{\omega}(i_0 - z_1^P) - c_2^P \ell_1^P + \kappa_2(k_0 - w_1^P) \geq R^{\omega}(i_0 - z_1') - c_2'\ell_1' + \kappa_2(k_0 - w_1'). \tag{21}$$

The LHS of expression (21) represents the equilibrium payoff of borrower type ω and the RHS of expression (21) represents the off-equilibrium payoff. The latter is determined by lenders' beliefs as specified in expression (18). The off-equilibrium belief prescribes that lenders believe to face the H-type when observing a deviation ($c_2' = R^L + \kappa_2, \ell_1' = c_1\ell_0$).[31] The off-equilibrium repayment condition yields that neither LTT nor collateral have to be liquidated, i.e., $z_1' = 0$ and $w_1' = 0$.

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

$$\text{Lender IR:} \qquad c_2^P \geq 1. \tag{22}$$

As long as lenders' individual rationality constraint (22) is satisfied, they provide their entire cash endowment as loans. The lender takes 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, $0 \leq f \leq f^{CCP}$. Lenders' break-even condition pins down the run threshold f^{CCP} when (22) holds with equality. The following lemma summarizes the COB market equilibrium

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

depending on the realization of the funding shock $f > 0$.

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

$$f^{CCP} = \frac{R^L - 1}{R^H - \lambda}\lambda + \frac{R^H}{R^H - \lambda}\kappa_1. \tag{23}$$

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 $\kappa_1 < f \leq f^{CCP}$, 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 $f > f^{CCP}$, both borrower types liquidate both collateral and LTT.

The proof is provided in Appendix C.

Second-round lenders provide a loan depending on the size of the funding shock. The larger the funding shock, the more of borrowers' collateral and LTT have to be liquidated reducing the capacity to repay the loan. For $\kappa_1 < f$, the loan rate c_2^P is determined by the H-type's incentive compatibility constraint (21). It is the largest rate borrowers are willing to pay in a pooling equilibrium.[32] 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^{CCP}. While the threshold decreases in the liquidation cost of 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. We defer the characterization of parameters under which it is optimal for borrowers to take loans and invest in the LTT ex-ante to Appendix C.

[32]Beyond this rate, the H-type would deviate from the equilibrium path. Notwithstanding a certain degree of competition, both in the OTC and COB equilibrium borrowers make some profit at $t = 1$. Clearly, it is always possible to allow for lender competition such that the loan rate is pinned down by lenders' IR.

3.3 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 3 *The run threshold in the COB market is larger than in the OTC market, $f^{CCP} > f^{OTC}$, 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, $f^{FB} > max\{f^{CCP}, f^{OTC}\}$.*

The intuition for the difference between the run thresholds in the COB market and the OTC market is that in the former the L-type borrower is insured by the H-type borrower. 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. 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.

The welfare in a pooling equilibrium in the COB market illustrates the two sides of the tradeoff. On the one hand, the COB provides an insurance benefit. On the other hand, the COB generates a welfare loss from resource misallocation. The next proposition compares ex-post net welfare in the COB market to the corresponding value in the OTC market.

Theorem 1 *The welfare difference between COB and OTC market can be positive or nega-*

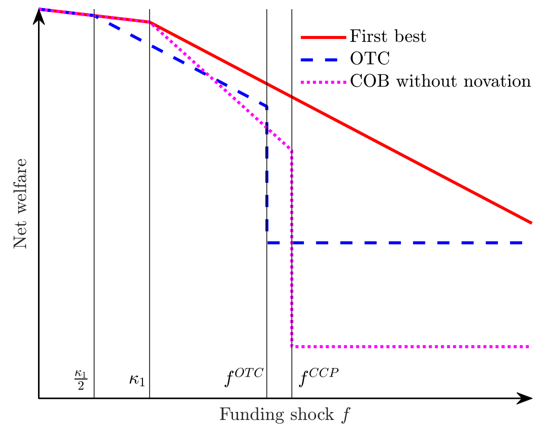

Figure 3: Welfare comparison: Systemic run in COB market vs. narrow run in OTC market

tive depending on the relation between collateral return, LTT return, and funding shock:

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

The explicit welfare expressions for OTC market and COB market are provided in Appendix B and C . 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 $0 \leq f \leq \kappa_1$. The COB market implements the first-best solution 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 collateral equally before they have to start liquidating their LTT. This mechanism provides insurance for the L-type. An economy with a COB market, due to the insurance mechanism, 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 collateral is cheaper than liquidating the LTT, welfare drops more in the OTC market than in the COB market after the L-type's collateral is used up, i.e., when $\frac{\kappa_1}{2} < f \leq \kappa$. For $\kappa_1 < f \leq f^{OTC}$, the welfare difference between COB and OTC market is ambiguous. In the COB market, welfare drops more 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. For $f^{OTC} < f \leq f^{CCP}$, welfare is always larger in the COB market than in the OTC market, since by Proposition 3, the run on the L-type in the OTC market occurs for a smaller funding shock than the systemic run in the COB market. For $f > f^{CCP}$, 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.

4 The Clearing Mechanism of CCP Markets

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

4.1 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. 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 $f \leq f^{CCP}$ the CCP novates the contracts agreed upon through the COB of both borrower types. When the funding shock exceeds the run threshold, $f > f^{CCP}$, the CCP only novates the contract of the solvent H-type borrower and not of the insolvent L-type borrower.[33] 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 3.2. 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,

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{CCP}, \\ \alpha(\beta c_{1,f>f^{CCP}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{CCP}} & \text{if } f > f^{CCP}. \end{cases} \tag{24}$$

Unlike in the COB market, there is no systemic run in a COB market with novation. The second line of expression (24) takes into account that the H-type borrower is able to repay first-round lenders even after a large funding shock, $f > f^{CCP}$. First-round lenders therefore require a lower repo rate $c_{1,f>f^{CCP}}$ 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, $f > f^{CCP}$, 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 with the H-type borrower. There is, by assumption, enough funding to roll over one borrower, $2(1-f)m \geq c_{1,f>f^{CCP}}\ell_0$, and thus second-round lenders compete for the H-type borrower such that they break even, $c^H_{2,f>f^{CCP}} = 1$. The loans extended to the H-type borrower allow them to continue the LTT without liquidation, $\ell^H_{1,f>f^{CCP}} = c_{1,f>f^{CCP}}\ell_0$. Detailed derivations of the equilibria are provided in Appendix C. The run threshold and the equilibria below the run threshold remain the same as in Section 3.2.

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 4 (COB market with novation) *A narrow run occurs in the COB market with novation if the funding shock exceeds the threshold f^{CCP} defined in (23). Ex-post welfare*

[33]In practice, the CCP regularly monitors CCP members and excludes those that do not satisfy the solvency criteria laid out in their rulebook.

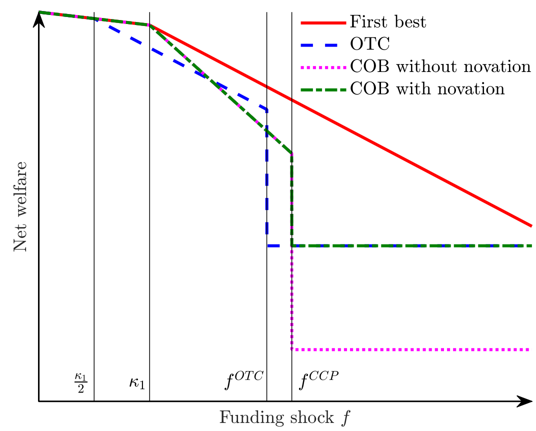

Figure 4: Welfare comparison: Narrow runs in COB vs. OTC market

in the COB market with novation welfare improves upon the COB market:

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

For the derivation of welfare when $f > f^{CCP}$ refer to Appendix C. Figure 4 illustrates Proposition 4. Welfare in the COB market with novation is identical to welfare in the COB market up to the run threshold f^{CCP}. 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.

4.2 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 ex-ante at the investment stage. 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, as long as there are positive expected profits for borrowers at $t = 0$, they are willing to contribute to the default fund. That is, for there to be a positive contribution to the default fund, the same condition as for borrowers' ex-ante investment decisions have to be satisfied.[34]

To study the effect of the default fund on financial stability, we derive the threshold at which second-round lenders stop providing loans, f_{DF}^{CCP}. Naturally, the threshold is beyond the point at which a run would occur without default fund, $f_{DF}^{CCP} > f^{CCP}$. At this point, the L-type borrower has run out of own funds to repay second round lenders. The default fund's objective is to, nonetheless, cover second round lenders' investment, $c_2^P = 1$. In their lending decision, lenders take into account the transfer through the default fund from the solvent to the insolvent borrower. The maximum contribution to the default fund is given by borrowers' ex-ante profit in Appendix C, yielding

$$\begin{aligned}\tau_{DF}^{CCP} =& \frac{1}{\alpha\beta}\Bigg[\alpha\bigg(\beta(R^H(i_0 - z_1^P) - c_2^P \ell_1^P) - \kappa_2 w_1^P\bigg) \\ &+ (1-\alpha)\bigg((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P\bigg) - (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0\Bigg].\end{aligned} \tag{25}$$

Indeed, the L-type borrower repays second-round lenders from both its own proceeds and the transfer up to a funding shock defined by the condition

$$R^L(i_0 - z_1^P) - c_{2,DF}^P \ell_1^P + \tau_{DF}^{CCP} = 0 \tag{26}$$

From expression (26) 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.

Since borrowers commit to the default fund contribution at $t = 0$, second-round lenders take this transfer into account in their lending decision at $= 1$. The largest funding shock that the CCP market can absorb is given by expression (26). The following proposition summarizes the financial stability effect of a default fund.

[34]The default fund works if borrowers commit to contributing to the default fund before they learn their type, otherwise the solvent borrower would withdraw its contribution to the default fund when types are revealed. A well-functioning default fund thus requires ex-ante commitment.

Proposition 5 *A narrow run occurs in the CCP market if the funding shock exceeds the threshold*

$$f_{DF}^{CCP} = \frac{(R^L - 1)\lambda + R^H \kappa_1}{R^H + R^L - 2\lambda} + \frac{(\lambda + \kappa_1)R^L - \lambda}{R^H + R^L - 2\lambda} + \frac{\lambda(\beta(R^H - R^L) - \kappa_0 R^L)}{\alpha\beta(R^H + R^L - 2\lambda)}. \tag{27}$$

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

Like in the first-best solution, the default fund allows to transfer proceeds from the solvent to the insolvent borrower.[35] 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.

5 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., 2020), a discussion among policy makers and industry 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.

[35] Modeling a profit-maximizing CCP is beyond the scope of this paper. Such CCP at $t = 1$ may want to preclude borrowers that will default at $t = 2$ from rolling over their loans, even though rollover can be socially optimal. The CCP's policy ultimately depends on their objective function and broader consequences of a borrower's default. We conjecture an ex-ante admission fee to the CCP does not affect the central tradeoff between market resilience and resource allocation.

5.1 Optimal market solution

Recall from the first-best solution that the H-type makes two types of transfers to the L-type, a collateral transfer at $t = 1$ and a profit transfer at $t = 2$. When the L-type runs out of collateral, instead of liquidating their profitable LTT, it is welfare improving, due to the pecking order of collateral and LTT, to use the H-type's collateral to repay the L-type's first-round lenders at $t = 1$, resulting in a collateral transfer. In addition, the social planner uses the H-type's profits at $t = 2$ to subsidize the L-type's repayment of second-round lenders, resulting in a profit transfer. We demonstrate that the privately optimal market solution is a non-anonymous OTC market with the aforementioned two types of transfers. An analogous result holds for the anonymous CCP market.

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

$$\tau^{OPT} = \frac{m}{\alpha\beta}[\alpha\beta(R^H - 1) + (1-\alpha)\beta(R^H - R^L) - (\beta R^H + (1-\beta)R^L - \alpha\beta(1 - w_1^H))\kappa_0]. \quad (28)$$

The payouts of the total transfer occur through:

- *collateral transfer at* $t = 1$*:* $w_1^H = \frac{c_1\ell_0 - \ell_1^L - \kappa_1 k_0}{\kappa_1}$ *for* $\kappa_1/2 < f \leq \kappa_1$ *and*
- *profit transfer at* $t = 2$*:* $\tau^{OPT}(w_1^H = m)$ *for* $f > f^{OPT}(\tau^{OPT} = 0)$.

The proof is provided in Appendix G.

At $t = 0$, borrowers commit to a legally enforceable 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 funding shocks as described in Theorem 2 occur. 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, $\tau^{OPT}(w_1^H)$, at $t = 2$ to subsidize repayment of second-round lenders. The collateral transfer at $t = 1$ reduces the profit transfer at $t = 2$. By transferring the H-type's collateral, $w_1^H > 0$, at $t = 1$, the

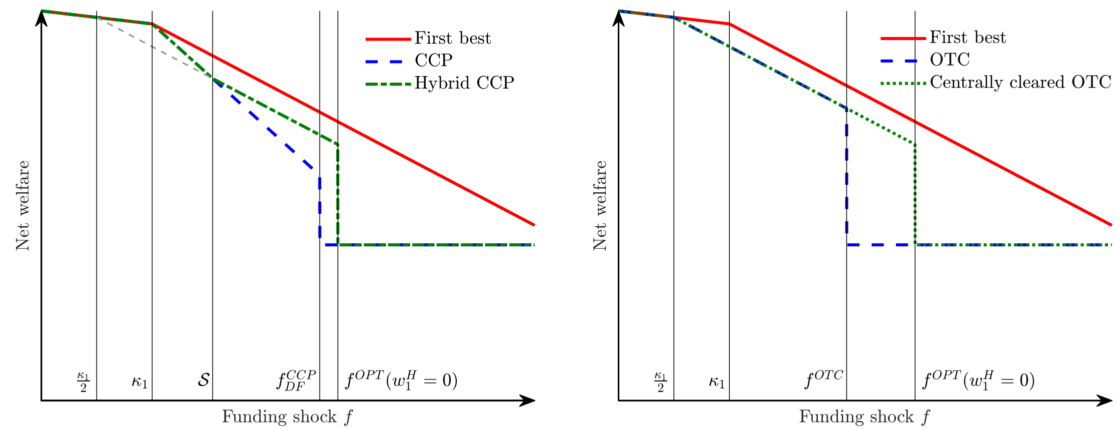

Figure 5: Welfare comparison: Hybrid CCP market (left) and centrally cleared OTC (right)

OTC market achieves allocative efficiency identical to the first-best solution.[36] The profit transfer, $\tau^{OPT}(w_1^H)$, at $t = 2$ increases the market's run resilience. While the profit transfer is already a feature of existing central clearing mechanisms, the collateral transfer presents an innovation that we discuss further below.

5.2 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 combining existing market features improve upon current market structures. The first-best solution is however only attainable by adopting a novel market feature—a two-tiered guarantee fund.

Hybrid trading mechanism: To improve upon existing CCP markets with novation and default fund, we propose a hybrid trading mechanism. CCP markets implement 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, CCPs inefficiently force liquidation of

[36] The collateral transfer can come at the cost of reducing resilience due to the reduction of the H-type's profit at $t = 2$. Although, in general, there is a tradeoff between collateral transfer and profit transfer in terms of welfare, the tradeoff is immaterial for the relevant parameter ranges in our model. 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.

part of the H-type's LTT for $f > \kappa_1$. To improve upon this inefficient resource allocation, CCP markets need to switch 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 equalized in Theorem 1:

$$\mathcal{S} = \left(\frac{R^H}{\lambda} - \frac{\kappa_2}{\kappa_1}\right)\frac{\kappa_1 \lambda}{R^H - R^L}. \tag{29}$$

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 $\mathcal{S}$ 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 sustainable with a default fund involving purely a profit transfer at $t = 2$ is given by $f^{OPT}(w_1^H = 0)$ as derived in Theorem 2. In Appendix G, we show when the run resilience of the hybrid market exceeds the run resilience in the CCP market, $f^{OPT}(w_1^H = 0) > f_{DF}^{CCP}$. The intuition is, since the H-type is not required to liquidate any of the LTT in the hybrid market as opposed to the CCP, there is more profit to redistribute which makes the hybrid market more resilient than the CCP market.

Figure 5 (left) illustrates that the hybrid trading mechanism improves upon existing CCP markets by allocating resource more efficiently for intermediate and large funding shocks, $\mathcal{S} < f \leq f^{OPT}(w_1^H = 0)$, but it does not attain the efficient resource allocation of the first-best solution. In addition, the hybrid market improves upon run resilience, $f^{OPT}(w_1^H = 0) > f_{DF}^{CCP}$, but again does not achieve first-best run resilience.

Bilateral trading and central clearing: Centrally cleared OTC markets are an important segment of U.S. repo markets (Duffie, 2020). Augmenting OTC markets with central clearing and a default fund that pays in case of a borrower's default is an alternative reform proposal for repo markets. Central clearing improves the resilience of OTC markets and resembles the functioning of some 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, $\tau^{OPT}(w_1^H = 0)$ at $t = 2$, financial stability is improved: $f^{OPT}(w_1^H = 0) > f^{OTC}$ for any $\tau^{OPT} > 0$. Figure 5 (right) illustrates that bilateral trading with central clearing improves run resilience, but the reform leaves allocative efficiency unchanged.

Two-tiered guarantee fund: Both of the solutions above, hybrid CCP market and centrally cleared OTC market, can be further improved to the point that they achieve first best and resolve the allocation-resilience tradeoff. 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 transfer at $t = 1$ and profit transfer at $t = 2$, derived in Theorem 2. The contribution is agreed upon before lending and borrowing take place, and it needs to be updated on a regular basis depending on participants' net exposure to the platform.

The two-tiered guarantee fund works as follows. Participants transfer both safe collateral and a fraction of the risky asset, i.e., LTT, into two separate escrow accounts. Collateral is used to support illiquid but solvent borrowers, so that, in terms of the model, the H-type's collateral is liquidated before the L-type's LTT. This implies 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 optimal repo market solution. 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 from 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 effectively 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.

6 Collateral, Market Structure, and Financial Fragility

6.1 Collateral quality and run resilience

This section studies how collateral quality impacts market resilience. For any given level of funding shock, riskiness of the LTT and collateral amount, a marginal increase in collateral value affects run thresholds in the CCP and OTC markets differently. 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 6 *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,* $\lambda < \frac{R^H - R^L}{2 - R^L}$, *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. When 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, $\lambda < \frac{R^H - R^L}{2 - R^L}$. 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.

6.2 Collateral convenience yield

This section studies why an asset is 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. We show that in addition to the liquidity of collateral and counterparty risk (Parlatore, 2019), the convenience yield of the given collateral asset depends on the market structure and funding risk. We provide support for the empirical evidence showing that the convenience yield increased during the GFC and decreased in the Covid-19 outbreak.

To provide a benchmark, we derive the collateral convenience yield in the first-best solution, $\widehat{\kappa}$, which gives an upper bound on the collateral premium:

$$\widehat{\kappa} \equiv \frac{(R^H + R^L - 2) - 2\alpha((\frac{R^L}{\lambda} - 1)f - \frac{R^L}{\lambda}\kappa_1)}{R^H + R^L - 2(1-\alpha)} \geq \kappa_0. \tag{30}$$

From borrowers' participation constraints at $t = 0$, we obtain that the convenience yield depends on funding market conditions and market structure, that is, CCP and OTC market. All derivations are deferred to Appendix F. The collateral premium is generally non-monotone in the funding shock in both markets. Our theoretical predictions for the critical ranges of the funding shock, i.e., $\kappa_1 < f \leq f^{CCP}$ and $\frac{\kappa_1}{2} < f \leq f^{OTC}$, 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 the OTC market, focusing on the range $\frac{\kappa_1}{2} < f \leq f^{OTC}$ 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.[37] We obtain the following result:

Proposition 7 *In the OTC market, for* $\frac{\kappa_1}{2} < f \leq f^{OTC}$ *and* $\alpha > R^H - R^L$*, the convenience yield on collateral* $\mathbf{cp}^{OTC}$ *decreases (increases) in* f *if* $\beta > (<) \frac{R^L}{\alpha + R^L - R^H}$.

The model predicts that when the economy is at the brink of a funding crisis, i.e., 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. Conversely, the collateral premium decreases in the size of the funding shock if average borrower quality is sufficiently high.

These predictions are in line with empirical evidence from the financial crisis 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. (2020).

6.3 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.[38] To investigate this issue, we introduce negative NPV projects and study the role of collateral scarcity. All derivations are relegated to Appendix F.

Assume that the LTT of the L-type has negative NPV, $R^L < 1$. There are two relevant cases to consider: 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 is welfare

[37] To which extent the convenience yield is impacted by the OTC or CCP market is ultimately an empirical question.

[38] 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.

optimal. Recall, we assume collateral scarcity at $t = 1$, i.e., fully liquidating collateral and LTT is not enough to repay first-round lenders, $c_1\ell_0 \geq \lambda i_0 + \kappa_1 k_0$.

For $1 > R^L > \lambda$, lenders are willing to provide loans even to the L-type if the collateral value, although scarce, is sufficiently large, $\kappa_2 > 1 - R^L$. From the lenders' viewpoint, collateral makes up for the missing return from the L-type LTT. Collateral is thus welfare increasing for $1 > R^L > \lambda$.

Moving to the situation in which $1 > \lambda > R^L$, implies a decrease in the L-type's return R^L. The OTC market implements the socially optimal solution, i.e., the L-type liquidates the LTT and the H-type continues regardless of the collateral value. If the collateral value is sufficiently large, the L-type borrower prefers to liquidate the LTT. If the collateral value is so small that the L-type is indifferent between rolling over or defaulting, lenders refuse to provide loans. That is, the L-type experiences a run.

We now turn to the question whether anonymous CCP markets allow low quality borrowers to hide among good quality borrowers. Socially optimal liquidation is also attainable in the CCP market due to novation. Even though the L-type borrower might continue the LTT in case they are able to promise repayment to second round lenders, i.e., if $\kappa_2 > 1 - R^L$, the CCP would exclude them from the market through the novation process. As a consequence, similar to the OTC market, there is a run on the L-type which forces them to liquidate the LTT and the H-type continues to obtain funding in the CCP market.

Infante and Vardoulakis (2020) and Kuong (2020) also obtain run results in the presence of collateral but the mechanisms differ. Infante and Vardoulakis (2020) 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 (2020) shows in a global games model with moral hazard how, notwithstanding collateral, runs can occur. In our model, the run is on borrowers and causes inefficient liquidation of collateral. It is an incentive driven run by lenders that occurs due to a combination of liquidity, counterparty and collateral risk.

7 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 insurance against funding shocks, 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.

References

Allen, Franklin, and Douglas Gale, 1998, Optimal financial crises, *Journal of Finance* 53, 1245–1284.

Auh, Jun Kyung, and Mattia Landoni, 2017, Loan terms and collateral: Evidence from the bilateral repo market, working paper, Georgetown University.

Baklanova, Viktoria, Ocean Dalton, and Stathis Tompaidis, 2017, Benefits and risks of central clearing in the repo market, OFR brief series 17-04, Office of Financial Research.

Biais, Bruno, Florian Heider, and Marie Hoerova, 2016, Risk-sharing or risk-taking? Counterparty risk, incentives and margins, *Journal of Finance* 71, 1669–1698.

Biais, Bruno, Florian Heider, and Marie Hoerova, 2020, Variation margins, fire sales, and information-constrained optimality, *Review of Economic Studies* forthcoming.

Bianchi, Javier, and Saki Bigio, 2020, Banks, liquidity management and monetary policy, NBER working paper 20490, University of California at Los Angeles.

BIS, 2017, Committee on the global financial system: Repo market functioning, April, 2017, Bank for International Settlements.

Bouvard, Matthieu, Pierre Chaigneau, and Adolfo de Motta, 2015, Transparency in the financial system: Rollover risk and crises, *Journal of Finance* 70, 1805–1837.

Brunnermeier, Markus K., 2009, Deciphering the liquidity and credit crunch 2007–2008, *Journal of Economic Perspectives* 23, 77–100.

Brunnermeier, Markus K., and Martin Oehmke, 2013, The maturity rat race, *Journal of Finance* 68, 483–521.

Burdett, Kenneth, and Maureen O'Hara, 1987, Building blocks: An introduction to block trading, *Journal of Banking and Finance* 11, 193–212.

Carlson, Mark, and Marco Macchiavelli, 2020, Emergency loans and collateral upgrades: How broker-dealers used federal reserve credit during the 2008 financial crisis, *Journal of Financial Economics* 137, 701–722.

Chen, Yehning, 1999, Banking panics: The role of the first-come, first-served rule and information externalities, *Journal of Political Economy* 107, 946–968.

Copeland, Adam, Antoine Martin, and Michael Walker, 2014, Repo runs: Evidence from the tri-party repo market, *Journal of Finance* 69, 2343–2380.

Dang, Tri Vi, Gary Gorton, Bengt Holmstrom, and Guillermo Ordoñez, 2017, Banks as secret keepers, *American Economic Review* 107, 1005–1029.

Diamond, Douglas W., and Philip H. Dybvig, 1983, Bank runs, deposit insurance, and liquidity, *Journal of Political Economy* 91, 401–419.

Duffie, Darrell, 2020, Still the world's safe haven? Redesigning the US treasury market after the COVID-19 crisis, Hutchins center working paper # 62, Stanford University.

Duffie, Darrell, and Haoxiang Zhu, 2011, Does a central clearing counterparty reduce counterparty risk?, *Review of Asset Pricing Studies* 1, 74–95.

Goldstein, Itay, and Yaron Leitner, 2018, Stress tests and information disclosure, *Journal of Economic Theory* 177, 34–69.

Goldstein, Itay, and Ady Pauzner, 2005, Demand–deposit contracts and the probability of bank runs, *Journal of Finance* 60, 1293–1327.

Gorton, Gary B., and Andrew Metrick, 2012, Securitized banking and the run on repo, *Journal of Financial Economics* 104, 425–451.

Gorton, Gary B., and Andrew Winton, 2003, Financial intermediation, *In Handbook of the Economics of Finance* 1, 431–552.

Gottardi, Piero, Vincent Maurin, and Cyril Monnet, 2019, A theory of repurchase agreements, collateral re-use, and repo intermediation., *Review of Economic Dynamics* 33, 30–56.

Grossman, Sanford J., 1992, The informational role of upstairs and downstairs trading, *Journal of Business* 65, 509–528.

He, Zhiguo, Stefan Nagel, and Zhaogang Song, 2020, Treasury inconvenience yields during the covid-19 crisis, NBER working paper 27416, University of Chicago.

Heider, Florian, Marie Hoerova, and Cornelia Holthausen, 2015, Liquidity hoarding and interbank market rates: The role of counterparty risk, *Journal of Financial Economics* 118, 336–354.

Infante, Sebastian, and Alexandros P Vardoulakis, 2020, Collateral Runs, *Review of Financial Studies* forthcoming.

Krishnamurthy, Arvind, Stefan Nagel, and Dmitry Orlov, 2014, Sizing up repo, *Journal of Finance* 69, 2381–2417.

Kuong, John C.F., 2020, Self-fulfilling fire sales: Fragility of collateralized short-term debt markets, *Review of Financial Studies* forthcoming.

Mancini, Loriano, Angelo Ranaldo, and Jan Wrampelmeyer, 2016, The euro interbank repo market, *Review of Financial Studies* 29, 1747–1779.

Martin, Antoine, David R. Skeie, and Ernst-Ludwig von Thadden, 2014a, The fragility of short-term secured funding markets, *Journal of Economic Theory* 149, 15–42.

Martin, Antoine, David R. Skeie, and Ernst-Ludwig von Thadden, 2014b, Repo runs, *Review of Financial Studies* 27, 957–989.

Oehmke, Martin, 2014, Liquidating illiquid collateral, *Journal of Economic Theory* 149, 183–210.

Parlatore, Cecilia, 2019, Collateralizing liquidity, *Journal of Financial Economics* 131, 299–322.

Pérignon, Christophe, David Thesmar, and Guillaume Vuillemey, 2018, Wholesale funding dry-ups, *Journal of Finance* 73, 575–617.

Postlewaite, Andrew, and Xavier Vives, 1987, Bank runs as an equilibrium phenomenon, *Journal of Political Economy* 95, 485–491.

Seppi, Duane J., 1990, Equilibrium block trading and asymmetric information, *Journal of Finance* 45, 73–94.

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

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

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 $\ell^L_{1,f=0} = \ell^H_{1,f=0} = m$. Moreover borrower competition yields

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

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

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:

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

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

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

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

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

Consider next the case in which $c_1\ell_0 > \ell_1^L + \kappa_1 k_0$, i.e. $\frac{\kappa_1}{2} < f \leq f^{OTC}$. 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 $\ell_1^L = 2(1-f)m - \ell_1^H$ and $z_1^L = \frac{2f-\kappa_1}{\lambda}m$.
It is indeed more profitable to take a loan than to liquidate collateral if the L-type's participation constraint is satisfied

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

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

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

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

Observe that $\frac{\partial c_2^{OTC}}{\partial f} < 0$. With $f = \kappa_1/2$, the H-type's profit is $(R^H + \kappa_2 - \frac{R^L}{1-\kappa_1})m$ which is weakly positive if $1 - \frac{R^L}{R^H+\kappa_2} \geq \kappa_1$.
Moving backward to $t = 0$. Consider the case when $\frac{\kappa_1}{2} < f \leq f^{OTC}$.The case $0 < f \leq \frac{\kappa_1}{2}$ 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:

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

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

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

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

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

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

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

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

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

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

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

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,

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

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

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

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 $c_{1,f>f^{OTC}}\ell_0 \leq 2(1-f)m$.

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

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

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

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

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

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

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

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

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

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

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

$$R^H i_0 - c^H_{2,f>f^{OTC}} \ell^H_{1,f>f^{OTC}} + c^H_{2,f>f^{OTC}} \ell^H_{1,f>f^{OTC}} - \ell^H_{1,f>f^{OTC}} + c_{1,f>f^{OTC}}\ell_0 + \lambda i_0 + \kappa_1 k_0 - \kappa_2 k_0 - 2\ell_0 \tag{IA35}$$
$$= (R^H + \lambda + \kappa_1 - \kappa_2 - 2)m \tag{IA36}$$

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:

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

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

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

Lenders are willing to provide funding if

$$c_2^P \geq 1 \tag{IA40}$$
$$\frac{R^L - 1}{\kappa_2 - \kappa_1}\kappa_1 + \frac{\kappa_2\kappa_1}{\kappa_2 - \kappa_1} \geq f. \tag{IA41}$$

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

If $\kappa_1 < f \leq f^{CCP}$, $w_1^P = k_0$ 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:

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

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

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

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

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

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

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

Call $f^{CCP} = \frac{R^L-1}{R^H-\lambda}\lambda + \frac{R^H\kappa_1}{R^H-\lambda}$.

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 $\kappa_1 < f \leq f^{CCP}$, if

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

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

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

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

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, $\kappa_1 < f \leq f^{CCP}$. Then with $(\beta R^H + (1-\beta)R^L)\kappa_0 - \beta(R^H - R^L) < 0$, i.e. $\kappa_0 \leq \frac{\beta(R^H - R^L)}{\beta R^H + (1-\beta)R^L}$, condition (IA50) is always satisfied.

C.2 Welfare

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

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

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

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

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

Ex-post welfare is

$$(R^H + R^L)(i_0 - z_1^P) - 2c_2^P\ell_1^P - 2\kappa_2 w_1^P + 2c_2^P\ell_1^P - 2(1-f)m + 2c_1\ell_0 - 2\ell_0 \tag{IA53}$$
$$=(R^H + R^L - 2)m - f(\frac{R^H + R^L}{\lambda} - 2)m + (\frac{R^H + R^L}{\lambda}\kappa_1 - 2\kappa_2)m \tag{IA54}$$

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

C.3 COB with novation

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

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

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

$$R^L i_0 - c^P_{2,f>f^{CCP}}\ell^P_{1,f>f^{CCP}} + \kappa_2(k_0 - k^P_{1,f>f^{CCP}}) \geq 0 \tag{IA57}$$
$$R^L + \kappa_2(1 - \frac{c_{1,f>f^{CCP}} - 1}{\kappa_1}) \geq c^P_{2,f>f^{CCP}} \tag{IA58}$$

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

$$R^\omega i_0 - c^P_{2,f>f^{CCP}}\ell^P_{1,f>f^{CCP}} + \kappa_2(k_0 - k^P_{1,f>f^{CCP}}) \geq R^\omega i_0 - c_2'\ell_1' + \kappa_2 k_0 \tag{IA59}$$
$$R^L + \kappa_2(1 - \frac{c_{1,f>f^{CCP}} - 1}{\kappa_1}) \geq c^P_{2,f>f^{CCP}}. \tag{IA60}$$

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

For second-round lenders to provide loans

$$R^L + \kappa_2(1 - \frac{c_{1,f>f^{CCP}} - 1}{\kappa_1}) \geq 1 \tag{IA61}$$
$$\kappa_2(1 - \frac{c_{1,f>f^{CCP}} - 1}{\kappa_1}) \geq 1 - R^L \tag{IA62}$$

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

At $t = 0$, competitive lenders require

$$\alpha(\beta c_{1,f>f^{CCP}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{CCP}} = 1 \tag{IA63}$$
$$c_{1,f>f^{CCP}} = \frac{1 - \alpha(1-\beta)c_1^D}{\alpha\beta + (1-\alpha)}. \tag{IA64}$$

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

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

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

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

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

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

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

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

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

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 $\kappa_1 < f \leq f^{CCP}$. 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 Separating equilibrium

We specify beliefs as follows:

$$Pr(R^H|c_2) = \begin{cases} 1 & \text{if } c_2 = c_2^{S,H}, \\ 0 & \text{if } c_2 = c_2^{S,L}, \\ 1 & \text{otherwise .} \end{cases} \tag{IA71}$$

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 $(\lambda + \kappa_1)m - c_1\ell_0 \leq 0$),

$$R^\omega(i_0 - z_1^{S,\omega}) - c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 - w_1^{S,\omega}) \geq 0, \tag{IA72}$$

the repayment condition is met,

$$-c_1\ell_0 + \lambda z_1^{S,\omega} + \ell_1^{S,\omega} + \kappa_1 w_1^{S,\omega} = 0, \tag{IA73}$$

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

$$R^\omega(i_0 - z_1^{S,\omega}) - c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 - w_1^{S,\omega}) \geq R^\omega(i_0 - z_1^{S,-\omega}) - c_2^{S,-\omega}\ell_1^{S,-\omega} + \kappa_2(k_0 - w_1^{S,-\omega}), \tag{IA74}$$

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

$$R^\omega(i_0 - z_1^{S,\omega}) - c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 - w_1^{S,\omega}) \geq R^\omega(i_0 - z_1') - c_2'\ell_1' + \kappa_2(k_0 - k_1'). \tag{IA75}$$

Second-round lenders are willing to provide a loan if

$$c_2^{S,\omega} \geq 1. \tag{IA76}$$

Small funding shock $f \leq f^{Sep}$: 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,

$$R^L(i_0 - z_{1,f=0}^{S,L}) - c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L} + \kappa_2(k_0 - w_{1,f=0}^{S,L}) = 0 \tag{IA77}$$

$$c_{2,f=0}^{S,L} = \frac{R^L i_0 + \kappa_2 k_0}{\ell_{1,f=0}^{S,L}} \tag{IA78}$$

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 IA74 and IA75 are satisfied provided $c_2' = R^L + \kappa_2$, $\ell_1' = c_1\ell_0$ and $k_1' = 0$.

At $t = 1$, if $0 < f \leq \frac{\kappa_1}{2}$, we construct an equilibrium with $\ell_1^{S,H} = c_1\ell_0$, $\ell_1^{S,L} = 2(1-f)m - \ell_1^{S,H}$, $w_1^{S,H} = 0$, $w_1^{S,L} = \frac{c_1\ell_0 - \ell_1^{S,L}}{\kappa_1}$, $z_1^{S,L} = 0$, $z_1^{S,H} = 0$. 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:

$$R^L i_0 - c_2^{S,L} \ell_1^{S,L} + \kappa_2(k_0 - w_1^{S,L}) = 0 \tag{IA79}$$

$$c_2^{S,L} = \frac{R^L i_0 + \kappa_2(k_0 - w_1^{S,L})}{\ell_1^{S,L}} \tag{IA80}$$

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 (IA74), is binding and their participation constraint, in expression (IA72), 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

$$\frac{\kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \geq c_2^{S,H} \geq \frac{\kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \tag{IA81}$$

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, $\ell_1^{S,L} = 2(1-f)m - \ell_1^{S,H}$.

With $c_2' = R^L + \kappa_2$, $\ell_1' = c_1\ell_0$ and $k_1' = 0$ it is straightforward to show that condition IA75 is satisfied for both types.

At $t = 1$, if $\frac{\kappa_1}{2} < f \leq f^{Sep}$, we construct an equilibrium with $\ell_1^{S,H} = c_1\ell_0$, $\ell_1^{S,L} = 2(1-f)m - \ell_1^{S,H}$, $w_1^{S,H} = 0$, $w_1^{S,L} = k_0$, $z_1^{S,L} = \frac{c_1\ell_0 - \ell_1^{S,L} - \kappa_1 w_1^{S,L}}{\lambda}$, $z_1^{S,H} = 0$. 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:

$$R^L(i_0 - z_1^{S,L}) - c_2^{S,L}\ell_1^{S,L} = 0 \tag{IA82}$$

$$c_2^{S,L} = \frac{R^L(i_0 - z_1^{S,L})}{\ell_1^{S,L}} \tag{IA83}$$

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 (IA74), is binding and their participation constraint, in expression (IA72), 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

$$\frac{R^H z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \geq c_2^{S,H} \geq \frac{R^L z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \tag{IA84}$$

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 $\frac{\kappa_1}{2} < f \leq f^{Sep}$ this is satisfied if $\kappa_2 > \frac{\kappa_1}{1-\kappa_1}$. 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 IA84, $c_2^{S,H} = \frac{R^L z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} = \frac{R^L i_0 + \kappa_2 k_0}{c_1 \ell_0}$.

With $c_2' = R^L + \kappa_2$, $\ell_1' = c_1\ell_0$ and $k_1' = 0$ it is straightforward to show that condition IA75 is satisfied for both types.

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

$$c_1 \geq 1. \tag{IA85}$$

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

$$\beta\Big(\alpha(R^H i_0 - c_2^{S,H}\ell_1^{S,H}) + (1-\alpha)(R^H i_0 - c_{2,f=0}^{S,H}\ell_{1,f=0}^{S,H})\Big) - \alpha(1-\beta)\kappa_0 m$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 m \tag{IA86}$$
$$\frac{\beta(R^H - R^L - \kappa_2)}{\beta R^H + (1-\beta)R^L + \alpha(1-\beta) - 1} \geq \kappa_0 \tag{IA87}$$

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, $c_2^{S,L} \geq 1$, i.e. $f < f^{Sep} = \frac{R^L-1}{R^L-\lambda}\frac{\lambda}{2} + \frac{R^L\kappa_1}{2(R^L-\lambda)} \geq f$. 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 $c_{1,f>f^{Sep}}\ell_0 \leq 2(1-f)m$. First-round lenders of the L-type are repaid the liquidation value of the L-type borrower

$$-c_1^D\ell_0 + \lambda i_0 + \kappa_1 k_0 = 0 \tag{IA88}$$
$$c_1^D = \lambda + \kappa_1. \tag{IA89}$$

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

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

$$R^L i_0 - c^L_{2,f=0}\ell^L_{1,f=0} + \kappa_2(k_0 - w^L_{1,f=0}) = 0 \tag{IA90}$$
$$c^L_{2,f=0} = \frac{R^L i_0 + \kappa_2(k_0 - w^L_{1,f=0})}{\ell^L_{1,f=0}} \tag{IA91}$$

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

$$\frac{\kappa_2 w^L_{1,f=0} + c^L_{2,f=0}\ell^L_{1,f=0}}{\ell^H_{1,f=0}} \geq c^H_{2,f=0} \geq \frac{\kappa_2 w^L_{1,f=0} + c^L_{2,f=0}\ell^L_{1,f=0}}{\ell^H_{1,f=0}} \tag{IA92}$$

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 $c_2' = \frac{R^L+\kappa_2}{c_{1,f>f^{Sep}}\ell_0}m$, $\ell_1' = c_{1,f>f^{Sep}}\ell_0$ and $w_1' = 0$ it is straightforward to show that condition IA75 is satisfied for both types.

At $t = 0$, competitive lenders require

$$\alpha(\beta c_{1,f>f^{Sep}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{Sep}} = 1 \tag{IA93}$$
$$c_{1,f>f^{Sep}} = \frac{1 - \alpha(1-\beta)c_1^D}{\alpha\beta + (1-\alpha)} \tag{IA94}$$

Borrowers decide to invest in the long-term technology if

$$
\begin{aligned}
&\beta\Big(\alpha(R^H i_0 - c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}}) + (1-\alpha)(R^H i_0 - c^{S,H}_{2,f=0}\ell^{S,H}_{1,f=0})\Big) - (1-\beta)\kappa_2 m \\
&\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 m && \text{(IA95)}\\
&\frac{\beta(R^H - \alpha c_{1,f>f^{Sep}} - (1-\alpha)R^L)}{\beta R^H + (1-\beta)R^L - 1 + (1-\beta) + \beta(1-\alpha)} \geq \kappa_0. && \text{(IA96)}
\end{aligned}
$$

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

D.1 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

$$
\begin{aligned}
&R^H i_0 - c^{S,H}_2\ell^{S,H}_1 + R^L i_0 - c^{S,L}_2\ell^{S,L}_1 - \kappa_2 w^{S,L}_1 + c^{S,H}_2\ell^{S,H}_1 + c^{S,L}_2\ell^{S,L}_1 - \ell^{S,H}_1 - \ell^{S,L}_1 + 2c_1\ell_0 - 2\ell_0 && \text{(IA97)}\\
=&R^H i_0 + R^L i_0 - \kappa_2 w^{S,L}_1 - \ell^{S,H}_1 - \ell^{S,L}_1 && \text{(IA98)}\\
=&(R^H + R^L - 2)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m. && \text{(IA99)}
\end{aligned}
$$

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

$$
\begin{aligned}
&R^H i_0 - c^{S,H}_2\ell^{S,H}_1 + R^L(i_0 - z^{S,L}_1) - c^{S,L}_2\ell^{S,L}_1 - \kappa_2 w^{S,L}_1 + c^{S,H}_2\ell^{S,H}_1 + c^{S,L}_2\ell^{S,L}_1 - \ell^{S,H}_1 - \ell^{S,L}_1 + 2c_1\ell_0 - 2\ell_0 && \text{(IA100)}\\
=&R^H i_0 + R^L(i_0 - z^{S,L}_1) - \kappa_2 w^{S,L}_1 - \ell^{S,H}_1 - \ell^{S,L}_1 && \text{(IA101)}\\
=&(R^H + R^L - 2)m - 2f(\frac{R^L}{\lambda} - 1)m + \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m. && \text{(IA102)}
\end{aligned}
$$

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

$$
\begin{aligned}
&R^H i_0 - c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}} + c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}} - \ell^H_{1,f>f^{Sep}} + c_{1,f>f^{Sep}}\ell_0 + \lambda i_0 + \kappa_1 k_0 - \kappa_2 k_0 - 2\ell_0 && \text{(IA103)}\\
=&(R^H + \lambda + \kappa_1 - \kappa_2 - 2)m && \text{(IA104)}
\end{aligned}
$$

D.2 Intuitive criterion: separating equilibrium

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

$$
Pr(R^H|c_2) = \begin{cases} 1 & \text{if } c_2 = c^{S,H}_2, \\ 0 & \text{if } c_2 = c^{S,L}_2, \\ 1 & \text{otherwise }. \end{cases} \tag{IA105}
$$

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

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

Consider first the L-type borrower:

$$
\begin{aligned}
0 >& R^L m - c'_2 m + \kappa_2 m\\
c'_2 >& R^L + \kappa_2.
\end{aligned}
$$

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

Similarly for the H-type:

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

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

We can therefore summarize that

- $c_2' \in [0, R^L + \kappa_2]$ is not equilibrium dominated for neither the H-type nor the L-type,
- $c_2' \in (R^L + \kappa_2, \infty)$ is equilibrium dominated for both types.

For any 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.

E 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 D, borrowers can signal their types through the loan contract and, consequently, lenders provide different loan contracts to different types. In Appendices C.4 and D.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 $f \leq f^{CCP}$. 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.

E.1 Ex-ante welfare

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

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

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

$$\begin{aligned}W^{Sep} = \alpha\Big(&R^H i_0 - c_2^{S,H}\ell_1^{S,H} + R^L(i_0 - z_1^{S,L}) - c_2^{S,L}\ell_1^{S,L} - \kappa_2 w_1^{S,L} + c_2^{S,H}\ell_1^{S,H} + c_2^{S,L}\ell_1^{S,L} - \ell_1^{S,H} - \ell_1^{S,L}\\ &+2c_1\ell_0 - 2\ell_0\Big) + (1-\alpha)\Big(R^H i_0 - c_{2,f=0}^{S,H}\ell_{1,f=0}^{S,H} + R^L i_0 - c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L}\\ &+c_{2,f=0}^{S,H}\ell_{1,f=0}^{S,H} + c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L} - \ell_{1,f=0}^{S,H} - \ell_{1,f=0}^{S,L} + 2c_1\ell_0 - 2\ell_0\Big) \quad \text{(IA106)}\\ = (R^H + R^L - 2)m - \alpha(2f(\frac{R^L}{\lambda} - 1) - \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_0}{\kappa_0})) \quad \text{(IA107)}\end{aligned}$$

Ex-ante welfare in the pooling equilibrium is:

$$\begin{aligned}W^{Pool} = \alpha\Big(&(R^H + R^L)(i_0 - z_1^P) - 2c_2^P\ell_1^P + 2\kappa_2(k_0 - w_1^P) - 2k_0\kappa_0 + 2c_2^P\ell_1^P - 2\ell_1^P + 2c_1\ell_0 - 2\ell_0\Big)\\ &+(1-\alpha)\Big((R^H + R^L)i_0 - 2c_{2,f=0}^P\ell_{1,f=0}^P + 2c_{2,f=0}^P\ell_{1,f=0}^P - 2\ell_{1,f=0}^P + 2c_1\ell_0 - 2\ell_0\Big) \quad \text{(IA108)}\\ = (R^H + R^L - 2)m - \alpha(f(\frac{R^H + R^L - 2\lambda}{\lambda} - 1) - \kappa_1(\frac{R^H + R^L}{\lambda} - 2\frac{\kappa_0}{\kappa_0})) \quad \text{(IA109)}\end{aligned}$$

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 $\kappa_1 < f \leq f^{Sep}$, we have to check that there exists a non-empty range for κ_1 which is the case since $\frac{R^H - R^L}{R^H} f < f$.

E.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. More precisely, borrowers finance illiquid assets rather via the COB market while they finance more liquid assets via the OTC market. The following proposition summarizes the results.

Proposition 8 *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. $\kappa_1 < f \leq f^{OTC}$.*

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

Consider borrowers' ex- ante profit in the CCP market

$$\begin{aligned}E(\Pi^{CCP}) =&\alpha\Big((\beta R^H + (1-\beta)R^L)(i_0 - z_1^P) - c_2^P\ell_1^P - \kappa_2 k_0\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P\ell_{1,f=0}^P\Big)\\ =&\beta(R^H - R^L) - \kappa_0 + \alpha(1-\beta)(R^H - R^L)\frac{f - \kappa_1}{\lambda}. \quad \text{(IA110)}\end{aligned}$$

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

$$\begin{aligned}E(\Pi^{OTC}) =&\alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big) + (1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big)\\ =&\beta(R^H - R^L) - \kappa_0 + \alpha\beta(\kappa_0 - R^L\frac{2f - \frac{2f - \kappa_1}{\lambda}}{1 - 2f}). \quad \text{(IA111)}\end{aligned}$$

Define $\bar{\lambda}$ by

$$E(\Pi^{CCP}) - E(\Pi^{OTC}) = 0$$
$$\bar{\lambda} = \frac{(1-\beta)(R^H - R^L)(f-\kappa_1) + \beta R^L \frac{2f-\kappa_1}{1-2f}}{\beta(\kappa_0 - \frac{2f}{1-2f}R^L)} \tag{IA112}$$

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

F Collateral and negative NPV

F.1 Convenience yield: OTC market

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

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

$$\alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H) - (1-\beta)\kappa_2 w_1^L\Big) + (1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)k_0\kappa_0 \tag{IA113}$$
$$\frac{\beta(R^H - R^L(\alpha\frac{1}{1-2f} + 1 - \alpha))}{\beta R^H + (1-\beta)R^L - 1 + \alpha(\beta\frac{\kappa_1 - 2f}{1-2f} + (1-\beta)2f)\frac{1}{\kappa_1} + (1-\alpha)} \geq \kappa_0, \tag{IA114}$$

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

$$\alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big) + (1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)k_0\kappa_0 \tag{IA115}$$
$$\frac{\beta(R^H - R^L(\alpha\frac{1-\frac{2f-\kappa_1}{\lambda}}{1-2f} + 1 - \alpha))}{\beta R^H + (1-\beta)R^L - 1 + (1-\beta) + (1-\alpha)\beta} \geq \kappa_0, \tag{IA116}$$

- $f > f^{OTC}$ if

$$\alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H) - (1-\beta)\kappa_2 w_1^L\Big) + (1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)k_0\kappa_0 \tag{IA117}$$
$$\frac{\beta(R^H - (\alpha + (1-\alpha)\frac{R^L + \kappa_2(1 - 2\frac{c_{1,f>f^{OTC}} - 1}{\kappa_1})}{2 - c_{1,f>f^{OTC}}})c_{1,f>f^{OTC}})}{\beta R^H + (1-\beta)R^L - 1 + (1-\beta)(\alpha 2\frac{c_{1,f>f^{OTC}} - 1}{\kappa_1} + (1-\alpha))} \geq \kappa_0. \tag{IA118}$$

The collateral premium in the OTC market is therefore defined by

$$\mathbf{cp}^{OTC} = \begin{cases} \frac{\beta(R^H - R^L(\alpha\frac{1}{1-2f} + 1 - \alpha))}{\beta R^H + (1-\beta)R^L - 1 + \alpha(\beta\frac{\kappa_1 - 2f}{1-2f} + (1-\beta)2f)\frac{1}{\kappa_1} + (1-\alpha)} - \kappa_0, & \text{if } 0 < f \leq \frac{\kappa_1}{2}, \\ \frac{\beta(R^H - R^L(\alpha\frac{1-\frac{2f-\kappa_1}{\lambda}}{1-2f} + 1 - \alpha))}{\beta R^H + (1-\beta)R^L - \alpha\beta} - \kappa_0, & \text{if } \frac{\kappa_1}{2} < f \leq f^{OTC}, \\ \frac{\beta(R^H - (\alpha + (1-\alpha)\frac{R^L + \kappa_2(1 - 2\frac{c_{1,f>f^{OTC}} - 1}{\kappa_1})}{2 - c_{1,f>f^{OTC}}})c_{1,f>f^{OTC}})}{\beta R^H + (1-\beta)R^L - 1 + (1-\beta)(\alpha 2\frac{c_{1,f>f^{OTC}} - 1}{\kappa_1} + (1-\alpha))} - \kappa_0, & \text{if } f > f^{OTC}. \end{cases} \tag{IA119}$$

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 $0 < f \leq \frac{\kappa_1}{2}$ and $\frac{\kappa_1}{2} < f \leq f^{OTC}$ is ambiguous.

F.2 Convenience yield: CCP market

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

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

$$\alpha\Big((\beta R^H + (1-\beta)R^L)i_0 - c_2^P \ell_1^P - \kappa_2 w_1^P\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA120}$$
$$\frac{\beta(R^H - R^L)}{\beta R^H + (1-\beta)R^L + (1-\alpha)} \geq \kappa_0 \tag{IA121}$$

- for $\kappa_1 < f \leq f^{CCP}$, if

$$\alpha\Big((\beta R^H + (1-\beta)R^L)(i_0 - z_1^P) - c_2^P \ell_1^P - \kappa_2 k_0\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA122}$$
$$\frac{(R^H - R^L)(\beta + \alpha(1-\beta)\frac{f-\kappa_1}{\lambda})}{\beta R^H + (1-\beta)R^L} \geq \kappa_0 \tag{IA123}$$

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

$$\alpha\Big(-\kappa_2 k_0\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P - k_2 w_{1,f=0}^P\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA124}$$
$$\frac{(1-\alpha)\beta(R^H - R^L)}{\beta R^H + (1-\beta)R^L} \geq \kappa_0 \tag{IA125}$$

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

$$\mathbf{cp}^{CCP} = \begin{cases} \frac{\beta(R^H - R^L)}{\beta R^H + (1-\beta)R^L + (1-\alpha)} - \kappa_0, & \text{if } 0 < f \leq \kappa_1, \\ \frac{(R^H - R^L)(\beta + \alpha(1-\beta)\frac{f-\kappa_1}{\lambda})}{\beta R^H + (1-\beta)R^L} - \kappa_0, & \text{if } \kappa_1 < f \leq f^{CCP}, \\ \frac{(1-\alpha)\beta(R^H - R^L)}{\beta R^H + (1-\beta)R^L} - \kappa_0, & \text{if } f > f^{CCP}. \end{cases} \tag{IA126}$$

F.3 Negative NPV and collateral

Assume that the NPV of the L-type LTT is negative, $R^L < 1$. Furthermore, there are two relevant cases. First, when the L-type LTT yields a negative NPV but still larger than the return from early liquidation, $1 > R^L > \lambda$. Second, when the L-type LTT yields a return even smaller than early liquidation $1 > \lambda > R^L$.

OTC market To highlight the role of collateral it is sufficient to show how lending is affected when no funding shock realizes. If $f = 0$, both borrowers obtain sufficiently large loans to repay first-round lenders

$\ell^L_{1,f=0} = \ell^H_{1,f=0} = m$. Moreover borrower competition yields

$$R^L i_0 - c^{OTC}_{2,f=0}\ell^L_{1,f=0} + \kappa_2 k_0 = 0 \tag{IA127}$$

Lenders provide funding to the L-type borrower as long as $c^{OTC}_{2,f=0} = R^L + \kappa_2 \geq 1$, i.e. $R^L \geq 1 - \kappa_2$. Note, the L-type borrower is indifferent between rolling over the initial loan and defaulting on it since they make zero profit anyway. The smaller the value of collateral available, the less likely the L-type borrower to obtain funding. Consider $\kappa_2 = 0$, then the L-type borrower with an LTT delivering $1 > R^L > \lambda$ does not obtain a second loan and has to, inefficiently, liquidate the LTT. In case $1 > R^L > \lambda$, the use of collateral is welfare improving if $R^L + \kappa_2 \geq 1$. Conversely, if $\lambda > R^L$, the LTT is liquidated early if $R^L + \kappa_2 < 1$ and efficiently so, since the pecking order is reversed $\frac{\kappa_2}{\kappa_1} > 1 > \frac{R^L}{\lambda}$. Therefore it is indeed socially optimal to liquidate the L-type LTT.

The L-type borrower's rollover problem is amplified if a funding shock, $f > 0$, realizes but the economics of collateral remain as described with no funding shock.

CCP market In the CCP market the effect of collateral depends on whether the H-type borrower is willing to pool with the L-type borrower. The L-type borrower is indifferent between liquidating and continuing the LTT since they obtain zero profit from either option.

Therefore, with $c_2' = R^L + \kappa_2$ and $\ell_1' = m$, the incentive compatibility constraint of the H-type is binding such that

$$R^H i_0 - c^P_2 \ell^P_1 + \kappa_2(k_0 - w^P_1) \geq R^H i_0 - c_2'\ell_1'\kappa_2 k_0 \tag{IA128}$$

$$\frac{R^L + \kappa_2 - f\frac{\kappa_2}{\kappa_1}}{1-f} \geq c^P_2. \tag{IA129}$$

with $i_0 = \ell_0 = m$ and $c_1 = 1$ and thus, for $0 \leq f \leq \kappa_1$, $z^P_1 = 0$ and $w^P_1 = \frac{f}{\kappa_1}m$ since $k_0\kappa_1 + \ell^P_1 \geq c_1\ell_0$. Note that $\frac{R^L+\kappa_2-1}{\kappa_2-\kappa_1}\kappa_1 > 0$ if $\kappa_2 > 1 - R^L$. The pecking order for the H-type is always intact, i.e. $\frac{R^H}{\lambda} \geq \frac{\kappa_2}{\kappa_1}$. Lenders are willing to provide a loan as long as

$$c^P_2 \geq 1 \tag{IA130}$$

$$\frac{R^L + \kappa_2 - 1}{\kappa_2 - \kappa_1}\kappa_1 \geq f. \tag{IA131}$$

If collateral is sufficiently valuable, $\kappa_2 > 1 - R^L$, then borrowers roll over their loans and liquidate collateral before the LTT. In case there is no collateral, $\kappa_t = 0$, borrowers have to liquidate the LTT, i.e. $z^P_1 = \frac{f}{\lambda}m$. Then, with $c_2' = R^L$ and $\ell_1' = m$, the incentive compatibility constraint of the H-type is binding such that

$$R^H(i_0 - z^P_1) - c^P_2\ell^P_1 \geq R^H i_0 - c_2'\ell_1' \tag{IA132}$$

$$\frac{R^L - R^H\frac{f}{\lambda}}{1-f} \geq c^P_2. \tag{IA133}$$

Borrowers never obtain a loan in the CCP market without collateral since for $R^L < 1$, $\frac{R^L - R^H\frac{f}{\lambda}}{1-f} < 1$.

To summarize, in the case of $1 > R^L > \lambda$, collateral helps to implement socially optimal rollover if $\kappa_2 > 1 - R^L$. It is the latter condition which determines the socially optimal level of collateral. Combining conditions $1 > R^L > \lambda$ and $\kappa_2 > 1 - R^L$, we require that the collateral value has to be sufficiently large, $\kappa_2 \geq 1 - \lambda$, to implement socially optimal rollover. If instead $1 > \lambda > R^L$, the optimal level of collateral is given by $R^L < 1 - \kappa_2$, such that $\kappa_2 < 1 - \lambda$. This level of collateral shuts down the CCP market and requires the H-type borrower to obtain funding elsewhere.

G Optimal market solution

G.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 $t=2$:

$$R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau \geq 0 \tag{IA134}$$
$$s.t. - c_1\ell_0 + \ell_1^H = 0 \tag{IA135}$$

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

$$R^L(i_0 - z_1^L) - c_2^L\ell_1^L + \kappa_2(k_0 - w_1^L) + \tau = 0 \tag{IA136}$$
$$s.t. - c_1\ell_0 + \ell_1^L + \kappa_1(w_1^L + w_1^H) + \lambda z_1^L = 0 \tag{IA137}$$

This yields

$$c_2^L = \frac{R^L(i_0 - z_1^L) + \kappa_2(k_0 - w_1^L) + \tau}{\ell_1^L} \tag{IA138}$$
$$z_1^L = \frac{c_1\ell_0 - \ell_1^L - \kappa_1(w_1^L + w_1^H)}{\lambda} \tag{IA139}$$

Note that the market rate is given by

$$R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \kappa_2(k_0 - w_1^L) = 0 \tag{IA140}$$
$$s.t. - c_1\ell_0 + \ell_1^L + \kappa_1 w_1^L + \lambda z_1^L = 0 \tag{IA141}$$

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

$$R^L i_0 - c_{2,f=0}^{OTC}\ell_{1,f=0}^L + \kappa_2 k_0 = 0 \tag{IA142}$$
$$s.t. - c_1\ell_0 + \ell_{1,f=0}^L = 0 \tag{IA143}$$

At $t=0$ expected borrower profit is

$$\begin{aligned}&\alpha\Big[\beta\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau - \kappa_0 k_0\big) - (1-\beta)\kappa_0 m\Big]\\ +&(1-\alpha)\Big[\beta\big(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H + (\kappa_2 - \kappa_0)k_0\big) - (1-\beta)\kappa_0 m\Big] \geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0\end{aligned} \tag{IA144}$$

To derive the transfer in case of default, consider $f > f^{OTC}$ such that $c_2^{OTC} = 1$. Then from expression (IA144), we obtain the maximum commitment borrowers are willing to make to the default fund:

$$\begin{aligned}\tau^{OPT} &= \frac{1}{\alpha\beta}\Bigg[\alpha\bigg(\beta((R^H - 1)m - \kappa_0 w_1^H) - (1-\beta)\kappa_0 m\bigg)\\ &\qquad + (1-\alpha)\bigg(\beta\big(R^H - R^L - \kappa_2\big) - (1-\beta)\kappa_0\bigg)m - (\beta R^H + (1-\beta)R^L - 1)\kappa_0 m\Bigg]\\ &= \frac{1}{\alpha\beta}\Big[\alpha\beta(R^H - 1) + (1-\alpha)\beta(R^H - R^L) - (\beta R^H + (1-\beta)R^L)\kappa_0 + \alpha\beta(1 - w_1^H)\kappa_0\Big]m\end{aligned} \tag{IA145}$$

The transfer decreases in the liquidation of the H-type's collateral, w_1^H. There is hence a tradeoff 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 $\frac{\beta(R^H-(\alpha+(1-\alpha)R^L))}{\beta R^H+(1-\beta)R^L} \geq \kappa_0$. 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 $t=1$.

G.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

$$\begin{aligned}
&\alpha\Big[\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau^{OPT} - \kappa_0 k_0 + c_2^{OTC}\ell_1^H - \ell_1^H + c_1\ell_0 - \ell_0\big) \\
&\quad + \big(R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \tau^{OPT} - \kappa_0 k_0 + c_2^{OTC}\ell_1^L - \ell_1^L + c_1\ell_0 - \ell_0\big)\Big] \\
&+(1-\alpha)\Big[\big(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H + (\kappa_2-\kappa_0)k_0 + c_{2,f=0}^{OTC}\ell_1^H - \ell_1^H + c_1\ell_0 - \ell_0\big) \\
&\quad + \big(R^L i_0 - c_{2,f=0}^{OTC}\ell_{1,f=0}^L(\kappa_2-\kappa_0)k_0 + c_{2,f=0}^{OTC}\ell_{1,f=0}^L - \ell_{1,f=0}^L + c_1\ell_0 - \ell_0\big)\Big]
\end{aligned} \tag{IA146}$$

$$\begin{aligned}
&= \alpha\Big[\big(R^H i_0 - \kappa_2 w_1^H - \ell_1^H\big) + \big(R^L(i_0 - z_1^L) - \kappa_0 k_0 - \ell_1^L\big)\Big] \\
&\quad +(1-\alpha)\Big[\big(R^H i_0 - \ell_1^H\big) + \big(R^L i_0 - \ell_{1,f=0}^L\big)\Big] && \text{(IA147)} \\
&= (R^H + R^L - 2)m - \alpha\Big(2fm(\frac{R^L}{\lambda} - 1) - \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})(w_1^H + m)\Big) && \text{(IA148)}
\end{aligned}$$

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

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

$$R^H i_0 - c_2^{OTC}\ell_1^H - \tau^{OPT} \geq 0 \tag{IA149}$$

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

G.3 Run threshold

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

Finally, we provide the condition up to which the L-type is able to repay second round lenders. Recall from expression (IA145) that τ^{OPT} is independent of f if $w_1^H = \{0, m\}$.

$$R^L(i_0 - z_1^L) - c_2^L\ell_1^L + \kappa_2(k_0 - w_1^L) + \tau^{OPT} = 0 \tag{IA150}$$

$$\frac{R^L-1}{R^L-\lambda}\frac{\lambda}{2} + \frac{R^L\kappa_1(w_1^H + w_1^L)}{2(R^L-\lambda)m} + \frac{\tau^{OPT}\lambda}{2(R^L-\lambda)m} \geq f \tag{IA151}$$

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

G.4 Ex-post welfare

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

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

$$\begin{aligned} &\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau^{OPT} - \kappa_0 k_0 + c_2^{OTC}\ell_1^H - \ell_1^H + c_1\ell_0 - \ell_0\big) \\ &\quad + \big(R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \tau^{OPT} - \kappa_0 k_0 + c_2^{OTC}\ell_1^L - \ell_1^L + c_1\ell_0 - \ell_0\big) \\ =&\big(R^H i_0 - \kappa_2 w_1^H - \ell_1^H\big) + \big(R^L(i_0 - z_1^L) - \kappa_0 k_0 - \ell_1^L\big) \\ s.t.& - c_1\ell_0 + \kappa_1(w_1^H + k_0) + \ell_1^L = 0. \end{aligned} \tag{IA152}$$

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

$$(R^H + R^L - 2)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m. \tag{IA153}$$

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

$$\begin{aligned} &\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau^{OPT} - \kappa_0 k_0 + c_2^{OTC}\ell_1^H - \ell_1^H + c_1\ell_0 - \ell_0\big) \\ &\quad + \big(R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \tau^{OPT} - \kappa_0 k_0 + c_2^{OTC}\ell_1^L - \ell_1^L + c_1\ell_0 - \ell_0\big) \\ =&\big(R^H i_0 - \kappa_2 k_0 - \ell_1^H\big) + \big(R^L(i_0 - z_1^L) - \kappa_0 k_0 - \ell_1^L\big) \\ s.t.& - c_1\ell_0 + 2\kappa_1 k_0 + \ell_1^L + \lambda z_1^L = 0. \end{aligned} \tag{IA154}$$

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

$$(R^H + R^L - 2)m - 2f(\frac{R^L}{\lambda} - 1)m + 2\kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m. \tag{IA155}$$

G.5 Run threshold comparison

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

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

Observe that $f^{OPT} > f_{DF}^{CCP}$ if $\frac{\beta(R^H-R^L)+2\alpha\beta(R^L+\kappa_1-1)}{\beta R^H+(1-\beta)R^L} > \kappa_0$.

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

G.6 OTC and default fund

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

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

$$(R^H + R^L - 2)m + \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1}) - 2f(\frac{R^L}{\lambda} - 1)m. \tag{IA156}$$

Observe that

$$W^{OPT} - W^{OPT}_{w_1^H=0} = \begin{cases} (\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})(\kappa_1 + 2f) & \text{if } \frac{\kappa_1}{2} < f \le \kappa_1 \\ (\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})\kappa_1 & \text{if } \kappa_1 < f \le f^{OPT} \end{cases} \tag{IA157}$$

G.7 Hybrid mechanism

To show that $f^{OPT}(w_1^H = 0) > f_{DF}^{CCP}$, we define a threshold $\bar{\tau}$ for which $f^{OPT}(w_1^H = 0) = f_{DF}^{CCP}$

$$\bar{\tau} = -\frac{(m(-2(\lambda - R^L)(-\beta R^H + (\beta + \kappa_0)R^L) + \alpha\beta(2\lambda(-1 + R^L) + (3 - 2\kappa_1 - 3R^L)R^L + R^H(-1 + 2\kappa_1 + R^L)))}{\alpha\beta(-2\lambda + R^H + R^L)}, \tag{IA158}$$

and then we show that $\tau^{OPT} > \bar{\tau}$ if

$$\beta > \frac{(R^H - R^L)(\kappa_0 R^L + beta(-R^H + R^L + \kappa_0(-2\lambda + R^H + R^L)))}{\alpha(2(R^H - R^L)(-1 + \kappa_1 + R^L) + \kappa_0(-2\lambda + R^H + R^L))}. \tag{IA159}$$