(In)efficient repo markets*

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Abstract

Repo markets suffer from funding misallocations and funding runs. We develop a rollover risk model with collateral to show how repo trading and clearing mechanisms can resolve these inefficiencies. In over-the-counter markets, non-anonymous trading prevents asset liquidations but causes runs on low-quality borrowers. In central-counterparty markets, anonymous trading provides insurance against small funding shocks but causes inefficient asset liquidations for large funding shocks. The privately optimal market structure requires central clearing with a two-tiered guarantee fund to insure against both illiquidity and insolvency. Our findings inform the policy debate on funding crises and explain empirical patterns of collateral premia.

JEL Classification: G01, G14, G21, G28

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

1 Introduction

Repo markets are an integral component of the financial plumbing of any modern economy (BIS, 2017). Repurchase agreements, or repos, are the primary source of short-term funding for long-term assets held by banks and shadow banks with outstanding repo volumes amounting to several trillion dollars in the U.S., Europe, and Asia (Gorton and Metrick, 2012; Copeland et al., 2014; Krishnamurthy et al., 2014).[1] Repo markets differ along three important dimensions: trading mechanism, clearing protocols, and collateral requirements. Some of these markets have experienced severe funding runs during the Great Financial Crisis (GFC) in 2008 (Brunnermeier, 2009; Mancini et al., 2016; Infante and Saravay, 2020), the repo blowup in September 2019[2] and the Covid-19 pandemic in March 2020 (Duffie, 2020). To avoid market collapse, the Federal Reserve and the ECB had to inject liquidity and implement collateral upgrades through their emergency facilities (Carlson and Macchiavelli, 2020). The recurrent funding crises have raised concerns among policy makers about the efficiency and resilience of repo markets, calling for structural reforms (Group of Thirty, 2022).

Repo markets suffer from two types of inefficiencies: misallocation of funding during normal periods and funding runs during crisis periods. In a model with rollover risk, safe collateral and asymmetric information about borrower quality, we compare existing repo market structures and show how different trading and clearing mechanisms determine the trade-off between the misallocation of funding and the resilience to runs. We focus on over-the-counter (OTC) markets with non-anonymous trading and bilateral clearing versus central counterparty (CCP) markets with anonymous trading and central clearing, but also consider hybrid trading and clearing protocols. We find that the welfare rankings between OTC and CCP repo markets switch repeatedly, unlike in previous maturity mismatch models (Bouvard et al., 2015), and depend on funding scarcity, collateral liquidity, and the severity of the maturity mismatch problem. Central to this result is a novel illiquidity-insurance channel through which collateral plays a dual role, improving fund-

[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.

ing allocation and resilience to runs. We characterize the privately optimal market solution which provides a benchmark to assess the welfare effect of different reform proposals. Current reform proposals improve welfare but do not achieve the privately optimal market solution (POMS). Central clearing with contract novation and a two-tiered guarantee fund that insures against illiquidity and insolvency implements the POMS. Our theory reconciles puzzling empirical evidence on collateral yields (He et al., 2022).

Figure 1 illustrates the repo market structures modelled in the paper. To capture the wide range of existing markets, we vary the repo trading protocol between non-anonymous trading in OTC markets and anonymous trading in central order book (COB) markets, affecting the degree of asymmetric information between repo traders.[3] We combine the repo trading protocol with bilateral clearing or central clearing. Bilaterally-cleared OTC trades are negotiated directly between borrowers and lenders that know each other's identity. Trading in COBs is anonymous and typically employs a central counterparty. Central clearing includes contract novation and a default fund. Novation is the legal process through which the CCP becomes the legal counterparty to both borrower and lender, which effectively allows the CCP to preclude lending to low-quality borrowers. A default fund makes market participants jointly liable to repay lenders. CCP markets combine anonymous trading with novation and default fund.[4] We also model alternative repo arrangements: COBs without novation resemble existing multilateral trading facilities (MTFs) with ex-post name give-up. Reform proposals by Duffie (2020) and Group of Thirty (2022) put forward a clearinghouse market structure that combines non-anonymous trading with central clearing.[5] Finally, we explore

[3]Our classification is not exhaustive but parsimoniously highlights important features of existing repo markets. OTC and CCP repo markets are the predominant market structures around the world. Trading in OTC repo markets such as (bilateral and triparty) U.S. customer repo segments is non-anonymous and clearing is bilateral. U.S. customer repo segments can be split into bilateral and triparty based on the settlement protocol. Bilateral repo is used when market participants want to interact directly with each other or if specific collateral is requested. Triparty is the preferred segment for general collateral funding given the efficiency gains from delegated collateral management. Triparty agents are not CCPs because they do not novate contracts and do not assume credit risk. In our model, the triparty market is effectively the same as the bilateral market.

[4]Important CCP markets are the U.S. interdealer markets (GCF Repo and FICC DVP) in which trades are executed through centralized platforms or interdealer brokers (e.g., BrokerTec), and the majority of European repo markets (e.g., Eurex, LCH.Clearnet, BrokerTec, and MTS). GFC Repo is a small part of the overall U.S. repo market (Baklanova et al., 2017).

[5]In clearinghouses, market participants execute trades non-anonymously, e.g., request-for-quote platforms (BrokerTec Quote, Tradeweb AiEX), and then have them centrally cleared. Recent reform proposals (Duffie, 2020; Group of Thirty, 2022) argue for central clearing of bilaterally negotiated Treasury repos.

Trading \ Clearing	**direct**	**central**
non-anonymous	OTC repo market (bilateral & tri-party U.S. customer repo)	Clearinghouse (reform proposals, e.g., Duffie (2020); Group of Thirty (2022))
anonymous	COB without novation (MTFs with ex-post name give-up)	CCP = COB + novation + default fund (GCF Repo & FICC DVP via, e.g., BrokerTec, EUREX, LCH.Clearnet)

Figure 1: Classification of repo trading and clearing mechanisms.

hybrid trading protocols where the mechanism switches depending on funding tightness and trade regulations in OTC and CCP markets.

In the model, borrowers (cash-strapped banks or shadow banks) have risky long-term assets and safe assets which they can use as additional collateral. They finance risky long-term assets through short-term collateralized loans (Brunnermeier and Oehmke, 2013).[6] At an intermediate stage, when borrowers have to roll over initial loans, they privately observe their long-term assets' quality and they face a publicly observable aggregate funding shock. For resource allocation to matter, we focus on the case in which borrowers turn out to have heterogeneous asset quality. To repay initial loans, borrowers employ a pecking order in which they prioritize new loans and collateral liquidation over early asset liquidation. There are two benchmarks in the model: *(i)* the socially optimal market structure (SOMS) highlights the benefits of two types of transfers, *(ii)* the privately optimal market structure (POMS) defines a repo market that is privately optimal and welfare maximizing (Kadan et al., 2017), that is, agents optimize given their private constraints and market rules.[7] Equipped with these benchmarks, we derive three main results.

The first main result is that repo trading and clearing mechanisms determine both the efficiency of funding allocations and the resilience to funding crises as captured by the endogenous thresholds at which incentive-based runs occur. Our theory predicts that existing repo markets, including

[6]Long-term assets capture borrowers' balance sheet items with maturity larger than that of repos. Typical maturities of repos are a few days.

[7]Note that the POMS differs from the second best in which agents optimize given their private constraints only.

non-anonymous OTC repo markets and anonymous CCPs, allocate funding inefficiently and their welfare rankings switch repeatedly depending on funding scarcity. When funding shocks are small, anonymous trading and collateral provide illiquidity insurance by pooling heterogeneous borrowers. Collateral thus provides insurance against illiquidity at the roll-over stage by preventing fire sales in anonymous repo markets. This illiquidity-insurance channel is absent in non-anonymous repo markets. Discriminatory pricing in non-anonymous OTC trading forces inefficient fire sales of assets. As a consequence, anonymous repo markets provide more efficient funding allocations than non-anonymous repo markets for small funding shocks. For intermediate funding shocks, pooling heterogeneous borrowers in anonymous trading forces inefficient liquidation of high-quality assets whereas discriminatory pricing in non-anonymous trading efficiently liquidates low-quality assets only. As a result, anonymous repo markets provide less efficient funding allocations than non-anonymous repo markets for intermediate funding shocks.

Our theory also predicts that repo market structures differ in their resilience to large funding shocks. The two types of funding runs that can occur in the model have different welfare costs. A narrow run on low-quality borrowers occurs in non-anonymous markets. The insurance effect allows anonymous repo markets to withstand larger funding shocks than non-anonymous repo markets. However, in anonymous repo markets a systemic run on all borrowers leads to market breakdown when funding shocks are large. By novating repo contracts the CCP effectively precludes lending to low quality borrowers and thereby prevents systemic runs, improving both resilience and efficiency. An appropriately endowed default fund further increases the market's run resilience because it allows for privately optimal profit transfers from high to low quality borrowers. In sum, anonymous repo markets provide illiquidity insurance for small funding shocks but fail to do so for intermediate funding shocks. In contrast, non-anonymous repo markets force fire sales of low-quality assets for small funding shocks but prevent fire sales of high-quality assets for intermediate funding shocks. Central clearing in CCP markets improves efficiency and can prevent systemic runs, further increasing resilience. However, none of the two markets yield a POMS.

The second main result is that current reform proposals to trading and clearing mechanisms improve welfare but do not achieve the POMS. The reason is the lack of a collateral transfer in case a borrower becomes illiquid. Central clearing of bilaterally negotiated trades in OTC markets increases resilience against narrow runs and improves financial stability, which provides theoretical support for the reform proposal by Duffie (2020) and Group of Thirty (2022). Alternatively, a liquidity-contingent trading mechanism in CCPs makes asset liquidation more efficient. Anonymous trading in CCP markets during normal times needs to switch to non-anonymous trading when funding becomes tight. Such a hybrid trading mechanism is similar to the downstairs/upstairs market system in equity markets (Burdett and O'Hara, 1987; Seppi, 1990; Grossman, 1992), with the novelty that the switch occurs contingent on aggregate funding conditions. An alternative to repo market reforms are trading regulations. We study *(i)* a floor on CCP trading, *(ii)* a cap on OTC trading with CCP present, or *(iii)* a CCP shutdown and a cap on OTC trading. Trading caps and floors improve upon existing markets but do not attain the POMS.

The third main result characterizes a novel market structure that achieves the POMS. This solution is implemented through a *two-tiered guarantee fund* consisting of *(i)* a liquidity fund to protect against fire sales in case of illiquidity and *(ii)* a default fund to cover losses in case of insolvency. The two-tiered guarantee fund can replace ex-post collateral upgrades by central banks during crisis periods. The key problem with existing repo markets is that collateral becomes inadvertently misallocated across heterogeneous borrowers when funding is scarce. The POMS requires a collateral transfer in case of borrower illiquidity and a profit transfer in case of insolvency—the two-tiered guarantee fund. Market participants are required to contribute ex-ante to the two types of funds. We highlight alternative implementations through collateral swaps between borrower banks, or ex-post collateral upgrades. The collateral transfer scheme is a private market solution that resembles, yet avoids, the collateral upgrades implemented by the ECB and Federal Reserve through their emergency facilities (Carlson and Macchiavelli, 2020).

Finally, the model delivers a number of empirical predictions. Collateral has a skin-in-the-game effect that aligns private and social incentives when it comes to liquidation of long-term assets. Collateral quality positively impacts market resilience and more so in CCP than OTC markets. The collateral convenience yield (He et al., 2022) hence varies with funding scarcity depending on market structure. Moreover, the resilience ranking derived in our model 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 whereas during the 2019/20 blowups, funding dried up but asset liquidity was hardly affected. In line with the empirical evidence, our model predicts that the OTC market is more susceptible to runs than the CCP market when a funding shock occurs and asset liquidity is low, whereas the CCP market is more prone to runs when asset liquidity remains unaffected.

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

In the optimal opacity literature, our model differs from Dang et al. (2017) because in their setting 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 differ from their analysis by allowing for scarce funding such that the economy's endowment is insufficient to fully fund both consumption needs and investment. We show that anonymity in the CCP market in the presence of scarce funding has important welfare effects arising from the efficiency-resilience trade-off.

In line with the literature building on Diamond and Dybvig (1983), we consider risk about borrowers' liability side.[8] 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) introduce 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.

Martin et al. (2014a,b) and Heider et al. (2015) study the breakdown of interbank markets. Martin et al. (2014a,b) show that non-anonymous triparty repo markets are subject to runs while bilateral repo markets suffer from drawn out losses of funding and eventual collapse. In their model runs occur due to coordination failure in a model with homogeneous borrower quality. Heider et al. (2015) study the adverse-selection problem of unsecured loans in anonymous markets. By contrast, we vary the information environment and 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 highlight how the trade-off between market resilience and resource allocation depends on asymmetric information and funding scarcity.

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, 2021) study optimal risk sharing in derivatives markets and show that novation in CCP markets and optimal margin requirements can provide insurance against counterparty risk. These papers focus on the role of derivatives markets in risk sharing. Our paper focuses on lending markets and their ability to allocate funding efficiently while providing financial stability. In addition, we highlight the different roles played by anonymity, collateral, and contractual features such as novation and guarantee funds.

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

We also contribute to the literature on collateral value (Oehmke, 2014; Parlatore, 2019; Gottardi et al., 2019). Collateral plays a dual role in our model, as liquid collateral improves both efficiency and resilience independent of repo market structure. However, collateral impacts OTC and CCP markets differently. When the borrower's long-term assets are 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 fact that CCPs often impose stringent collateral requirements. The convenience yield on collateral stems from its usage as collateral. In our model, the convenience yield can switch 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 scarcity. This prediction is consistent with the different empirical patterns of collateral convenience yields observed during the GFC and Covid-19 pandemic (He et al., 2022).

Finally, we generate incentive-based runs due to a combination of asset illiquidity, collateral, and counterparty risk under asymmetric information. Infante and Vardoulakis (2021) and Kuong (2021) obtain runs under different mechanisms. Infante and Vardoulakis (2021) show that, when borrowers internalize the risk of losing collateral in case of lender default, borrowers withdraw it which causes a collateral run on lenders. Kuong (2021) shows in a global games model with moral hazard how, notwithstanding collateral, runs can occur. These modelling approaches are complementary. In our model, runs are on borrowers and collateral aligns private with social incentives.

The remainder of the paper is organized as follows. Section 2 describes the model. Section 3 derives the socially optimal and the privately optimal market solutions. Section 4 compares anonymous to non-anonymous trading in repo markets. Section 5 analyses the different clearing mechanisms. Section 6 explores the optimal repo market and possible reforms and regulations. Section 7 shows the effects of collateral quality and funding scarcity and provides empirical predictions. Section 8 concludes. All proofs are contained in the appendix.

2 Model

Consider an economy with two rounds of short-term lending at $t = 0, 1$ and terminal date $t = 2$. There are two types $\omega \in \{L, H\}$ of ex-ante identical, ex-post heterogeneous borrowers and two generations of a finite mass of identical lenders subject to an aggregate funding shock $f \in [0, \frac{1}{2})$.[9] The borrower type is private information and reflects borrowers' quality of risky assets on their balance sheet while the funding shock that captures lenders' margin calls, fund outflows, and balance sheet constraints is publicly observable. All agents in the economy are risk neutral and there is no discounting. Figure 2 summarizes the sequence of events. At $t = 0$, borrowers seek one-period loans to invest in a long-term technology (LTT). At $t = 1$, lenders are subject to the funding shock and borrowers and lenders take the rollover decision on maturing first-period loans. Second-period loans mature and payoffs from the LTT realize at $t = 2$.

Agents and assets. The two generations of finite mass $2m$ identical lenders have unit endowment of cash per lender. Lenders are present in the market for one period, entering at $t = \{0, 1\}$ and exiting at $t + 1$. Upon exit, lenders consume both their initial endowment and investment return c_{t+1}. Second-round lenders are subject to the random funding shock f that has a distribution known to all agents at $t = 0$.[10] With probability $(1 - \alpha)$ the funding shock is $f = 0$ and with probability α the funding shock is $f > 0$.[11] The larger the funding shock, f, the larger the difference between the funding available at the investment stage, $t = 0$, and the rollover stage $t = 1$, requiring $2(1 - f)m < 2m$.

Asymmetric information about borrower type is one source of risk in our model. To capture how it interacts with collateral and repo market structure, we assume the LTT's quality is borrowers' private information and they learn it over time. The timing is as follows: At $t = 0$, agents know

[9] Cash-strapped banks and non-bank financial institutions such as hedge funds are typical borrowers in the repo market. Cash-rich banks, money-market funds, and other institutional investors are typical lenders.

[10] 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.

[11] The Postlewaite and Vives (1987) critique of Diamond and Dybvig (1983) says a bank run is not part of the equilibrium which features the socially optimal market 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. We show under which conditions the equilibria with and without run, respectively, attain the socially optimal market solution.

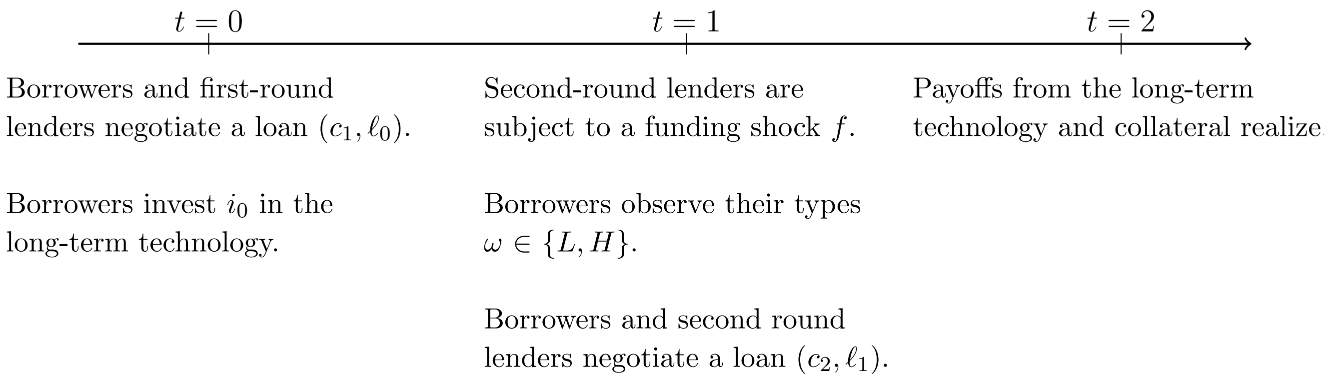

Figure 2: Timeline.

there will be a high-type R^H with probability β and a low-type borrower R^L with the probability $1-\beta$. We study the relevant case in which the two borrowers turn out to be of opposite type. If borrowers were of identical type, resource allocation would be irrelevant. At the investment stage, $t = 0$, each borrower invests i_0 in the LTT yielding a gross return R^ω at $t = 2$ depending on type $\omega \in \{L, H\}$. At $t = 1$, borrowers learn their type R^ω. Early liquidation of the LTT is costly and yields $\lambda < 1$ per unit of investment. At $t = 2$, payoffs from the long-term technology realize.

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

Repo loans are collateralized. Each borrower has a collateral endowment of $k_0 = m$ at $t = 0$. The value of collateral is given by κ_t per unit of collateral at $t = \{0, 1, 2\}$. We assume that $\kappa_1 \leq \kappa_0$ and $\kappa_2 = \kappa_0$, that is, there are collateral liquidation costs at $t = 1$ while the long-term return on collateral is normalized to zero.[12] Repo haircuts are given by the relative difference between collateral value and loan value, i.e., $\frac{\kappa_t k_t}{\ell_t} - 1$. 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.

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

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 $i_0 \leq \ell_0$. At $t = 1$, borrowers need to roll over maturing loans. For most of the analysis we consider the case in which at least one borrower can fully roll over their initial loan. This is formalised in the following assumption.

Assumption 2 *We restrict the funding shock such that resource allocation matters* $2(1-f)m \geq m$.

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 $w_1 \leq k_0$ 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 3 *The opportunity cost from liquidating the LTT is larger than the opportunity cost from liquidating collateral,* $\frac{R^L}{\lambda} \geq \frac{\kappa_2}{\kappa_1} \geq 1$.

Assumption 3 establishes a pecking order in which assets are liquidated. At the rollover stage, it is always cheaper to liquidate collateral than the LTT. While Assumption 3 encompasses negative net present value (NPV) projects, to help intuition consider positive NPV projects, i.e., $R^H > R^L \geq 1 > \lambda$. We come back to negative NPV projects in Section 7.3.

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.[13]

[13]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.

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

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

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

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

The continuation value is the left-hand side (LHS) of (2). The gross return R^ω of the LTT is scaled by $(i_0 - z_1)$. The latter is the amount that is still invested in the technology after liquidation. Borrowers have to repay $c_2 \ell_1$ to second-round lenders that require a gross return of $c_2 \geq 1$. The gross return from collateral after partial liquidation amounts to $\kappa_2(k_0 - w_1)$. Alternatively, borrowers can default on the initial loan which causes liquidation of their assets and yields, by Assumption 4 and limited liability, a value of zero, which is the right-hand side (RHS) of (2). Observe that the return in our model is scalable $R^\omega(i_0 - z_1)$ whereas Bouvard et al. (2015) consider a fixed return. This subtle but important difference in production functions reverses some of the results of Bouvard et al. (2015). From the repayment condition (1) and borrowers' continuation value in (2) note, 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, the liquidation cost, and it carries an opportunity cost from foregone profits $R^\omega - 1$ and $\kappa_2 - \kappa_0$. Considering both liquidation cost and opportunity cost of assets creates a trade-off between different asset types and is absent in a fixed investment model.

Run type and repo market structure. The repo trading mechanism impacts the information environment at the rollover stage which determines the run type. 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 borrower for funding shocks $f \in (f^{Narrow}, \frac{1}{2})$. A systemic run is an equilibrium in which second-round lenders refuse to provide loans to any borrower for funding shocks $f \in (f^{Systemic}, \frac{1}{2})$.*

In the OTC market in Section 4.1, we assume that due to the non-anonymous nature of trading there is no information asymmetry about borrower type and, hence, lenders are able to condition loan terms on borrower type, $(c_2^{\omega}, \ell_1^{\omega})$, $\omega \in \{L, H\}$. As a consequence, only a narrow run is part of the set of equilibria in the OTC market. In the COB market in Section 4.2, we assume there is asymmetric information about the borrower type and characterize Perfect Bayesian Equilibria. We focus on the pooling equilibrium in which borrowers and lenders contract on gross loan rate and loan amount (c_2^P, ℓ_1^P). As a consequence, a systemic run or a narrow run are possible equilibrium outcomes in a COB market depending on the clearing mechanism. In Sections 5 we consider several clearing mechanisms: Bilateral and central clearing in OTC markets, and central clearing in CCPs with novation, default fund, and collateral fund. In addition to anonymous and non-anonymous trading mechanism, in Section 6 we investigate alternative trading protocols, we allow for simultaneous trading on both CCP and OTC markets, and we explore whether regulators should impose a floor on CCP trading, a cap on OTC trading, or both.

Discussion: Anonymous trading and asymmetric information. In non-anonymous OTC market knowing the counterparty's identity reduces asymmetric information with respect to anonymous CCP markets in which the counterparty's identity is unknown. It is important to note that 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. In Appendix D we consider a setup in which after learning the counterparty's identity there is still residual counterparty risk. The results from the simpler model, in the main text, without residual counterparty risk carry over. For our results to hold we simply need an information wedge between OTC and COB markets.

3 Repo Market Structure: Efficiency vs. Resilience

We start by deriving the socially optimal market solution (SOMS) from the perspective of a social planner, regulator, or central bank in Section 3.1, and the privately optimal market structure (POMS) that does not rely on government intervention in Section 3.2. The results in this section highlight the tradeoff between efficiency and resilience in repo markets and, in particular, the need for two types of transfers, a collateral transfer at $t = 1$ and a profit transfer at $t = 2$, as part of the privately optimal market structure. While the profit transfer is already a feature of existing central clearing mechanisms, implemented through a default fund, the collateral transfer is an innovation that we discuss further in Section 6.

3.1 Socially optimal market solution with two types of transfers

In the SOMS a social planner observes borrower types and is bound to repay first-round lenders. Welfare could be further maximized by not repaying first-round lenders or allowing for an external liquidity injection by, e.g., a central bank, because this would effectively eliminate the maturity mismatch problem and allow borrowers to continue the LTT to maturity.

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, $c_1 \geq 1$. With a positive expected return from the long-term technology, borrowers invest the entire loan amount in the LTT, $i_0 = \ell_0$. From a welfare perspective, it is optimal to give zero profit to first-round lenders, $c_1 = 1$, as it reduces the funding required at the rollover stage.[14] The social planner maximizes ex-ante net welfare as of $t = 0$. Taking a loan and investing it in the LTT, $i_0 = \ell_0 = m$, must weakly exceed ex-ante welfare from liquidating collateral and investing the proceeds in the LTT. Note, liquidating collateral and investing in the LTT generates larger net welfare than merely holding collateral to maturity.

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

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

The pecking order dictates that the social planner first liquidates the collateral of both borrowers,

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

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

To derive the largest funding shock that an economy with social planner can withstand, there are two cases to consider depending on collateral return relative to funding shock:

Case 1: If $0 < f \leq \kappa_1$, there is enough collateral to make up for the missing funding from second-round lenders. First-round lenders are repaid with a mix of new loans and collateral, $-2c_1\ell_0 + \ell_1^H + \ell_1^L + 2\kappa_1 w_1 = 0$, which yields

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

The larger the funding shock, the more collateral w_1 has to be liquidated. The effect is amplified by less liquid collateral, that is, if κ_1 is smaller.

Case 2: If $\kappa_1 < f \leq \frac{1}{2}$, borrowers' collateral is exhausted and the social planner has to liquidate the L-type LTT. Then the repayment condition yields the amount of liquidation of the L-type LTT, $-2c_1\ell_0 + \ell_1^H + \ell_1^L + 2\kappa_1 k_0 + \lambda z_1^L = 0$, which yields

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

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

We can now state the maximum funding shock the SOMS can withstand which is attained when welfare is zero. This determines the funding shock at which all collateral is liquidated, and part of the L-type LTT and the H-type's profit are used up.

Proposition 1 (SOMS 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*

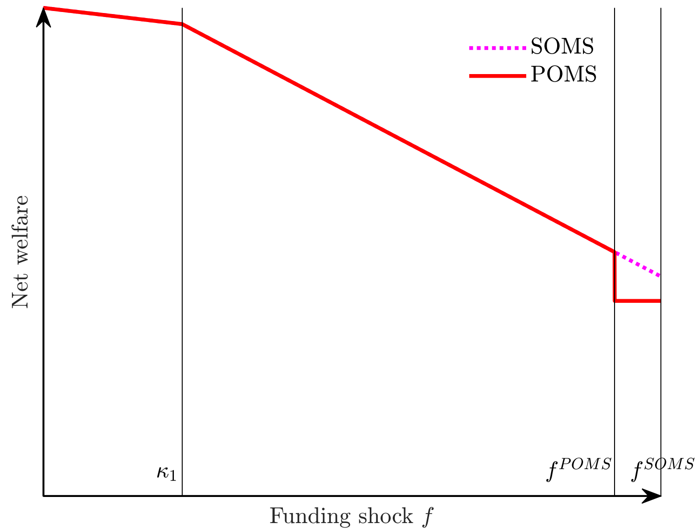

Figure 3: Socially optimal and privately optimal welfare and run thresholds.

funding shock that the economy can withstand is

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

Ex-post welfare conditional on the funding shock is

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

Figure 3 displays the socially optimal market welfare as a function of the funding shock f. For $0 \le f \le \kappa_1$ in (7), welfare decreases in the size of the funding shock but less so the smaller the difference between the collateral's liquidation value κ_1 and the collateral's value at maturity κ_2. For $\kappa_1 < f \le f^{SOMS}$ in (7), the intermediate collateral value κ_1 helps to preserve the LTT and the positive value is reflected in the expression $\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1}$ which is strictly positive by the pecking order in Assumption 3. Ex-post welfare decreases in the funding shock and the more so the larger the foregone profit of liquidating the L-type LTT, $(\frac{R^L}{\lambda} - 1)$.

3.2 Privately optimal repo market structure

Recall from the SOMS that the social planner implements two transfers from the H-type to the L-type: a collateral transfer at $t = 1$ and a profit transfer at $t = 2$. The POMS also implements two types of transfers but not to the same magnitude as the SOMS.

At $t = 0$, borrowers commit to a transfer τ^{POMS} that amounts up to their expected net profit. Borrowers take into account that the transfer is due if they turn out to be of H-type, and the funding shock has depleted the L-type's repayment capacity consisting of *(i)* second-round loan and collateral or *(ii)* second-round loan, collateral and LTT. Naturally, for case *(ii)* to occur the funding shock has to be larger than in case *(i)*.

The transfer is split into two payments: A collateral transfer w_1^H at $t = 1$ to repay first-round lenders once the L-type has run out of collateral, and a profit transfer τ^{POMS} at $t = 2$ to subsidize L-type's repayment of second-round lenders. By transferring the H-type's collateral w_1^H at $t = 1$, the POMS achieves allocative efficiency identical to the SOMS.[15] The profit transfer τ^{POMS} from the H-type to the L-type at $t = 2$, increases the latter's repayment capacity so that second-round lenders at $t = 1$ are willing to provide loans even to the L-type. As a result, the profit transfer increases the market's run resilience. We state now the first main result.

Theorem 1 (Privately optimal market solution) *The privately optimal market solution implements the socially optimal market solution, but only for* $0 < f \leq f^{POMS}$*, with run threshold*

$$f^{POMS} = \frac{R^L - 1}{R^L - \lambda}\frac{\lambda}{2} + \frac{R^L \kappa_1 (w_1^H + k_0)}{2(R^L - \lambda)m} + \frac{\tau^{POMS}\lambda}{2(R^L - \lambda)m} \tag{8}$$

where $w_1^H = [0, k_0]$ *and the ex-ante committed total transfer is equal to*

$$\tau^{POMS} = \frac{m}{\alpha\beta}[\alpha\beta(R^H - 1) + (1-\alpha)\beta(R^H - R^L) - (\beta R^H + (1-\beta)R^L - \alpha\beta(1 - w_1^H))\kappa_0]. \tag{9}$$

The payouts of the total transfer occur through:

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

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

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

Ex-post welfare conditional on the funding shock is

$$W^{POMS} = \begin{cases} (R^H + R^L - 2)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m & \text{if } 0 \leq f \leq \kappa_1, \\ (R^H + R^L - 2)m + 2\kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m - 2f(\frac{R^L}{\lambda} - 1)m & \text{if } \kappa_1 < f \leq f^{POMS}, \\ (R^H + \lambda + \kappa_1 - \kappa_2 - 2)m & \text{if } f^{POMS} < f \leq f^{SOMS}. \end{cases} \tag{10}$$

While the profit transfer is already a feature of existing central clearing mechanisms, implemented through a default fund, the collateral transfer is an innovation that we discuss further when we study reforms and regulations in Section 6. The collateral transfer is implemented when the collateral of the L-type is used up, i.e., $w_1^L = k_0$. Then the H-type's collateral is liquidated, $w_1^H = k_0$, to prevent the liquidation of the L-type LTT, an improvement in allocative efficiency due to the pecking order. The maximum run threshold attainable in case of the collateral transfer is $f^{POMS}|_{\tau^{POMS}=0} = \frac{R^L-1}{R^L-\lambda}\frac{\lambda}{2} + \frac{R^L\kappa_1}{(R^L-\lambda)}$. The profit transfer leaves allocative efficiency unaffected since the effective transfer takes place after the realization of the LTT. The profit transfer maximizes the run resilience because it increases the L-type's repayment capacity.

The welfare and run threshold comparison from Theorem 1 are depicted in Figure 3 as a function of the funding shock f. Theorem 1 confirms that resilience is strictly larger in the SOMS than in the POMS, $f^{SOMS} > f^{POMS}$, because the privately optimal transfer at $t = 2$ does not attain the socially optimal transfer. Intuitively, the profit transfer in the SOMS is larger than in the POMS because it is the realised, rather than the expected, profit to be transferred from the H-type to the L-type borrower. Beyond the threshold f^{POMS}, it is optimal to preclude the L-type borrower from funding so as to continue the H-type's LTT. This implies that both the L-type's collateral and LTT are liquidated before maturity which comes at a welfare cost.

4 Repo Trading Mechanisms

This section studies the impact of the trading mechanisms in OTC and COB markets on resource allocation, resilience to funding shocks, and welfare. We focus on comparing the main existing repo trading mechanisms and explore whether they implement the privately optimal repo market structure derived in Section 3.2. In the non-anonymous OTC market we derive the constrained POMS without collateral and profit transfers. In the anonymous COB market we derive a Perfect Bayesian equilibrium and focus on the pooling equilibrium in which the two borrowers obtain the same loan terms as a distinguishing outcome of COB markets.

We focus on the pooling equilibrium for several reasons. First, we show that for the relevant parameter space the pooling equilibrium welfare dominates the separating equilibrium (Appendix G). Second, CCPs, which are profit maximizing entities, have an incentive to coordinate the market on the pooling equilibrium because it generates the largest welfare. By appropriating a percentage fee of the total repo volume, maximizing welfare is equivalent to the CCP maximizing fee revenue. The decision by CCPs to have participants trade anonymously can be viewed as an effort to coordinate on the pooling equilibrium, maximizing welfare and CCPs' profit. Third, the nature of existing COB markets is such that borrowers tend to split repo contracts in several tranches. Consequently, borrowers are not able to signal their types through contracts.[16] Below, we characterize run thresholds, lending terms, and welfare for OTC markets in Section 4.1 and for COB markets in Section 4.2.

4.1 OTC market: Loans, run threshold, and welfare

Lenders in the OTC market observe borrowers' identity, i.e., there is no asymmetric information, and hence can condition their loan terms on 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 efficient solution. The constrained efficient solution deviates from the POMS solution in Section 3.2, insofar as there are no collateral and profit transfers.

[16]In theory, a separating equilibrium may exist and we derive it in Appendix H.

The run threshold f^{OTC} is the largest funding shock up to which both borrower types are able to repay their loans $c_1\ell_0$, at the rollover stage $t = 1$, to first-round lenders. Beyond this threshold only the H-type continues to obtain funding from second-round lenders whereas the L-type borrower is refused further loans. The L-type therefore defaults on the loans from first-round lenders and they obtain the L-type's liquidation value $c_1^D\ell_0$. If no funding shocks occur, both borrowers repay their initial loans.

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

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{OTC}, \\ \alpha(\beta c_{1,f>f^{OTC}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{OTC}} & \text{if } f > f^{OTC}. \end{cases} \tag{11}$$

The IR constraint (11) is from a single lender's perspective and, therefore, the conditions are expressed per unit of loan. We differentiate between the gross loan rate c_1 for $f \leq f^{OTC}$ and the gross loan rate $c_{1,f>f^{OTC}}$ for $f > f^{OTC}$. With borrowers holding the bargaining power at $t = 0$, expression (11) holds with equality.[17] 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, if the expected return from the former is weakly larger than the return from the latter.[18] We come back to the optimality of using loans instead of liquidating collateral when we discuss the collateral convenience yield in Section 7.2.

At $t = 1$, borrowers' individual rationality constraint reflects the cash-flow as described in (2)

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

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

conditional on borrower type and subject to the repayment condition of first-round lenders:[19]

$$\text{Borrower IR:} \qquad R^{\omega}(i_0 - z_1^{\omega}) - c_2^{\omega}\ell_1^{\omega} + \kappa_2(k_0 - w_1^{\omega}) \geq 0, \tag{12}$$

$$s.t. \quad -c_1\ell_0 + \ell_1^{\omega} + w_1^{\omega}\kappa_1 + z_1^{\omega}\lambda = 0. \tag{13}$$

Last, the model is about scarcity of funding at the rollover stage. To capture this effect in the loan terms, we make the additional assumption that borrowers compete for funding by setting interest rates at $t = 1$ à la Bertrand.[20] Lenders set interest rates at $t = 1$ by take-it-or-leave-it offers to perfectly competitive borrowers. Loan contracts are then

$$c_2^{OTC} = c_2^H = c_2^L = \frac{R^L(i_0 - z_1^L) + \kappa_2(k_0 - w_1^L)}{\ell_1^L}, \tag{14}$$

$$\ell_1^H = c_1\ell_0, \quad \ell_1^L = 2(1-f)m - \ell_1^H. \tag{15}$$

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 (14). 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, $2(1-f)m \geq m$. 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 IR constraint has to be satisfied.

$$\text{Lender IR:} \qquad c_2^{OTC} \geq 1. \tag{16}$$

When lenders decide on offering a loan, they contemplate the loan rate given by the L-type's break-even condition in (14). In particular, observing the size of the funding shock, lenders know how

[19]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 (12), is zero due to limited liability.
[20]While borrower competition at $t = 1$ seems to be the natural assumption, the assumption on the distribution of bargaining power can be relaxed without affecting the main results.

much collateral and LTT has been liquidated. This in turn implies that 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 uses up the collateral and in addition they have to partially liquidate their 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}. For large funding shocks $f > f^{OTC}$, lenders do not provide loans to the L-type borrower. First-round lenders do not require a risk premium as long as $f \leq f^{OTC}$, and from (11) we obtain $c_1 = 1$. The following proposition summarizes the OTC market equilibrium depending on the realization of the funding shock f.[21]

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

$$f^{OTC} = \frac{R^L - 1}{R^L - \lambda}\frac{\lambda}{2} + \frac{R^L}{R^L - \lambda}\frac{\kappa_1}{2}. \tag{17}$$

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.*

The run threshold f^{OTC} is increasing in the liquidity of collateral, $\kappa_1 > 0$, according to (17). While the threshold decreases in the opportunity cost of liquidating the LTT, $R^L - \lambda$, it increases in the returns from the LTT both at the rollover stage, λ, and at maturity, R^L.

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

4.2 COB market: Loans, run threshold, and welfare

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

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

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{COB}, \\ \alpha c_1^D + (1-\alpha)c_{1,f>f^{COB}} & \text{if } f > f^{COB}. \end{cases} \tag{18}$$

With borrowers holding the bargaining power at $t = 0$, expression (18) is binding. Borrowers compute the expected profit at $t = 0$ taking into account the distributions of funding shock and LTT quality. They finance the LTT with loans, $i_0 = \ell_0$, instead of liquidating collateral.[22]

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

$$Pr(R^H|c_2) = \begin{cases} \beta & \text{if } c_2 = c_2^P, \\ 1 & \text{otherwise.} \end{cases} \tag{19}$$

On the equilibrium path, lenders cannot infer types from the loan contract and keep their prior

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

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 (Cho and Kreps, 1987).

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

$$\text{Borrower IR:} \qquad R^{\omega}(i_0 - z_1^P) - c_2^P \ell_1^P + \kappa_2(k_0 - w_1^P) \geq 0 \tag{20}$$

$$s.t. \quad -c_1\ell_0 + \ell_1^P + \lambda z_1^P + \kappa_1 w_1^P = 0. \tag{21}$$

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

$$\text{Borrower IC:} \quad R^{\omega}(i_0 - z_1^P) - c_2^P \ell_1^P + \kappa_2(k_0 - w_1^P) \geq R^{\omega}(i_0 - z_1') - c_2'\ell_1' + \kappa_2(k_0 - w_1'). \tag{22}$$

The LHS of (22) represents the equilibrium payoff of borrower type ω and the RHS of (22) represents the off-equilibrium payoff. The latter is determined by lenders' beliefs given by (19). The off-equilibrium belief prescribes that lenders believe to face the H-type when observing a deviation ($c_2' = R^L + \kappa_2, \ell_1' = c_1\ell_0$).[23] The off-equilibrium repayment condition yields that neither LTT nor collateral have to be liquidated, i.e., $z_1' = 0$ and $w_1' = 0$. Second-round lenders require at least their initial investment back, which yields

$$\text{Lender IR:} \qquad c_2^P \geq 1. \tag{23}$$

As long as lenders' IR constraint (23) is satisfied, they provide their entire cash endowment as loans. Lenders take into account the size of the funding shock when deciding on providing a loan. Knowing the size of the funding shock, lenders anticipate how much collateral and LTT have been liquidated which, in turn, implies lenders know how much the L-type borrower is able to repay at $t = 2$. Since they cannot condition on borrower types, lenders offer a one-fits-all loan that amounts to half of

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

the cash endowment of the economy, $\ell_1^P = (1-f)m$, for any size of funding shock up to the run threshold, $0 \leq f \leq f^{COB}$. Lenders' break-even condition pins down the run threshold f^{COB}, i.e., when (23) holds with equality. The following proposition summarizes the COB market equilibrium depending on the realization of the funding shock f.

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

$$f^{COB} = \frac{R^L - 1}{R^H - \lambda}\,\lambda + \frac{R^H}{R^H - \lambda}\,\kappa_1. \tag{24}$$

Borrowers' strategy depends on the size of the funding shock:

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

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

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

In case *(i)* of Proposition 3 borrowers have to liquidate their collateral. Since both borrowers bear the funding shock, unlike in the OTC market, the economy's entire collateral is used up before any borrower has to start liquidating the LTT. This is welfare optimal due to the pecking order of collateral and LTT. In case *(ii)* both borrowers liquidate all of their collateral and a part of their LTT. Liquidating the H-type LTT, instead of liquidating only the L-type LTT as in the OTC market, is costly from a welfare perspective. To determine the run threshold f^{COB} for $\kappa_1 < f$, lenders consider the loan rate c_2^P pinned down by the H-type's incentive compatibility constraint (22). It is the largest rate borrowers are willing to pay in a pooling equilibrium.[24] In case *(iii)*, second-round lenders stop providing loans altogether, a systemic run.

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

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

4.3 Comparison between OTC and COB market

In this section, we rank OTC and COB markets in terms of welfare and compare them to SOMS. As a preliminary step, we compare run thresholds.

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

The run threshold in the SOMS is largest since the social planner redistributes, for small funding shocks, collateral from liquid (H-type) to illiquid (L-type) borrower and, for large funding shocks, the return from risky assets from the solvent (H-type) to the insolvent (L-type) borrower. The difference between the run thresholds in the COB market and the OTC market arises because in the former the L-type borrower is implicitly insured by the H-type borrower via the loan contract. The L-type borrower has to liquidate less of their LTT for a given funding shock in the COB market than in the OTC market. For any given funding shock, this is due to the larger loan in the COB market, ℓ_1^P, than in the OTC market, ℓ_1^L. Pooling H-type and L-type borrower makes the market more resilient against a funding run if the LTT is illiquid. Notice that this is not possible in Bouvard et al. (2015). We discuss why after Theorem 2.

Our results are in line with empirical evidence from the GFC when both available 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 halt of the repo market at the onset of the Covid-19 pandemic, asset quality barely changed but funding liquidity became scarce (Duffie, 2020). Accordingly, our model predicts that CCP-based markets are more susceptible to runs than OTC markets.

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

Theorem 2 *The welfare ranking between an anonymous COB market and a non-anonymous OTC market switches repeatedly, and depends on the size of the funding shock:*

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

Theorem 2 is illustrated in Figure 4. The welfare difference between COB and OTC markets is identical to the difference between SOMS and OTC market for $0 \leq f \leq \kappa_1$. The COB market implements the SOMS, which effectively transfers collateral from H-type to L-type borrower, through the loan contract. In the COB market, at the rollover stage when funding is scarce, the H-type subsidizes the L-type by accepting a smaller loan amount in return for a smaller loan rate and, therefore, the H-type leaves relatively more funding to the L-type. This causes both the H-type and the L-type to liquidate collateral equally before they have to start liquidating their LTT—the illiquidity-insurance. An economy with a COB market implements an implicit collateral transfer and thus can withstand larger funding shocks before borrowers have to liquidate their LTT. In contrast, in the OTC market the cost of the funding shock is entirely born by the L-type. For funding shocks so large that their collateral endowment is used up, borrowers have to liquidate their LTT. Since liquidating the LTT is more expensive than liquidating collateral, the welfare decrease is steeper in the OTC market than in the SOMS and the COB market. The welfare difference between COB and OTC markets occurs for funding shocks which exceed the L-type's collateral endowment, i.e., $\frac{\kappa_1}{2} < f \leq \kappa$.

For $\kappa_1 < f \leq f^{OTC}$, the welfare ranking between COB and OTC markets is ambiguous. In the COB market, the decrease in welfare is steeper than in the OTC market, because in the COB market

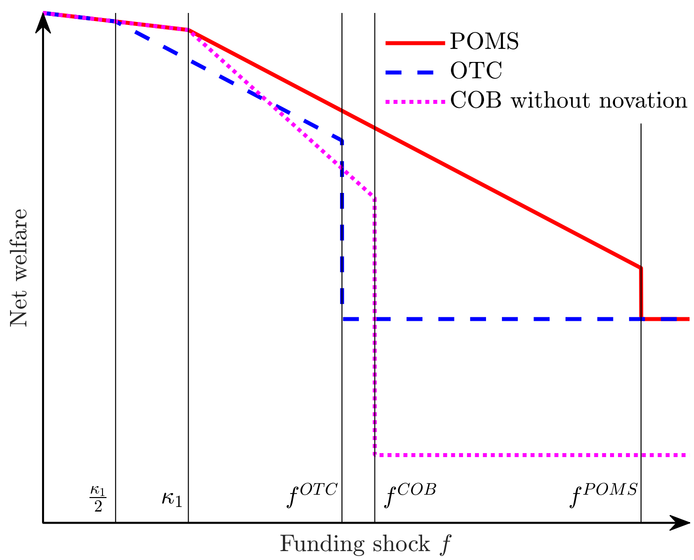

Figure 4: Repeated switches in welfare rankings of OTC and COB markets.

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

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

Hirshleifer effect and comparison to POMS. The role of idiosyncratic information in our model is reminiscent of Hirshleifer (1971), who provides a model in which the knowledge of realizations of uncertainty prevents individuals from sharing risk efficiently through transactions.[25] Different from the previous literature utilising the Hirshleifer effect, we show, when aggregate (funding) risk and idiosyncratic risk interact, the risk sharing benefits from asymmetric information are *(i)* positive even for small funding shocks (in normal times), *(ii)* ambiguous for intermediate funding shocks unlike, e.g., Bouvard et al. (2015), and *(iii)* positive even for large funding shocks, meaning that the anonymous market is more resilient against runs than the non-anonymous market.

Comparing to the POMS, the collateral transfer in Theorem 1 not only improves allocative efficiency but also increases run resilience compared to the OTC market, $f^{POMS}|_{\tau^{POMS}=0} > f^{OTC}$.[26] For $\kappa_1 < f$, the run threshold in the COB market may be smaller than the one in the privately optimal market with collateral transfer.[27] Both markets implement collateral transfers but in the COB market both H-type and L-type LTT are liquidated whereas in the privately optimal market only the L-type LTT is liquidated. This shows that there exist well-designed, privately optimal transfers which alleviate the Hirshleifer trade-off (Hirshleifer, 1971) between allocative efficiency and resilience.

Borrower connectedness. There is a concern among policy makers and market participants (BIS, FSB, and IOSCO, 2018) that through CCP markets banks become too connected and thus the market's risk is concentrated in CCPs. Our model is able to address these concerns of borrower connectedness.[28] The more borrowers are connected, the more similar they are in terms of their payoffs, i.e., the closer R^H and R^L. We study how the efficiency-resilience trade-off in Theorem 2 is affected by borrowers' connectedness. We consider the relevant case in which the average borrower quality decreases, i.e., R^H approaches R^L from above. The more connected they are, the smaller the insurance benefit from anonymity for intermediate and large funding shocks, $\kappa_1 < f \leq f^{COB}$.

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

[26]Notice that $f^{POMS}|_{w_1^H=0,\,\tau^{POMS}=0} = f^{OTC}$, as the OTC market is the POMS without transfers.

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

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

In sum, to increase allocative efficiency of COB relative to OTC markets, borrowers should be disconnected and average borrower quality needs to be sufficiently large.

5 Repo Clearing Mechanisms

So far we have compared the trading mechanisms in OTC and COB markets. We now introduce the clearing mechanism. The clearing mechanism of a CCP consists of novation and default fund, which we study in Sections 5.1 and 5.2.

5.1 Novation

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

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

At the investment stage $t = 0$, first-round lenders require at least their initial investment back,

$$\text{Lender IR:} \qquad 1 \leq \begin{cases} c_1 & \text{if } f \leq f^{COB}, \\ \alpha(\beta c_{1,f>f^{COB}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{COB}} & \text{if } f > f^{COB}. \end{cases} \tag{25}$$

While in a COB market without novation there is a systemic run on all borrowers, in a COB market with novation there is only a narrow run on the L-type borrower. The second line of (25) takes into account that the H-type borrower is able to repay first-round lenders even after a large funding shock occurs, $f > f^{COB}$. First-round lenders therefore require a lower repo rate $c_{1,f>f^{COB}}$ than in COB markets without novation in (18). This enlarges the parameter space with respect to the parameter space for the COB market for which a functioning lending market exists. Moreover, a lower repo rate implies less refinancing pressure at the rollover stage $t = 1$. If the realization of the funding shock is larger than the run threshold, $f > f^{COB}$, the COB market with novation exhibits the same solution as the OTC market. Second-round lenders know that the L-type borrower is effectively excluded from the market since the CCP only novates repos with the H-type borrower. When there is enough funding to roll over one borrower's loan, $2(1-f)m \geq c_{1,f>f^{COB}}\ell_0$, second-round lenders compete for the H-type borrower so that they break even at $c^H_{2,f>f^{COB}} = 1$. The loans extended to the H-type borrower allow them to continue the LTT without liquidation, $\ell^H_{1,f>f^{COB}} = c_{1,f>f^{COB}}\ell_0$. The run threshold and the equilibria below the run threshold remain the same as in Section 4.2.

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

Proposition 5 (COB market with novation) *A narrow run occurs in the COB market with novation if the funding shock exceeds the threshold f^{COB} defined in (24). Novation improves welfare*

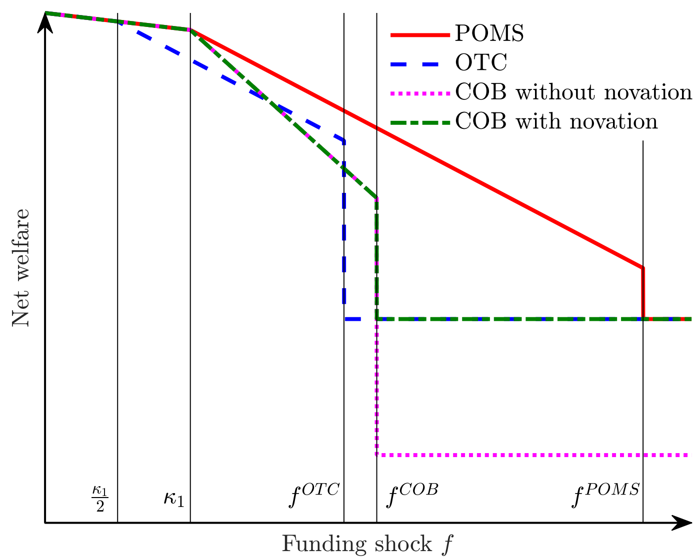

Figure 5: Welfare comparison: Narrow runs in COB vs. OTC market.

in the COB market:

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

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

Note that there is a role for novation even in the case of positive NPV projects. When heterogeneous borrowers compete for scarce funding, it is socially optimal to liquidate the least productive asset. And that is precisely what novation achieves. We come back to the role of novation when we discuss negative NPV projects and the skin-in-the-game effect of collateral in Section 7.3.

5.2 CCP: COB with novation and default fund

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

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

$$\begin{aligned}\tau_{DF}^{CCP} =& \frac{1}{\alpha\beta}\Bigg[\alpha\Bigg(\beta(R^H(i_0 - z_1^P) - c_2^P \ell_1^P) - \kappa_2 w_1^P\Bigg) \\ &+ (1-\alpha)\Bigg((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P\Bigg) - (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0\Bigg]. \qquad (26)\end{aligned}$$

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

$$R^L(i_0 - z_1^P) - c_{2,DF}^P \ell_1^P + \tau_{DF}^{CCP} = 0. \qquad (27)$$

From (27) it is clear that the CCP with default fund can withstand a larger funding shock the larger the transfer τ_{DF}^{CCP}, since it increases the L-type's repayment capacity. Notice that the default fund, like in real world CCP markets, is only drawn upon after the defaulting borrower's resources, that is the proceeds from collateral and LTT, are exhausted. The following proposition summarizes the financial stability effect of a default fund.

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

$$f^{CCP} = \frac{(R^L - 1)\lambda + R^H \kappa_1}{R^H + R^L - 2\lambda} + \frac{(\lambda + \kappa_1)R^L - \lambda}{R^H + R^L - 2\lambda} + \frac{\lambda(\beta(R^H - R^L) - \kappa_0 R^L)}{\alpha\beta(R^H + R^L - 2\lambda)}. \tag{28}$$

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

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

The default fund is desirable from a social planner viewpoint as it helps to continue, instead of liquidating, the L-type LTT, a positive NPV project. The socially optimal novation policy therefore considers the repayment capacity of both borrowers through the default fund. Only if both are exhausted should the CCP exclude the L-type borrower.

Coexistence of OTC and CCP markets. The welfare comparison between markets requires that OTC and CCP markets exist in parallel. In the model, these markets coexist when borrowers are indifferent in obtaining funding from either OTC or CCP markets. By comparing borrowers' ex-ante profits, we show that there exists a level $\bar{\lambda}$ of the LTT's illiquidity such that borrowers are indifferent between the two markets. Furthermore, we determine the level of a search cost τ in the OTC market which ensures the coexistence of these markets.

Proposition 7 *For $\kappa_1 < f \leq f^{OTC}$, borrowers are indifferent between OTC and CCP markets*

(i) when the LTT's illiquidity is given by $\lambda = \bar{\lambda}$, or

(ii) there exists a search cost $\tau > 0$ in OTC markets such that $\tau = \lambda - \bar{\lambda}$.

The proposition considers the relevant parameter space for resource allocation and market resilience, i.e., $\kappa_1 < f \leq f^{OTC}$. Borrowers with illiquid LTT, $\lambda < \bar{\lambda}$, prefer the CCP while borrowers with liquid LTT, $\lambda > \bar{\lambda}$, prefer the OTC market over the CCP. The difference in *(ii)*, $\lambda - \bar{\lambda}$, delivers a theoretical prediction of search cost in the OTC market. In practice OTC and CCP markets exist in parallel, for example the OTC interdealer and GCF repo markets in the United States (Figure 1).

6 Reforming or Regulating Repo Markets?

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., 2022), a discussion among policy makers, industry leaders, and academics has emerged as to whether OTC repos should be centrally cleared more often (Duffie, 2020; Group of Thirty, 2022). Our analysis contributes to this debate by exploring the costs and benefits of different policy proposals. We proceed by first discussing whether and how repo market reforms implement the privately optimal market structure, and then by addressing the question if repo market trading regulations achieve the same outcome.

6.1 Repo arrangements to achieve POMS

We show that current reform proposals improve upon existing market structure but do not achieve the POMS. In the following we assess existing proposals and suggest novel market reforms. The POMS derived in Theorem 1 can be implemented with a combination of existing and novel market features.

Reform 1: Bilateral trading and central clearing. Centrally cleared OTC markets are an important segment of U.S. repo markets. Augmenting OTC markets with central clearing and a default fund that pays in case of a borrower's default is a general reform proposal which is currently being discussed (Duffie, 2020; Group of Thirty, 2022). Central clearing improves the resilience of OTC markets and resembles the functioning of existing request-for-quote platforms.

A corollary of Theorem 1 is that, when non-anonymous markets are augmented with a default

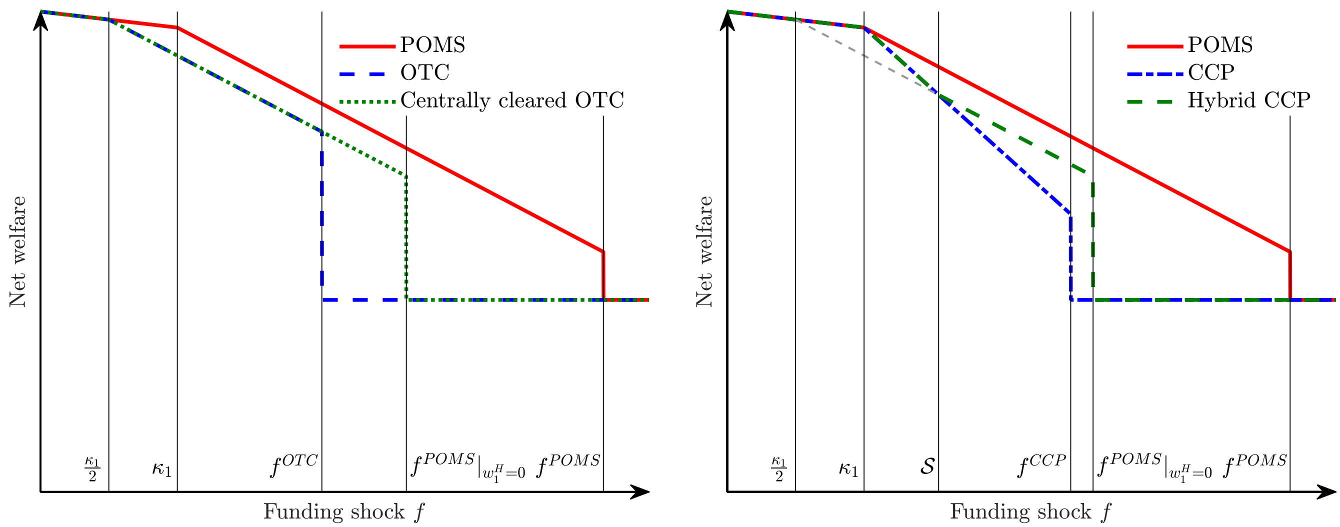

Figure 6: Welfare comparison: Centrally cleared OTC (left) and hybrid CCP market (right).

fund involving profit transfers τ^{POMS} at $t = 2$, run resilience improves because $f^{POMS}|_{w_1^H=0} > f^{OTC}$. Figure 6 (left) illustrates that bilateral trading with central clearing improves run resilience, but the reform leaves both allocative efficiency and resilience suboptimal, i.e., does not achieve the POMS.

Reform 2: Hybrid trading mechanism. A specific hybrid trading mechanism improves upon existing CCP markets with novation and default fund. The COB trading mechanism already implements the collateral transfer through one-fits-all loans for $f \leq \kappa_1$. Therefore, it achieves the POMS welfare for small funding shocks. However, the COB inefficiently forces partial liquidation of the H-type's LTT for $f > \kappa_1$. To improve upon this, the trading mechanism needs to switch from an anonymous COB to a non-anonymous trading mechanism for funding shocks $f \geq \mathcal{S}$, as depicted in Figure 6 (right). The switching point $\mathcal{S}$ is defined by the funding shock at which net welfare in the COB and OTC markets are equal in Theorem 2:

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

The hybrid repo trading mechanism resembles 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, $f \geq \mathcal{S}$, the hybrid market with a default fund can withstand is given by $f^{POMS}|_{w_1^H=0}$. Since the H-type is not required to liquidate neither LTT nor collateral in the hybrid market, as opposed to the anonymous COB trading in a CCP market, there is more profit to redistribute which makes the hybrid market more resilient than the CCP market, $f^{POMS}|_{w_1^H=0} > f^{CCP}$. In sum, Figure 6 (right) illustrates that the hybrid trading mechanism improves upon existing CCP markets by allocating resource more efficiently for intermediate and large funding shocks, $\mathcal{S} < f \leq f^{POMS}|_{w_1^H=0}$, but it does not attain the efficient resource allocation of the POMS.

Reform 3: Two-tiered guarantee fund. Both of the above reforms, centrally cleared OTC market and hybrid CCP market, can be further improved to the point that they achieve the POMS in Theorem 1 and resolve the allocation-resilience trade-off. Setting up a two-tiered guarantee fund is needed. Regardless of the trading mechanism, the two-tiered guarantee fund requires an initial contribution given by the two transfers (collateral and profit) derived in Theorem 1. The contribution is agreed upon before trading takes place and is updated on a regular basis depending on participants' net exposure.

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

The two-tiered guarantee fund resembles the collateral upgrade, as implemented by the ECB and the Federal Reserve through emergency facilities (Carlson and Macchiavelli, 2020), which effectively allow borrowers to increase their collateral endowment. The risky asset escrow is used to bail out defaulting borrowers. This captures the profit transfer described in the privately optimal repo market solution in Theorem 1. 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.

Reform 4: Collateral swap contracts. As an alternative to the two-tiered guarantee fund, the transfer scheme in Theorem 1 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^{POMS}, from the H-type borrower to the L-type borrower who is subject to credit rationing. Borrowers write the swaps at $t = 0$. The collateral swap is triggered if the L-type borrower runs out of collateral and transfers the H-type's collateral to the L-type. This prevents inefficient liquidation of the L-type's LTT at $t = 1$. The credit default swap is triggered if the L-type is insolvent at $t = 2$. In this case the H-type effectively repays part of the L-type's lenders. Second-round lenders take into account this transfer and provide funding to the L-type at $t = 1$ even for large funding shocks enhancing the resilience of the market.

6.2 Forcing CCP-based trading?

The question whether regulators should force repo trading on a CCP has recently received much attention. We consider simultaneous trading on both CCP and OTC markets, and study the impact of regulations that impose a floor on CCP trading, a cap on OTC trading, or both.

From our prior analysis we know that the POMS can be implemented by anonymous trading for small funding shocks $0 < f < \kappa_1$. However, for $f > \kappa_1$, neither anonymous nor non-anonymous lending implement the POMS. In anonymous lending there is too much liquidation of the H-type LTT and in non-anonymous lending there is too much liquidation of the L-type LTT. To achieve the POMS for $f > \kappa_1$, there must be *(i)* a collateral transfer from the H-type to the L-type at $t = 1$ and *(ii)* a profit transfer from the H-type to the L-type at $t = 2$ for large funding shocks.

The collateral transfer can be implemented via trading caps and floors, whereas the profit transfer cannot. Since they implement the collateral transfer but not the profit transfer, trading caps and floors attain the POMS for a range of funding shocks that is smaller than the one in the POMS. Borrowers and lenders trade via both the anonymous CCP and non-anonymous OTC markets. Define the total loan L_1^ω that a borrower of type $\omega \in \{L, H\}$ obtains from CCP, ℓ_1^P, and OTC, ℓ_1^ω:

$$L_1^\omega = \ell_1^P + \ell_1^\omega. \tag{30}$$

The profit transfer at $t = 2$ is not implementable via trading caps or floors since loans are agreed at $t = 1$ and the H-type has to realize the profit from the LTT at $t = 2$. It is not optimal to reduce lending to the H-type at $t = 1$ such that they have to liquidate their LTT since it is the most valuable asset. Due to the liquidation pecking order it is optimal instead to reduce the H-type's loan forcing it to liquidate collateral in order to leave more funding to the L-type allowing it not to liquidate the LTT. To implement the collateral transfer, consider borrowers' repayment condition:

$$-c_1\ell_0 + L_1^\omega + w_1^\omega \kappa_1 + z_1^\omega \lambda = 0. \tag{31}$$

An optimal floor or cap does not require the H-type to liquidate the LTT, $z_1^H = 0$, and it requires both H-type and L-type to liquidate their collateral, $w_1^H = w_1^L = k_0$. With the total funding available, we obtain the market clearing condition

$$2(1-f)m = L_1^H + L_1^L. \tag{32}$$

Together with the repayment condition (31), total loans are equal to

$$L_1^H = c_1\ell_0 - \kappa_1 k_0, \quad L_1^L = 2(1-f)m - L_1^H, \quad z_1^L = \frac{c_1\ell_0 - L_1^L - \kappa_1 k_0}{\lambda}. \tag{33}$$

As before, we assume borrower competition at $t = 1$ because of funding scarcity. Recall, in an anonymous CCP market, borrowers obtain one-fits-all loans regardless of borrower type, ℓ_1^P, while in a non-anonymous OTC market there is discriminatory lending, $\ell_1^\omega, \omega \in \{L, H\}$. We now discuss how to implement the different volume regulations.

Regulation 1: Limiting CCP and OTC trading. The following two regulations are identical in terms of equilibrium quantities and interest rates:

1. Floor on CCP trading equal to L_1^L.
2. Cap on OTC trading equal to $L_1^H - L_1^L$ with CCP present.

Borrowers pool on the L-type borrower's loan, $\ell_1^P = L_1^L$, in the CCP market and the H-type obtains the additional funding, $L_1^H - \ell_1^P$, from the OTC market by outbidding the L-type. Lenders are indifferent between lending in the OTC or CCP markets when $c_2^P = c_2^{OTC} \equiv c_2$. Outbidding the L-type implies a gross interest rate c_2 that is defined by the zero-profit condition of the L-type, $R^L(i_0 - z_1^L) - c_2 L_1^L = 0$. Hence,

$$c_2 = R^L \frac{i_0 - z_1^L}{L_1^L}. \tag{34}$$

In Appendix I we verify that $\ell_1^P = L_1^L$, $\ell_1^L = 0$, $\ell_1^H = L_1^H - \ell_1^P$ and c_2 given by (34) indeed constitute an equilibrium in which the L-type and H-type pool in the CCP market, the L-type obtains funding exclusively from the CCP, and only the H-type obtains additional funding from the OTC market. The run threshold with trading cap/floor,

$$f^{cap/floor} = \frac{(R^L - 1)\lambda + \kappa_1(2R^L - \lambda)}{2(R^L - \lambda)}, \tag{35}$$

is strictly smaller than the one in the POMS, f^{POMS}, with collateral transfer, $w_1^H = w_1^L = k_0$, and without the default fund, $\tau^{DF} = 0$. At first look, this may seem surprising because in both cases there is a collateral transfer. The reason why the collateral transfer through the loan cap/floor induces a smaller run threshold is because it is an indirect transfer through the loan amount. By reducing the amount of lending to the H-type so that there are more funds available to the L-type, the H-type is effectively forced to liquidate collateral. While this allows the L-type to obtain a larger loan, they still have to repay the loan at $t = 2$ which is not the case with the direct transfer in the privately optimal market solution.

Regulation 2: CCP shutdown. Another potential regulation is to close down the CCP and impose a trading cap in the OTC market. The cap is given by the maximum loan amount L_1^H that the H-type should obtain, so that the H-type is forced to liquidate collateral. Borrower competition pins down the equilibrium quantities. Because the H-type borrower can marginally outbid the L-type borrower, the former obtains loans up to the cap, $\ell_1^H = L_1^H$, and the L-type obtains the remaining funding available, $\ell_1^L = L_1^L$. Borrower competition drives the gross interest rate up to the L-type's break-even condition (34), just like in Regulation 1, so that the IR of the H-type is satisfied. Since there is no asymmetric information in the OTC market, lenders can observe borrower types and thus there is no concern about incentive compatibility. The run threshold is identical to Regulation 1, and given by (35).

7 Empirical Predictions

This section develops predictions for how collateral quality impacts market resilience, how the collateral convenience yield varies with funding scarcity depending on market structure, and how collateral has a skin-in-the-game effect.

7.1 Run resilience and collateral quality

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

Proposition 8 *The CCP market's resilience to a run is more sensitive to collateral value than the OTC market's resilience, $\frac{\partial f^{CCP}}{\partial \kappa_1} > \frac{\partial f^{OTC}}{\partial \kappa_1}$, when the LTT is illiquid, $\lambda < \frac{R^L(R^H - R^L)}{2R^H}$, and vice versa.*

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

7.2 Collateral convenience yield

When 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. Specifically, the collateral premium at $t = 0$ is the difference between a borrower's expected payoff from using the asset as collateral to obtain a loan to invest in the LTT, and the expected payoff from investing the proceeds of the asset sale in the LTT.

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

To speak to the empirical evidence on the convenience yield from the United States (He et al., 2022), we focus on the OTC market as this seems to be the predominant market structure. 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. The following proposition formalises this result.

Proposition 9 *In the OTC market, for $\frac{\kappa_1}{2} < f \leq f^{OTC}$ and $\alpha > R^H - R^L$, the convenience yield on collateral $\mathbf{cp}^{OTC}$ increases (decreases) 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, α is large, the collateral premium in the OTC market increases in the size of the funding shock if average borrower quality is sufficiently low, β is low. Conversely, the collateral premium decreases in the size of the funding shock if average borrower quality is sufficiently high, β is large. The proposition highlights the protective role of collateral in a funding crisis. When idiosyncratic borrower risk is high, collateral becomes more valuable to borrowers because it protects their LTT investment.

These predictions are in line with empirical evidence from the GFC when average borrower quality was low due to large positions in asset-backed securities on banks' balance sheets. The model predicts a resulting rise in the convenience yield as the funding shock hits. During the Covid-19 pandemic, by contrast, banks were better capitalized and had higher creditworthiness than during the GFC. The model then predicts that the convenience yield should decline during a liquidity crisis such as the Covid-19 pandemic, which is consistent with the empirical evidence in He et al. (2022).

7.3 Collateral's skin-in-the-game effect

Market participants have voiced concerns that in anonymous CCP based markets low-quality borrowers can hide amongst high-quality borrowers.[29] To investigate this issue, we introduce negative NPV projects and study the role of collateral scarcity and pecking order.

We demonstrate that only socially optimal rollover takes place in CCP markets with an anonymous COB because collateral has a skin-in-the-game effect. To that purpose, consider a L-type borrower with a negative NPV LTT, $R^L < 1$. There are two cases: the L-type LTT yields a

[29]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.

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

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

$$R^L + \kappa_1 \geq 1. \tag{36}$$

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

$$1 \geq \kappa_1 + \lambda, \tag{37}$$

with $i_0 = k_0 = m$. Combining conditions (36) and (37),

$$1 - \lambda \geq \kappa_1 \geq 1 - R^L, \tag{38}$$

yields $R^L > \lambda$. That is, in a COB market with scarce collateral and negative NPV LTT ($R^L > \lambda$) rollover takes place and is socially optimal.

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

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

8 Conclusion

Well-functioning repo markets are integral to an efficient banking system, monetary policy transmission, and overall financial market resilience and stability. Both the ECB and Federal Reserve have not only injected liquidity but also implemented collateral upgrades through their emergency facilities in order to avoid market collapse during recent funding crises, calling for market reforms.

We develop a maturity-mismatch model with two types of funding runs that depend on repo market structure and two types of shocks, privately observed shocks about borrower quality and publicly observed aggregate funding shocks. We then study how repo market structure affects the allocation-resilience trade-off and how a privately optimal market solution, which does not require government intervention, can be implemented.

Repo trading and clearing mechanisms determine the efficiency of short-term funding and the resilience to funding shocks in crisis times. The predominant repo markets around the world, non-anonymous bilaterally-cleared over-the-counter (OTC) markets and anonymous centralized order books with default fund and novation by a central counterparty (CCP), do not achieve the privately optimal market structure. At the core of this result is the lack of illiquidity insurance provided by existing repo markets.

Repo market reforms that implement a collateral transfer scheme improve efficiency. The privately optimal repo market structure can be implemented through a two-tiered guarantee fund with transfers contingent on both borrower illiquidity and default. Central clearing of bilateral OTC trading (Duffie, 2020; Group of Thirty, 2022) and CCPs with a hybrid trading protocol contingent on aggregate funding scarcity improve funding allocations and market resilience but do not achieve the same level of welfare as a two-tiered guarantee fund.

The model explains several stylized facts on recent funding crises and collateral convenience yields. Repo market resilience depends on both funding liquidity and asset liquidity. CCPs are more resilient than OTC markets when there is both low funding and low asset liquidity, such as during the Great Financial Crisis. OTC markets are more resilient when funding is scarce while asset liquidity is high, such as during the onset of the Covid-19 pandemic. These predictions reconcile the halt of OTC repo markets in 2008 with the 2019 and 2020 blowups in CCP based markets.

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Internet Appendix

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

A Constrained efficient solution

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

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

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

B OTC

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

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

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

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

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

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

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

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

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

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

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

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

$$R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2 k_0 \geq 0 \quad \text{(IA7)}$$

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

$$R^H i_0 - c_2^{OTC}\ell_1^H + R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L - \kappa_2 k_0 + c_2^{OTC}(\ell_1^H + \ell_1^L) - \ell_1^H - \ell_1^L + 2c_1\ell_0 - 2\ell_0 \quad \text{(IA32)}$$

$$=R^H i_0 + R^L(i_0 - z_1^L) - \kappa_2 w_1^L - \ell_1^H - \ell_1^L \quad \text{(IA33)}$$

$$=(R^H + R^L - 2)m - 2f(\frac{R^L}{\lambda} - 1)m + \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m. \quad \text{(IA34)}$$

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

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

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

C CCP

C.1 COB market

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

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

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

$$R^L i_0 - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P) = 0 \quad \text{(IA37)}$$

$$\frac{R^L + \kappa_2(1 - \frac{f}{\kappa_1})}{1 - f} = c_2^P \quad \text{(IA38)}$$

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

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

Lenders are willing to provide funding if

$$c_2^P \geq 1 \quad \text{(IA40)}$$

$$\frac{R^L - 1}{\kappa_2 - \kappa_1}\kappa_1 + \frac{\kappa_2\kappa_1}{\kappa_2 - \kappa_1} \geq f. \quad \text{(IA41)}$$

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

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

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

$$R^L(i_0 - z_1^P) - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P) \geq 0 \quad \text{(IA42)}$$

$$\frac{R^L(1 - \frac{f-\kappa_1}{\lambda})}{1 - f} \geq c_2^P \quad \text{(IA43)}$$

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

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

$$\frac{R^L - R^H\frac{f-\kappa_1}{\lambda}}{1 - f} \geq c_2^P \quad \text{(IA45)}$$

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

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

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

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

At $t=1$ if $f=0$, it is straightforward to show that $c^P_{2,f=0} = R^L + \kappa_2$, $\ell^P_{1,f=0} = m$, $k^P_{1,f=0} = 0$.

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

$$\begin{aligned}
&\alpha\Big((\beta R^H + (1-\beta)R^L)(i_0 - z_1^P) - c_2^P\ell_1^P - \kappa_2 w_1^P\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c^P_{2,f=0}\ell^P_{1,f=0}\Big) \\
&\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \qquad \text{(IA48)}\\
&\frac{(R^H - R^L)(\beta + \alpha(1-\beta)\frac{f-\kappa_1}{\lambda})}{\beta R^H + (1-\beta)R^L} \geq \kappa_0 \qquad \text{(IA49)}
\end{aligned}$$

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 IR 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, $\kappa_1 < f \leq f^{COB}$. 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

$$\begin{aligned}
&(R^H + R^L)i_0 - 2c_2^P\ell_1^P - 2\kappa_2 w_1^P + 2c_2^P\ell_1^P - 2(1-f)m + 2c_1\ell_0 - 2\ell_0 \qquad \text{(IA51)}\\
=&(R^H + R^L - 2)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m \qquad \text{(IA52)}
\end{aligned}$$

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

Ex-post welfare is

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

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

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

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

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

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

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

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

For second-round lenders to provide loans

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

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

At $t = 0$, competitive lenders require

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

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

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

$$\alpha\Big(\beta(R^H i_0 - c^H_{2,f>f^{COB}}\ell^H_{1,f>f^{COB}}) - (1-\beta)\kappa_2 k_0\Big) \tag{IA65}$$
$$+ (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c^P_{2,f>f^{COB}}\ell^P_{1,f>f^{COB}} - \kappa_2 k^P_{1,f>f^{COB}}\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA66}$$
$$\frac{\beta(R^H - (\alpha c_{1,f>f^{COB}} + (1-\alpha)R^L))}{\beta R^H + (1-\beta)R^L - 1 + (1-\alpha) + \alpha(1-\beta)} \geq \kappa_0 \tag{IA67}$$

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

$$R^H i_0 - c^H_{2,f>f^{COB}}\ell^H_{1,f>f^{COB}} - \kappa_2 k_0 + c^H_{2,f>f^{COB}}\ell^H_{1,f>f^{COB}} - \ell^H_{1,f>f^{COB}} + c_{1,f>f^{COB}}\ell_0 + c_1^D\ell_0 - 2\ell_0 \tag{IA68}$$
$$=(R^H + \lambda + \kappa_1 - \kappa_2 - 2)m \tag{IA69}$$

C.4 Intuitive Criterion: pooling equilibrium

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

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

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

Assume there is a noisy signal $S^{\omega,i}$ about borrower quality, which consists of a part, R^ω, that is privately observable by borrowers and a noise component ϵ^i such that

$$S^{\omega,i} = R^\omega + \epsilon^i, \tag{IA71}$$
$$\text{where } Prob(R^H) = \beta, Prob(R^L) = 1 - \beta, \tag{IA72}$$
$$Prob(\epsilon^H) = \gamma, Prob(\epsilon^L) = 1 - \gamma. \tag{IA73}$$

Both follow a binomial distribution, where R^ω is privately observable at the rollover stage, $t = 1$, whereas the noise element is only observable by all agents at $t = 2$. In economic terms, the information wedge between OTC and CCP markets arises from the observable part of the signal, R^ω. But even if R^ω is known there remains counterparty risk due to ϵ^i. We require that signals are informative:

$$R^H + \epsilon^H > R^H + \epsilon^L > R^L + \epsilon^H > R^L + \epsilon^L. \tag{IA74}$$

We focus on positive NPV projects, i.e. $R^L + \epsilon^L \geq 1$, but also with a noisy signal we can make an analogous argument to Section 7.3. If signals are uninformative, knowing the type, R^ω, has no value and thus there is no difference between symmetric and asymmetric information. In other words, learning the borrower's identity would have no value. To simplify notation, we further assume that in expectation, noise does not change borrowers' private information

$$\gamma\epsilon^H + (1-\gamma)\epsilon^L = 0. \tag{IA75}$$

D.1 OTC markets

Instead of repeating all the derivations for the OTC market from Appendix B we highlight the relevant changes. Solving for the subgame at $t = 1$, consider borrowers' individual rationality constraint,

$$E\Big(S^{\omega,i}(i_0 - z_1) - c_2\ell_1 + \kappa_2(k_0 - w_1)\Big) \geq 0, \tag{IA76}$$

where E is the expectation operator. Because of symmetric information, contracts are conditioned on borrower type R^ω. Rewrite (IA76)

$$R^\omega(i_0 - z_1^\omega) - c_2^\omega \ell_1^\omega + \kappa_2(k_0 - w_1^\omega) \geq 0, \tag{IA77}$$

with the repayment condition

$$-c_1\ell_0 + \ell_1^\omega + \kappa_1 w_1^\omega + \lambda z_1^\omega = 0. \tag{IA78}$$

Lenders condition contracts on borrower types and they are willing to provide repos if

$$c_2^\omega \geq 1, \tag{IA79}$$

as long as the NPV is non-negative and the aggregate funding shock is below the run-threshold $f \leq f^{OTC}$. Observe that agents' individual rationality constraints and repayment conditions are identical to the simpler setup without a noisy signal. We can therefore conclude that the results at the rollover stage from the model without a noisy signal carry over to the model with a noisy signal. This reasoning extends to the subgame at the investment stage $t = 0$.

D.2 COB markets

In the anonymous COB market there is asymmetric information about borrower types R^ω and therefore we derive a Perfect Bayesian Nash equilibrium. For the same reasons as in the main part we focus on the pooling equilibrium in which, regardless of borrower type, borrowers obtain a one-fits-all repo contract. It is the rollover stage, $t = 1$, at which there is asymmetric information between borrowers and lenders. Consider a borrower's individual rationality constraint

$$\begin{aligned} &E\Big(S^{\omega,i}(i_0 - z_1^P) - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P)\Big) \geq 0 \\ &R^\omega(i_0 - z_1^P) - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P) \geq 0, \end{aligned} \tag{IA80}$$

and their repayment condition

$$-c_1\ell_0 + \ell_1^P + \kappa_1 w_1^P + \lambda z_1^P = 0. \tag{IA81}$$

Borrowers' incentive compatibility constraints are

$$\begin{aligned} &E\Big(S^{\omega,i}(i_0 - z_1^P) - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P)\Big) \geq E\Big(S^{\omega,i}(i_0 - z_1') - c_2'\ell_1' + \kappa_2(k_0 - w_1')\Big) \\ &R^\omega(i_0 - z_1^P) - c_2^P\ell_1^P + \kappa_2(k_0 - w_1^P) \geq R^\omega(i_0 - z_1') - c_2'\ell_1' + \kappa_2(k_0 - w_1'). \end{aligned} \tag{IA82}$$

Where the off-equilibrium contract is identical to the setup without noisy signal ($c_2' = R^L + \kappa_2, \ell_1' = c_1\ell_0$).

Lenders contract unconditional of borrower types and they are willing to provide repos if

$$c_2^P \geq 1, \tag{IA83}$$

as long as the NPV is non-negative and the aggregate funding shock is below the run-threshold $f \leq f^{COB}$. Observe that agents' individual rationality constraints and repayment conditions are identical to the simpler setup without a noisy signal. We can therefore conclude that the results at the rollover stage from the model without a noisy signal carry over to the model with a noisy signal. This reasoning extends to the subgame at the investment stage $t = 0$.

E Optimal market solution

E.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 $t = 2$:

$$R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau \geq 0 \tag{IA84}$$
$$s.t. - c_1\ell_0 + \ell_1^H = 0 \tag{IA85}$$

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

$$R^L(i_0 - z_1^L) - c_2^L\ell_1^L + \kappa_2(k_0 - w_1^L) + \tau = 0 \tag{IA86}$$
$$s.t. - c_1\ell_0 + \ell_1^L + \kappa_1(w_1^L + w_1^H) + \lambda z_1^L = 0 \tag{IA87}$$

This yields

$$c_2^L = \frac{R^L(i_0 - z_1^L) + \kappa_2(k_0 - w_1^L) + \tau}{\ell_1^L} \tag{IA88}$$
$$z_1^L = \frac{c_1\ell_0 - \ell_1^L - \kappa_1(w_1^L + w_1^H)}{\lambda} \tag{IA89}$$

Note that the market rate is given by

$$R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \kappa_2(k_0 - w_1^L) = 0 \tag{IA90}$$
$$s.t. - c_1\ell_0 + \ell_1^L + \kappa_1 w_1^L + \lambda z_1^L = 0 \tag{IA91}$$

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

$$R^L i_0 - c_{2,f=0}^{OTC}\ell_{1,f=0}^L + \kappa_2 k_0 = 0 \tag{IA92}$$
$$s.t. - c_1\ell_0 + \ell_{1,f=0}^L = 0 \tag{IA93}$$

At $t = 0$ expected borrower profit is

$$\begin{aligned}&\alpha\Big[\beta\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau - \kappa_0 k_0\big) - (1-\beta)\kappa_0 m\Big]\\ &+(1-\alpha)\Big[\beta\big(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H + (\kappa_2 - \kappa_0)k_0\big) - (1-\beta)\kappa_0 m\Big] \geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0\end{aligned} \tag{IA94}$$

To derive the transfer in case of default, consider $f > f^{OTC}$ such that $c_2^{OTC} = 1$. Then from expression (IA94), we obtain the maximum commitment borrowers are willing to make to the default fund:

$$\begin{aligned}\tau^{POMS} &= \frac{1}{\alpha\beta}\Big[\alpha\Big(\beta((R^H-1)m - \kappa_0 w_1^H) - (1-\beta)\kappa_0 m\Big)\\ &\qquad + (1-\alpha)\Big(\beta\big(R^H - R^L - \kappa_2\big) - (1-\beta)\kappa_0\Big)m - (\beta R^H + (1-\beta)R^L - 1)\kappa_0 m\Big]\\ &= \frac{1}{\alpha\beta}\Big[\alpha\beta(R^H - 1) + (1-\alpha)\beta(R^H - R^L) - (\beta R^H + (1-\beta)R^L)\kappa_0 + \alpha\beta(1 - w_1^H)\kappa_0\Big]m\end{aligned} \tag{IA95}$$

The transfer decreases in the liquidation of the H-type's collateral, w_1^H. There is hence a trade-off for the policy maker between increasing the repayment capacity of the L-type borrower at $t=1$ and $t=2$. We show below that it is socially optimal to liquidate the H-type's collateral at $t=1$, i.e. $w_1^H = k_0$. With $w_1^H = k_0$, $\tau^{POMS} > 0$ 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 $t=1$.

E.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

$$\begin{aligned}
&\alpha\Big[\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau^{POMS} - \kappa_0 k_0 + c_2^{OTC}\ell_1^H - \ell_1^H + c_1\ell_0 - \ell_0\big)\\
&\quad + \big(R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \tau^{POMS} - \kappa_0 k_0 + c_2^{OTC}\ell_1^L - \ell_1^L + c_1\ell_0 - \ell_0\big)\Big]\\
&+(1-\alpha)\Big[\big(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H + (\kappa_2 - \kappa_0)k_0 + c_{2,f=0}^{OTC}\ell_1^H - \ell_1^H + c_1\ell_0 - \ell_0\big)\\
&\quad + \big(R^L i_0 - c_{2,f=0}^{OTC}\ell_{1,f=0}^L(\kappa_2 - \kappa_0)k_0 + c_{2,f=0}^{OTC}\ell_{1,f=0}^L - \ell_{1,f=0}^L + c_1\ell_0 - \ell_0\big)\Big]
\end{aligned} \tag{IA96}$$

$$\begin{aligned}
&= \alpha\Big[\big(R^H i_0 - \kappa_2 w_1^H - \ell_1^H\big) + \big(R^L(i_0 - z_1^L) - \kappa_0 k_0 - \ell_1^L\big)\Big]\\
&+(1-\alpha)\Big[\big(R^H i_0 - \ell_1^H\big) + \big(R^L i_0 - \ell_{1,f=0}^L\big)\Big]
\end{aligned} \tag{IA97}$$

$$= (R^H + R^L - 2)m - \alpha\Big(2fm(\frac{R^L}{\lambda} - 1) - \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})(w_1^H + m)\Big) \tag{IA98}$$

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 $t=2$

$$R^H i_0 - c_2^{OTC}\ell_1^H - \tau^{POMS} \geq 0 \tag{IA99}$$

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 $\tau^{POMS} \geq 0$. It is straightforward to show that there exists indeed a non-empty range for κ_0.

E.3 Run threshold

Finally, we provide the condition up to which the L-type is able to repay second round lenders. Recall from expression (IA95) that τ^{POMS} is independent of f if $w_1^H = \{0, m\}$.

$$R^L(i_0 - z_1^L) - c_2^L\ell_1^L + \kappa_2(k_0 - w_1^L) + \tau^{POMS} = 0 \tag{IA100}$$

$$\frac{R^L - 1}{R^L - \lambda}\frac{\lambda}{2} + \frac{R^L\kappa_1(w_1^H + w_1^L)}{2(R^L - \lambda)m} + \frac{\tau^{POMS}\lambda}{2(R^L - \lambda)m} \geq f \tag{IA101}$$

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

E.4 Ex-post welfare

This is to show that the above mechanism implements the SOMS up to f^{POMS}.

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

$$\begin{aligned}
&\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau^{POMS} - \kappa_0 k_0 + c_2^{OTC}\ell_1^H - \ell_1^H + c_1\ell_0 - \ell_0\big)\\
&+ \big(R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \tau^{POMS} - \kappa_0 k_0 + c_2^{OTC}\ell_1^L - \ell_1^L + c_1\ell_0 - \ell_0\big)\\
=&\big(R^H i_0 - \kappa_2 w_1^H - \ell_1^H\big) + \big(R^L(i_0 - z_1^L) - \kappa_0 k_0 - \ell_1^L\big)\\
s.t. &- c_1\ell_0 + \kappa_1(w_1^H + k_0) + \ell_1^L = 0.
\end{aligned} \tag{IA102}$$

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

$$(R^H + R^L - 2)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m. \tag{IA103}$$

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

$$\begin{aligned}
&\big(R^H i_0 - c_2^{OTC}\ell_1^H + \kappa_2(k_0 - w_1^H) - \tau^{POMS} - \kappa_0 k_0 + c_2^{OTC}\ell_1^H - \ell_1^H + c_1\ell_0 - \ell_0\big)\\
&+ \big(R^L(i_0 - z_1^L) - c_2^{OTC}\ell_1^L + \tau^{POMS} - \kappa_0 k_0 + c_2^{OTC}\ell_1^L - \ell_1^L + c_1\ell_0 - \ell_0\big)\\
=&\big(R^H i_0 - \kappa_0 k_0 - \ell_1^H\big) + \big(R^L(i_0 - z_1^L) - \kappa_0 k_0 - \ell_1^L\big)\\
s.t. &- c_1\ell_0 + 2\kappa_1 k_0 + \ell_1^L + \lambda z_1^L = 0.
\end{aligned} \tag{IA104}$$

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

$$(R^H + R^L - 2)m - 2f(\frac{R^L}{\lambda} - 1)m + 2\kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m. \tag{IA105}$$

E.5 Run threshold comparison

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

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

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

E.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

$$(R^H + R^L - 2)m + \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1}) - 2f(\frac{R^L}{\lambda} - 1)m. \tag{IA106}$$

Observe that

$$W^{POMS} - W^{POMS}_{w_1^H=0} = \begin{cases} (\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})(\kappa_1 + 2f) & \text{if } \frac{\kappa_1}{2} < f \leq \kappa_1 \\ (\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})\kappa_1 & \text{if } \kappa_1 < f \leq f^{POMS} \end{cases} \tag{IA107}$$

E.7 Hybrid mechanism

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

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

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

F Convenience yield

F.1 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

$$
\alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H)-(1-\beta)\kappa_2 w_1^L\Big)+(1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H)-(1-\beta)\kappa_2 k_0\Big)
$$
$$
\geq (\beta R^H+(1-\beta)R^L-1)k_0\kappa_0 \tag{IA108}
$$
$$
\frac{\beta(R^H-R^L(\alpha\frac{1}{1-2f}+1-\alpha))}{\beta R^H+(1-\beta)R^L-1+\alpha(\beta\frac{\kappa_1-2f}{1-2f}+(1-\beta)2f)\frac{1}{\kappa_1}+(1-\alpha)} \geq \kappa_0, \tag{IA109}
$$

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

$$
\alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H)-(1-\beta)\kappa_2 k_0\Big)+(1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H)-(1-\beta)\kappa_2 k_0\Big)
$$
$$
\geq (\beta R^H+(1-\beta)R^L-1)k_0\kappa_0 \tag{IA110}
$$
$$
\frac{\beta(R^H-R^L(\alpha\frac{1-\frac{2f-\kappa_1}{\lambda}}{1-2f}+1-\alpha))}{\beta R^H+(1-\beta)R^L-1+(1-\beta)+(1-\alpha)\beta} \geq \kappa_0, \tag{IA111}
$$

- $f > f^{OTC}$ if

$$
\alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H)-(1-\beta)\kappa_2 w_1^L\Big)+(1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H)-(1-\beta)\kappa_2 k_0\Big)
$$
$$
\geq (\beta R^H+(1-\beta)R^L-1)k_0\kappa_0 \tag{IA112}
$$
$$
\frac{\beta(R^H-(\alpha+(1-\alpha)\frac{R^L+\kappa_2(1-2\frac{c_{1,f>f^{OTC}}-1}{\kappa_1})}{2-c_{1,f>f^{OTC}}})c_{1,f>f^{OTC}})}{\beta R^H+(1-\beta)R^L-1+(1-\beta)(\alpha 2\frac{c_{1,f>f^{OTC}}-1}{\kappa_1}+(1-\alpha))} \geq \kappa_0. \tag{IA113}
$$

The collateral premium in the OTC market is therefore defined by

$$
\mathbf{cp}^{OTC} = \begin{cases}
\frac{\beta(R^H-R^L(\alpha\frac{1}{1-2f}+1-\alpha))}{\beta R^H+(1-\beta)R^L-1+\alpha(\beta\frac{\kappa_1-2f}{1-2f}+(1-\beta)2f)\frac{1}{\kappa_1}+(1-\alpha)}-\kappa_0, & \text{if } 0 < f \leq \frac{\kappa_1}{2}, \\
\frac{\beta(R^H-R^L(\alpha\frac{1-\frac{2f-\kappa_1}{\lambda}}{1-2f}+1-\alpha))}{\beta R^H+(1-\beta)R^L-\alpha\beta}-\kappa_0, & \text{if } \frac{\kappa_1}{2} < f \leq f^{OTC}, \\
\frac{\beta(R^H-(\alpha+(1-\alpha)\frac{R^L+\kappa_2(1-2\frac{c_{1,f>f^{OTC}}-1}{\kappa_1})}{2-c_{1,f>f^{OTC}}})c_{1,f>f^{OTC}})}{\beta R^H+(1-\beta)R^L-1+(1-\beta)(\alpha 2\frac{c_{1,f>f^{OTC}}-1}{\kappa_1}+(1-\alpha))}-\kappa_0, & \text{if } f > f^{OTC}.
\end{cases} \tag{IA114}
$$

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 CCP market

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

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

$$\alpha\Big((\beta R^H + (1-\beta)R^L)i_0 - c_2^P \ell_1^P - \kappa_2 w_1^P\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA115}$$
$$\frac{\beta(R^H - R^L)}{\beta R^H + (1-\beta)R^L + (1-\alpha)} \geq \kappa_0 \tag{IA116}$$

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

$$\alpha\Big((\beta R^H + (1-\beta)R^L)(i_0 - z_1^P) - c_2^P \ell_1^P - \kappa_2 k_0\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA117}$$
$$\frac{(R^H - R^L)(\beta + \alpha(1-\beta)\frac{f-\kappa_1}{\lambda})}{\beta R^H + (1-\beta)R^L} \geq \kappa_0 \tag{IA118}$$

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

$$\alpha\Big(-\kappa_2 k_0\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P \ell_{1,f=0}^P - k_2 w_{1,f=0}^P\Big)$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 k_0 \tag{IA119}$$
$$\frac{(1-\alpha)\beta(R^H - R^L)}{\beta R^H + (1-\beta)R^L} \geq \kappa_0 \tag{IA120}$$

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

$$\mathbf{cp}^{COB} = \begin{cases} \frac{\beta(R^H-R^L)}{\beta R^H+(1-\beta)R^L+(1-\alpha)} - \kappa_0, & \text{if } 0 < f \leq \kappa_1, \\ \frac{(R^H-R^L)(\beta+\alpha(1-\beta)\frac{f-\kappa_1}{\lambda})}{\beta R^H+(1-\beta)R^L} - \kappa_0, & \text{if } \kappa_1 < f \leq f^{COB}, \\ \frac{(1-\alpha)\beta(R^H-R^L)}{\beta R^H+(1-\beta)R^L} - \kappa_0, & \text{if } f > f^{COB}. \end{cases} \tag{IA121}$$

G 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 H, borrowers can signal their types through the loan contract and, consequently, lenders provide different loan contracts to different types. In Appendices C.4 and H.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 $f \leq f^{COB}$. The H-type borrower makes identical profits in both separating and pooling equilibrium while the L-type borrower is strictly better off in the pooling equilibrium. The pooling equilibrium also yields weakly larger ex-ante welfare than the separating equilibrium for most parameter values. We provide the proof in the following subsection.

G.1 Welfare dominance

Ex-ante welfare in the separating and pooling equilibrium differ and are non-monotonic. To develop some intuition for the difference, observe that welfare in the separating equilibrium is identical to welfare in the constrained efficient 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 efficient solution), 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 efficient 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 2, 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 $f^{Sep} < f \leq f^{COB}$ with probability α and $f = 0$ with probability $1 - \alpha$.

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

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

$$
\begin{aligned}
W^{Sep} = \alpha\Big(& R^H i_0 - c_2^{S,H}\ell_1^{S,H} + R^L(i_0 - z_1^{S,L}) - c_2^{S,L}\ell_1^{S,L} - \kappa_2 w_1^{S,L} + c_2^{S,H}\ell_1^{S,H} + c_2^{S,L}\ell_1^{S,L} - \ell_1^{S,H} - \ell_1^{S,L} \\
& +2c_1\ell_0 - 2\ell_0\Big) + (1-\alpha)\Big(R^H i_0 - c_{2,f=0}^{S,H}\ell_{1,f=0}^{S,H} + R^L i_0 - c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L} \\
& +c_{2,f=0}^{S,H}\ell_{1,f=0}^{S,H} + c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L} - \ell_{1,f=0}^{S,H} - \ell_{1,f=0}^{S,L} + 2c_1\ell_0 - 2\ell_0\Big) \qquad \text{(IA122)} \\
= {} & (R^H + R^L - 2)m - \alpha(2f(\frac{R^L}{\lambda} - 1) - \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_0}{\kappa_0})) \qquad \text{(IA123)}
\end{aligned}
$$

Ex-ante welfare in the pooling equilibrium is:

$$
\begin{aligned}
W^{Pool} = \alpha\Big(& (R^H + R^L)(i_0 - z_1^P) - 2c_2^P\ell_1^P + 2\kappa_2(k_0 - w_1^P) - 2k_0\kappa_0 + 2c_2^P\ell_1^P - 2\ell_1^P + 2c_1\ell_0 - 2\ell_0\Big) \\
& +(1-\alpha)\Big((R^H + R^L)i_0 - 2c_{2,f=0}^P\ell_{1,f=0}^P + 2c_{2,f=0}^P\ell_{1,f=0}^P - 2\ell_{1,f=0}^P + 2c_1\ell_0 - 2\ell_0\Big) \qquad \text{(IA124)} \\
= {} & (R^H + R^L - 2)m - \alpha(f(\frac{R^H + R^L - 2\lambda}{\lambda} - 1) - \kappa_1(\frac{R^H + R^L}{\lambda} - 2\frac{\kappa_0}{\kappa_0})) \qquad \text{(IA125)}
\end{aligned}
$$

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 $\frac{R^H - R^L}{R^H} f < f$.

G.2 Market coexistence

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 case of COB trading in the CCP market

$$
\begin{aligned}
E(\Pi^{COB}) = & \alpha\Big((\beta R^H + (1-\beta)R^L)(i_0 - z_1^P) - c_2^P\ell_1^P - \kappa_2 k_0\Big) + (1-\alpha)\Big((\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}^P\ell_{1,f=0}^P\Big) \\
= & \beta(R^H - R^L) - \kappa_0 + \alpha(1-\beta)(R^H - R^L)\frac{f - \kappa_1}{\lambda}. \qquad \text{(IA126)}
\end{aligned}
$$

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

$$\begin{aligned}E(\Pi^{OTC}) =&\alpha\Big(\beta(R^H i_0 - c_2^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big) + (1-\alpha)\Big(\beta(R^H i_0 - c_{2,f=0}^{OTC}\ell_1^H) - (1-\beta)\kappa_2 k_0\Big)\\ =&\beta(R^H - R^L) - \kappa_0 + \alpha\beta(\kappa_0 - R^L\frac{2f - \frac{2f-\kappa_1}{\lambda}}{1-2f}).\end{aligned} \tag{IA127}$$

Define $\bar{\lambda}$ by

$$\begin{aligned}&E(\Pi^{CCP}) - E(\Pi^{OTC}) = 0\\ &\bar{\lambda} = \frac{(1-\beta)(R^H - R^L)(f-\kappa_1) + \beta R^L\frac{2f-\kappa_1}{1-2f}}{\beta(\kappa_0 - \frac{2f}{1-2f}R^L)}\end{aligned} \tag{IA128}$$

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

H Separating equilibrium

We specify beliefs as follows:

$$Pr(R^H|c_2) = \begin{cases} 1 & \text{if } c_2 = c_2^{S,H}, \\ 0 & \text{if } c_2 = c_2^{S,L}, \\ 1 & \text{otherwise .}\end{cases} \tag{IA129}$$

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

$$R^\omega(i_0 - z_1^{S,\omega}) - c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 - w_1^{S,\omega}) \ge 0, \tag{IA130}$$

the repayment condition is met,

$$-c_1\ell_0 + \lambda z_1^{S,\omega} + \ell_1^{S,\omega} + \kappa_1 w_1^{S,\omega} = 0, \tag{IA131}$$

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

$$R^\omega(i_0 - z_1^{S,\omega}) - c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 - w_1^{S,\omega}) \ge R^\omega(i_0 - z_1^{S,-\omega}) - c_2^{S,-\omega}\ell_1^{S,-\omega} + \kappa_2(k_0 - w_1^{S,-\omega}), \tag{IA132}$$

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

$$R^\omega(i_0 - z_1^{S,\omega}) - c_2^{S,\omega}\ell_1^{S,\omega} + \kappa_2(k_0 - w_1^{S,\omega}) \ge R^\omega(i_0 - z_1') - c_2'\ell_1' + \kappa_2(k_0 - k_1'). \tag{IA133}$$

Second-round lenders are willing to provide a loan if

$$c_2^{S,\omega} \ge 1. \tag{IA134}$$

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

$$R^L(i_0 - z_{1,f=0}^{S,L}) - c_{2,f=0}^{S,L}\ell_{1,f=0}^{S,L} + \kappa_2(k_0 - w_{1,f=0}^{S,L}) = 0 \tag{IA135}$$

$$c_{2,f=0}^{S,L} = \frac{R^L i_0 + \kappa_2 k_0}{\ell_{1,f=0}^{S,L}} \tag{IA136}$$

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 IA132 and IA133 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:

$$R^L i_0 - c_2^{S,L}\ell_1^{S,L} + \kappa_2(k_0 - w_1^{S,L}) = 0 \tag{IA137}$$

$$c_2^{S,L} = \frac{R^L i_0 + \kappa_2(k_0 - w_1^{S,L})}{\ell_1^{S,L}} \tag{IA138}$$

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 (IA132), is binding and their participation constraint, in expression (IA130), 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

$$\frac{\kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \geq c_2^{S,H} \geq \frac{\kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \tag{IA139}$$

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 IA133 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:

$$R^L(i_0 - z_1^{S,L}) - c_2^{S,L}\ell_1^{S,L} = 0 \tag{IA140}$$

$$c_2^{S,L} = \frac{R^L(i_0 - z_1^{S,L})}{\ell_1^{S,L}} \tag{IA141}$$

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 (IA132), is binding and their participation constraint, in expression (IA130), 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

$$\frac{R^H z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \geq c_2^{S,H} \geq \frac{R^L z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} \tag{IA142}$$

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 IA142, $c_2^{S,H} = \frac{R^L z_1^{S,L} + \kappa_2 w_1^{S,L} + c_2^{S,L}\ell_1^{S,L}}{\ell_1^{S,H}} = \frac{R^L i_0 + \kappa_2 k_0}{c_1\ell_0}$.

With $c_2' = R^L + \kappa_2$, $\ell_1' = c_1\ell_0$ and $k_1' = 0$ it is straightforward to show that condition IA133 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

$$c_1 \geq 1. \tag{IA143}$$

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

$$\beta\Big(\alpha(R^H i_0 - c_2^{S,H}\ell_1^{S,H}) + (1-\alpha)(R^H i_0 - c_{2,f=0}^{S,H}\ell_{1,f=0}^{S,H})\Big) - \alpha(1-\beta)\kappa_0 m$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 m \tag{IA144}$$
$$\frac{\beta(R^H - R^L - \kappa_2)}{\beta R^H + (1-\beta)R^L + \alpha(1-\beta) - 1} \geq \kappa_0 \tag{IA145}$$

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, $c_{2,f>f^{Sep}}^H = 1$ and $\ell_{1,f>f^{Sep}}^H = c_{1,f>f^{Sep}}\ell_0$. 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

$$-c_1^D\ell_0 + \lambda i_0 + \kappa_1 k_0 = 0 \tag{IA146}$$
$$c_1^D = \lambda + \kappa_1. \tag{IA147}$$

If $f = 0$, we construct an equilibrium with $\ell_{1,f=0}^H = c_{1,f>f^{Sep}}\ell_0$, $\ell_{1,f=0}^L = 2m - \ell_{1,f=0}^H$, $w_{1,f=0}^H = 0$, $w_{1,f=0}^L = \frac{c_{1,f>f^{Sep}}\ell_0 - \ell_{1,f=0}}{\kappa_1}$, $z_{1,f=0}^L = 0$, $z_{1,f=0}^H = 0$.

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

$$R^L i_0 - c_{2,f=0}^L\ell_{1,f=0}^L + \kappa_2(k_0 - w_{1,f=0}^L) = 0 \tag{IA148}$$
$$c_{2,f=0}^L = \frac{R^L i_0 + \kappa_2(k_0 - w_{1,f=0}^L)}{\ell_{1,f=0}^L} \tag{IA149}$$

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

$$\frac{\kappa_2 w_{1,f=0}^L + c_{2,f=0}^L\ell_{1,f=0}^L}{\ell_{1,f=0}^H} \geq c_{2,f=0}^H \geq \frac{\kappa_2 w_{1,f=0}^L + c_{2,f=0}^L\ell_{1,f=0}^L}{\ell_{1,f=0}^H} \tag{IA150}$$

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

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 IA133 is satisfied for both types.

At $t = 0$, competitive lenders require

$$\alpha(\beta c_{1,f>f^{Sep}} + (1-\beta)c_1^D) + (1-\alpha)c_{1,f>f^{Sep}} = 1 \tag{IA151}$$
$$c_{1,f>f^{Sep}} = \frac{1 - \alpha(1-\beta)c_1^D}{\alpha\beta + (1-\alpha)} \tag{IA152}$$

Borrowers decide to invest in the long-term technology if

$$\beta\Big(\alpha(R^H i_0 - c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}}) + (1-\alpha)(R^H i_0 - c^{S,H}_{2,f=0}\ell^{S,H}_{1,f=0})\Big) - (1-\beta)\kappa_2 m$$
$$\geq (\beta R^H + (1-\beta)R^L - 1)\kappa_0 m \tag{IA153}$$
$$\frac{\beta(R^H - \alpha c_{1,f>f^{Sep}} - (1-\alpha)R^L)}{\beta R^H + (1-\beta)R^L - 1 + (1-\beta) + \beta(1-\alpha)} \geq \kappa_0. \tag{IA154}$$

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

H.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

$$R^H i_0 - c^{S,H}_2\ell^{S,H}_1 + R^L i_0 - c^{S,L}_2\ell^{S,L}_1 - \kappa_2 w^{S,L}_1 + c^{S,H}_2\ell^{S,H}_1 + c^{S,L}_2\ell^{S,L}_1 - \ell^{S,H}_1 - \ell^{S,L}_1 + 2c_1\ell_0 - 2\ell_0 \tag{IA155}$$
$$=R^H i_0 + R^L i_0 - \kappa_2 w^{S,L}_1 - \ell^{S,H}_1 - \ell^{S,L}_1 \tag{IA156}$$
$$=(R^H + R^L - 2)m - 2f(\frac{\kappa_2}{\kappa_1} - 1)m. \tag{IA157}$$

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

$$R^H i_0 - c^{S,H}_2\ell^{S,H}_1 + R^L(i_0 - z^{S,L}_1) - c^{S,L}_2\ell^{S,L}_1 - \kappa_2 w^{S,L}_1 + c^{S,H}_2\ell^{S,H}_1 + c^{S,L}_2\ell^{S,L}_1 - \ell^{S,H}_1 - \ell^{S,L}_1 + 2c_1\ell_0 - 2\ell_0 \tag{IA158}$$
$$=R^H i_0 + R^L(i_0 - z^{S,L}_1) - \kappa_2 w^{S,L}_1 - \ell^{S,H}_1 - \ell^{S,L}_1 \tag{IA159}$$
$$=(R^H + R^L - 2)m - 2f(\frac{R^L}{\lambda} - 1)m + \kappa_1(\frac{R^L}{\lambda} - \frac{\kappa_2}{\kappa_1})m. \tag{IA160}$$

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

$$R^H i_0 - c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}} + c^H_{2,f>f^{Sep}}\ell^H_{1,f>f^{Sep}} - \ell^H_{1,f>f^{Sep}} + c_{1,f>f^{Sep}}\ell_0 + \lambda i_0 + \kappa_1 k_0 - \kappa_2 k_0 - 2\ell_0 \tag{IA161}$$
$$=(R^H + \lambda + \kappa_1 - \kappa_2 - 2)m \tag{IA162}$$

H.2 Intuitive criterion: separating equilibrium

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

$$Pr(R^H|c_2) = \begin{cases} 1 & \text{if } c_2 = c^{S,H}_2, \\ 0 & \text{if } c_2 = c^{S,L}_2, \\ 1 & \text{otherwise }. \end{cases} \tag{IA163}$$

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:

$$0 > R^L m - c'_2 m + \kappa_2 m$$
$$c'_2 > R^L + \kappa_2.$$

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

I Caps and floors on OTC and CCP trading

We study a set of policy instruments consisting of loan volume caps or floors at the rollover stage $t = 1$. The objective is to compare the welfare effect of these instruments to the POMS.

1.–2. Trading regulations. Regulations 1. and 2. are identical in terms of equilibrium quantities and interest rates. Because of scarce funding, we assume borrower competition in all of the analysis. Recall, in the anonymous CCP market borrowers obtain one-fits-all loans, ℓ_1^P, regardless of borrower type and there is discriminatory lending in the non-anonymous OTC market ℓ_1^ω.

We need show that $\ell_1^P = L_1^L$, $\ell_1^L = 0$, $\ell_1^H = L_1^H - \ell_1^P$ and c_2 given by (34) indeed constitute an equilibrium in which L-type and H-type pool in the CCP market and the L-type obtains funding exclusively from the CCP and only the H-type obtains additional funding from the OTC market.

Suppose, and we will show this holds in equilibrium, that the initial investment is $i_0 = \ell_0 = m$ and that first-round lenders break even $c_1 = 1$. Then we can write

$$
L_1^H = c_1\ell_0 - \kappa_1 k_0 = (1-\kappa_1)m, \tag{IA164}
$$

$$
L_1^L = 2(1-f)m - L_1^H = (1 - 2f + \kappa_1)m \text{ and} \tag{IA165}
$$

$$
z_1^L = \frac{c_1\ell_0 - L_1^L - \kappa_1 k_0}{\lambda} = \frac{2(f-\kappa_1)}{\lambda}m. \tag{IA166}
$$

The L-type's IR constraint is satisfied by construction and

$$
c_2 = R^L \frac{i_0 - z_1^L}{L_1^L}, \tag{IA167}
$$

$$
c_2 = R^L \frac{1 - \frac{2(f-\kappa_1)}{\lambda}}{1 - 2f + \kappa_1}. \tag{IA168}
$$

The H-type's IR is satisfied if

$$
R^H i_0 - c_2 L_1^H \geq 0, \tag{IA169}
$$

$$
R^H \frac{i_0}{L_1^H} \geq c_2. \tag{IA170}
$$

It can be shown that if $\frac{R^H}{R^L} > \frac{1-\kappa_1}{\lambda}$, then $R^H \frac{i_0}{L_1^H} \geq c_2$.

Next, we consider incentive compatibility (IC) in the anonymous CCP market and we assume (in an Intuitive Criterion spirit) that the off-equilibrium contract to which borrowers can deviate satisfies their funding needs $\ell_1' = c_1\ell_0$ such that $z_1' = w_1' = 0$ and $c_2' = R^L + \kappa_2$. Then the L-type's IC is satisfied since

$$
R^L(i_0 - z_1^L) - c_2 L_1^L \geq R^L(i_0 - z_1') - c_2\ell_1^L - c_2'\ell_1' + \kappa_2(k_0 - w_1'). \tag{IA171}
$$

Next, we show that the H-type's IC is satisfied too, with $\ell_1' = c_1\ell_0 - \ell_1^H$,

$$
R^H i_0 - c_2 L_1^H \geq R^L(i_0 - z_1') - c_2\ell_1^H - c_2'\ell_1' + \kappa_2(k_0 - w_1'), \tag{IA172}
$$

if $R^L > \frac{\lambda}{(1-\lambda)}\kappa_2$.

Second-round lenders are willing to provide loans as long as

$$c_2 = R^L \frac{1 - \frac{2(f-\kappa_1)}{\lambda}}{1 - 2f + \kappa_1} \geq 1, \tag{IA173}$$

$$\frac{(R^L - 1)\lambda + \kappa_1(2R^L - \lambda)}{2(R^L - \lambda)} \geq f. \tag{IA174}$$

3. CCP shut down. As an alternative regulation, the policy maker can implement a cap in the OTC market and close the CCP. The cap is given by the maximum loan the H-type should obtain so that they are forced to liquidate collateral, L_1^H. Borrower competition pins down the equilibrium quantities.

The run threshold, just like in 1. and 2., is given second-round lenders' IR:

$$c_2 = R^L \frac{1 - \frac{2(f-\kappa_1)}{\lambda}}{1 - 2f + \kappa_1} \geq 1 \tag{IA175}$$

$$\frac{(R^L - 1)\lambda + \kappa_1(2R^L - \lambda)}{2(R^L - \lambda)} \geq f. \tag{IA176}$$

These conditions yield the same threshold as in 1. and 2.

At $t = 0$, a funding shock $\kappa_1 < f < f^{cap}$ occurs with probability α and no funding shock $f = 0$ with probability $1 - \alpha$. Note that if $f = 0$ (with probability $1 - \alpha$ at $t = 0$), regardless of whether trade takes place over the CCP or OTC, $c_{2,f=0} = R^L + \kappa_2$ and $\ell_1 = \ell_1^P = \ell_1^H = \ell_1^L = m$. Hence, we can write a borrower's IR at $t = 0$ as

$$\begin{aligned}(1-\alpha)(\beta R^H + (1-\beta)R^L)i_0 - c_{2,f=0}\ell_1) + \alpha(\beta(R^H i_0 - c_2 L_1^H) - \kappa_2 k_0)\\ \geq (\beta R^H + (1-\beta)R^L - 1)k_0\kappa_0.\end{aligned} \tag{IA177}$$

With $i_0 = \ell_0 = m$ and lender competition for borrowers $c_1 = 1$, the borrower's IR holds if

$$\frac{\beta R^H - R^L(1 - \alpha + \alpha\frac{1-\frac{2(f-\kappa_1)}{\lambda}}{1-2f+\kappa_1}(1-\kappa_1)}{\beta R^H + (1-\beta)R^L} \geq \kappa_0. \tag{IA178}$$