Rewiring repo

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Abstract

We develop a model of the repo market with strategic interactions among dealers who compete for funding in a decentralized over-the-counter market and have access to a centrally cleared interdealer market. We show that such "wiring" of the repo market combined with imperfect competition in dealer funding could result in market inefficiencies and instability. The model allows us to disentangle supply and demand factors, and we use these factors to estimate supply and demand elasticities. Our estimates suggest that the instability of the market in September 2019 was driven by a large supply shock facing inelastic dealer funding demand, amplified by strategic interactions among dealers. We evaluate different interventions for market functioning and efficiency, including the Standing Repo Facility.

JEL Classification: G23, L14, L16

Keywords: Networked markets, repo market, Standing Repo Facility, over-the-counter markets, market efficiency, centrally cleared markets

1 Introduction

Financial markets are often assumed to be efficient, but evidence suggests otherwise. Imperfect competition, market segmentation, and associated frictions could result in deviations from market efficiency. Inefficient financial markets are less resilient to shocks and could affect the stability of the financial system.

One large financial market that has exhibited instability is the tri-party repo market for government securities. The market is a general collateral repo market for Treasury and agency mortgage-backed securities (MBS) with about $4 trillion in daily transactions at the end of 2022.[1] The tri-party repo market provides funding for dealers, is a conduit of U.S. monetary policy implementation, and its market rates form the basis of the Secured Overnight Financing Rate (SOFR),the reference rate for trillions of dollars of loan and derivative contracts.

The tri-party repo market has experienced recent episodes of instability. In September 2019, repo spreads spiked, absent credit risk events or a financial crisis. In March 2020, repo spreads also climbed, reverberating the financial market shock associated with the onset of the COVID-19 pandemic. The Federal Reserve intervened by conducting temporary repo operations in 2019 and 2020 to provide additional cash to dealers. Later, the Federal Reserve established the Standing Repo Facility (SRF) as a liquidity backstop aimed at supporting monetary policy implementation and market functioning. Following the episodes of market stress, regulators have started to examine Treasury cash and repo market structure. Many recent proposals introduce central clearing of contracts to support market efficiency and stability.

Our paper examines factors that affect tri-party repo market efficiency and stability. We argue that the structure of the repo market, or the *wiring of the market*, when combined with imperfect competition among market participants, affects the potential for the repo market to amplify shocks. The structure of the tri-party repo market integrates four components. The first component is a decentralized over-the-counter (OTC) funding market, characterized by stable relationships between borrowing dealers and cash lenders. The second component is a centrally cleared anonymous interdealer segment, where no additional aggregate cash is provided to dealers, but some dealers borrow and other dealers lend. The third component is a bilateral segment be-

[1] Agency mortgage-backed securities are issued by a government-sponsored enterprise (GSE). Information on the size of the tri-party repo market and its different segments can be found at Federal Reserve Bank of New York Tri-Party and GCF Repo website.

tween lending dealers and other borrowing counterparties in which specific collateral is pledged. The final component incorporates the repo and reverse repo operations of the the Federal Reserve, which borrows cash through the Overnight Reverse Repurchase Agreement Program (ON RRP) and lends cash through the Standing Repo Facility (SRF).

Our main hypothesis is that imperfect competition and strategic interactions of dealers in the decentralized market, in which dealers compete for quantities, alongside an anonymous centrally cleared market, in which dealers face a common borrowing rate, amplify shocks and result in market instability. Large shifts in cash demand arising from the bilateral segment or large supply shocks in the OTC segment can also be destabilizing. Federal Reserve operations on both the lending side and the borrowing side can dampen supply and demand shocks and decrease volatility in rates. However, such interventions, if not parameterized properly, could introduce inefficiencies related to crowding-out of private borrowing and lending relationships.

Our analysis has three main components. First, we introduce a model of a decentralized networked market with established trading relationships among dealers and cash lenders. We assume that dealers compete in quantities in the decentralized market in the spirit of Cournot. However, unlike the standard Cournot competition in a single market, competition occurs in a networked market in which strategic substitutability or complementarity of actions depends on the nature of connectedness or "wiring" of the market. We show that when interacting with common lenders, dealers' funding decisions are strategic substitutes, but depending on the wiring of the market, dealers' funding decisions across non-common lenders could be strategic complements, which results in amplification of supply shocks.

We prove the existence and uniqueness of the equilibrium both without and with a centrally cleared market, and illustrate differences in strategic interactions depending on the existence of a centrally cleared market. Without a centrally cleared market, both individual supply and demand shocks affect all equilibrium quantities. Individual dealer demand shocks have larger effects on dealers that compete directly relative to those that compete indirectly. With a centrally cleared market, dealers' interactions are coordinated by the equilibrium rate in the centrally cleared market. The equilibrium rate aggregates individual demand conditions, which implies that all dealer-specific demand shocks affect the equilibrium rate equally, and so idiosyncratic demand shocks have less price impact than they do in market wirings without central clearing. In contrast, the centrally cleared market introduces higher sensitivity to supply, particularly from lenders with certain characteristics, including a form of higher supply elasticities in the decentralized market, a concept closely related to Katz-Bonacich centrality. This asymmetry between the effects of demand shocks and supply shocks is due to the existence of a centrally cleared market in which only dealers but not lenders can participate.

Second, we empirically estimate and test the predictions of the model. To resolve the endogeneity of quantities and prices, we decompose observed movements in quantities into dealer demand and lender supply factors following Amiti and Weinstein [2018]. With these factors in hand, first, we test for strategic substitutability in actions in the decentralized market. We establish that if a dealer's competitors increase borrowing from a common lender by a percentage point, the dealer responds by reducing its borrowing from the common lender by 30 basis points. Second, we use the supply and demand factors as instruments to estimate micro-level and aggregate supply and demand elasticities. Our estimates indicate dealer demand is substantially less elastic than lender supply. The estimates of the demand elasticity for dealers, which takes into account the endogenous participation of dealers in the interdealer market as either a borrower or a lender, indicates that net borrowers in the GCF market reduce borrowing by \$0.028 billion for every 1 basis point increase in repo spreads, whereas dealers are willing to supply an additional \$0.042 billion in funding for every 1 basis point widening in spreads. The estimated aggregate lender supply elasticity is substantially larger than the dealer demand elasticities. While small cash lenders may face capacity constraints, in the aggregate, unconstrained lenders are willing to supply an additional \$4 billion to \$6.5 billion of funding for every 1 basis point increase in spreads depending on the empirical specifications. Third, we create indices that track the build-up of imbalances in the repo market by aggregating the demand and supply factors identified in the previous step. These indices reveal that the disruptions in the repo markets on September 17, 2019, were due to a large supply shock facing inelastic dealer demand and our elasticity estimates can match the magnitudes of the repo spikes. Furthermore, as predicted by the model, the large supply shocks propagated through more central dealer-lender trading relationships.

Finally, we examine how the SRF could affect equilibrium quantities and prices. We show that the SRF introduces a trade-off between providing a liquidity buffer to the repo market and potentially crowding out relationships in the decentralized market. An optimal SRF design involves the calibration of quantity caps and the minimum bid rate to achieve a desirable balance between the use of SRF as a liquidity backstop and the incentives of dealers to maintain relationships with lenders.

Our paper contributes to the empirical and theoretical literature on repo markets. The empirical literature often focuses on measuring repo market characteristics and describing key parts of its structure. For example, [Krishnamurthy, Nagel, and Orlov, 2014; Hu, Pan, and Wang, 2020] describe the market size and pricing of repo trades, [Anderson and Kandrac, 2017; Munyan, 2015] discuss monetary policy implementation and regulatory factors, and [Cocco, Gomes, and Martins, 2009; Han and Nikolaou, 2016; Anbil, Anderson, and Senyuz, 2020] explore the role of long-term trading relationships. Similar to our work, Huber [2023] applies a structural industrial organization model to the repo market, but focuses on the role of money market mutual funds. Copeland, Duffie, and Yang [2025] attribute the September 2019 spikes in repo rates to declines in reserves at large bank holding companies. We build on these results and examine lower-frequency strategic mechanisms that amplify supply and demand shocks and result in rate spikes.

Beyond the literature on measurement and market structure, other literature explores repo market instability. Brunnermeier and Pedersen [2009] characterizes mechanisms that generate market instability and feedback loops between borrowing capacity and liquidity in collateralized markets, and Gorton and Metrick [2012] and Gorton, Laarits, and Metrick [2020] provide empirical evidence for these feedback loops during the Global Financial Crisis. Martin, Skeie, and Von Thadden [2014] present a model of repo runs akin to bank runs, while Infante and Vardoulakis [2020] discuss repo runs that occur on the collateral assets rather than liabilities. Ennis [2011] emphasises the fragility of the tri-party repo market in the presence of strategic cash lenders and the provision of intraday credit by the custodian bank. Chang [2019] and Chang and Chuan [2024] show how contagion through both debt and collateral channels can lead to collapse in the repo market. Our analysis emphasizes a novel mechanism through which the repo market can become unstable; that is, imbalances in supply and demand that are amplified by strategic interactions in the decentralized market and market clearing conditions in the centralized market.

We also contribute to a growing literature on networked markets. Kranton and Minehart [2001] were first to illustrate that network structure determines market efficiency, and Elliott [2015] shows how differences in bargaining power and incentives to form relationships can lead to market inefficiency. Manea [2011] studies how bargaining is affected by network structure, while Nava [2015] and Wittwer [2021] show that networked markets approach efficiency with greater numbers of counterparties. Other literature has introduced imperfect competition in networked markets, including Bulow, Geanakoplos, and Klemperer [1985], Vives [2002], Vives [2011], Nava [2015], Malamud and Rostek [2017], and Bimpikis, Ehsani, and İlkılıç [2019].[2] The Nash equilibrium incorporates the role of the market wiring for the equilibrium quantities and prices and has similar structure to equilibria defined in Ballester, Calvó-Armengol, and Zenou [2006] and Bimpikis, Ehsani, and İlkılıç [2019], where the Nash equilibrium action of each player is proportional to their Bonacich centrality. Similar to Malamud and Rostek [2017], we show that the existence of a centrally cleared market may not always be improving market efficiency. However, unlike Malamud and Rostek [2017], which emphasize differences in risk allocations, we emphasize the effects of different market structures on strategic interactions, clearing of supply and demand imbalances, and their price impacts.

The remainder of the paper is as follows. Section 2 provides stylized facts on the wiring of the repo market. Then section 3 brings those key features into a model of a networked market that features a decentralized market and a centrally cleared market. Section 4 applies the model to the data, develops a decomposition of changes in quantities traded into supply and demand factors, estimates the main model parameters, and tests the main model assumptions and mechanisms. Section 5 explores different counterfactuals based on the estimated model to understand the role of the centrally cleared market for the propagation of supply and demand shocks, their price impacts, and policy interventions in the market including through the introduction of the Standing Repo Facility. Section 6 concludes.

2 The wiring of the tri-party repo market

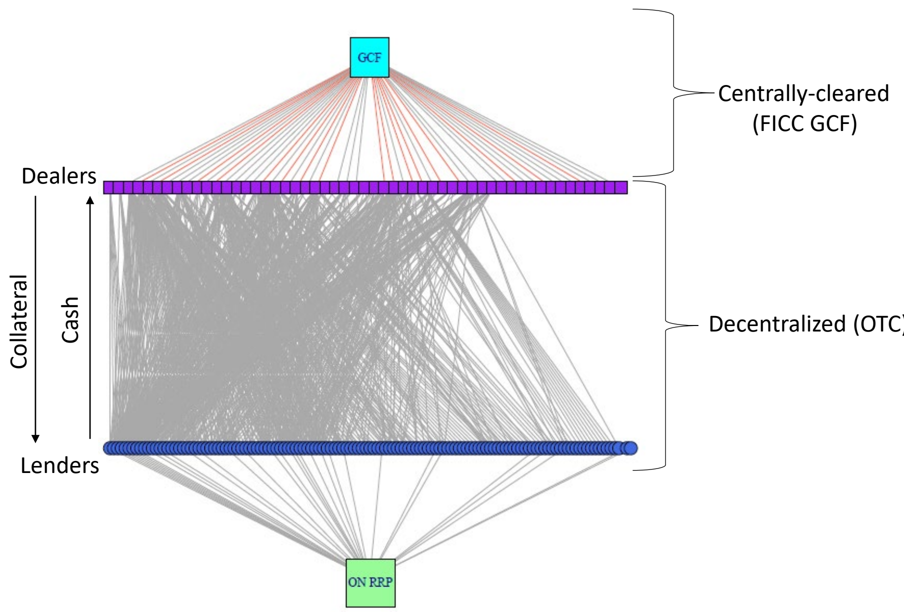
Figure 1 illustrates the wiring of the government collateral tri-party repo market. In the middle is the decentralized OTC repo market. The decentralized market is a bi-partite graph with dealers (purple squares) on one side that borrow cash from lenders (blue circles) on the other side.[3] Each line that connects a dealer with a lender

[2] Rostek and Yoon [2023] reviews the importance of imperfect competition in financial markets.

[3] Government collateral includes U.S. Treasury securities, agency debt, and agency mortgage backed securities (MBS). Private collateral such as asset backed securities (ABS), corporate bonds,

represents a long-term trading relationship between the dealer and the lender.

Figure 1: The wiring of the tri-party repo market



NOTE: The decentralized dealer-lender OTC market is represented by the set of dealers in purple squares and the set of lenders as blue circles at the bottom along with the trading relationships indicated as gray lines among the two. Dealers that borrow from the GCF market are connected with a red line to the GCF, whereas the dealers that lend to the GCF market are connected with a gray line. Lenders with cash held at the Fed's ON RRP are indicated with a line connection to the ON RRP. SOURCE: FRBNY Tri-party repo and the authors' construction.

The market also includes FICC-GCF, which is an anonymous centrally cleared market. It is represented as the node labeled GCF (General Collateral Finance) in the figure. A link between a dealer and the GCF indicates that the dealer on net borrows (red links) or lends (gray links) from the interdealer market. The centrally-cleared market only reallocates cash and collateral among dealers and does not provide additional funding; that is, aggregate borrowing equals aggregate lending.

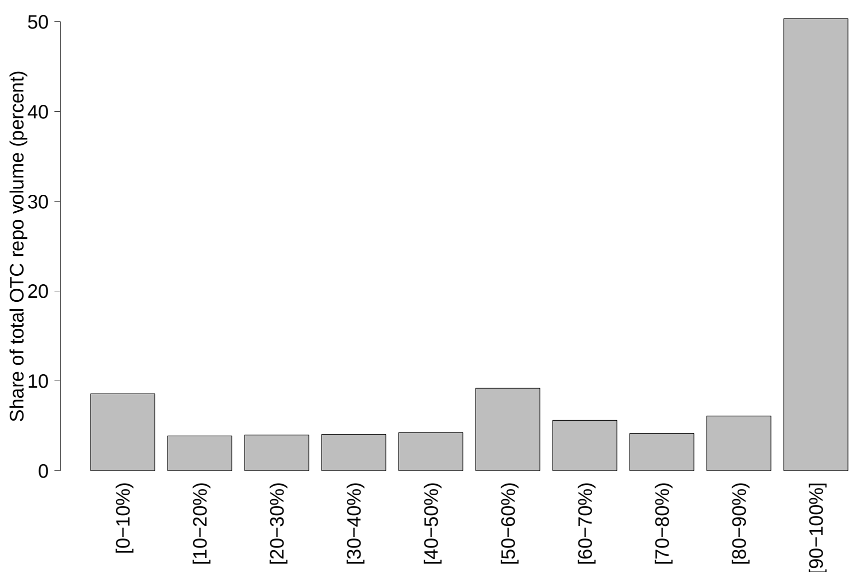
Finally, the Federal Reserve's overnight reverse repo (ON RRP) facility is illustrated as a node at the bottom of the decentralized market. Not all lenders have

equities, and private-label MBS are used in a smaller segment of the tri-party repo market, with different structure and pricing.

access to the ON RRP facility. However, all lenders that access the ON RRP have a trading relationship with a dealer in the OTC market.

There are several stylized facts that emerge from the repo market wiring. First, the decentralized market is not fully connected. Each dealer borrows from a subset of lenders and no dealer has access to all lenders. Second, some dealers do not borrow from lenders in the decentralized market and instead obtain funding through the centrally-cleared GCF market only. Third, not all dealers participate in the GCF market and only transact in the decentralized market. Fourth, some dealers are net lenders in the GCF market, whereas others are net borrowers. Finally, not all lenders have access to the ON RRP facility. The model in the next section incorporates most of those features of the wiring. The incomplete wiring is also important for the ability to decompose movements in quantities in supply and demand and identify the supply and demand elasticities.

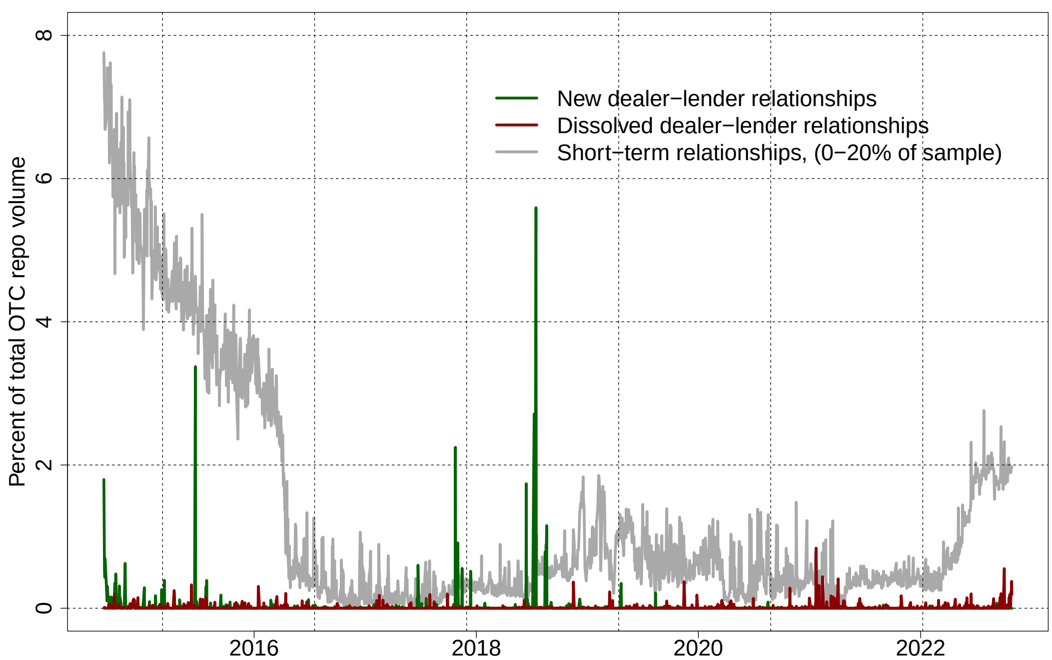
Figure 2: Duration of trading relationships as fraction of the sample period



Note: The x-axis is the duration of dealer-lender relationships as a fraction of the sample period from July 2014 to October 2022 or 2005 trading days. Source: FRBNY Tri-party repo and authors' calculations.

There are also important stylized facts regarding the duration of dealer-lender relationships in the OTC market. Most dealer-lender relationships and especially those that involve the largest counterparties are long-term. Figure 2 reveals that more than 50 percent of aggregate repo trade volume is among dealer-lender trading pairs that transact continuously for most of our sample period. More than 78 percent of the aggregate repo trade volume are among dealers and lenders that trade continuously for at least 50 percent of the sample period or for at least 4 years.

Figure 3: Trading volume at new, dissolved, and short-term trading relationships



NOTE: The graph plots the volume of repo trades at newly established, dissolved, and short-term dealer-lender trading relationships. Short-term trading relationships are defined as those that last no more than a fifth of the sample period or two years or less. SOURCE: FRBNY Tri-party repo and authors' calculations.

Our sample is an unbalanced panel, reflecting both entry and exit of repo counterparties as well as the creation and dissolution of trading relationships. Even so, the market wiring is stable and most trading occurs within long-term dealer-lender relationships. Figure 3 shows that new dealer-lender relationships represent a small share of aggregate trading volume in our sample period, with the largest new dealer-lender relationships contributing no more than 6 percent of aggregate volume.

New relationships often reflect the entry of new counterparties in the sample, and both borrower and lender entrants tend to be smaller than established ones. The dissolution of dealer-lender relationships is infrequent and contributes to a relatively small percent of the aggregate OTC repo trade volume.[4] Finally, the share of OTC repo trades at short-term trading relationships, which last for less than 20 percent our sample or less than two years, comprise less than 2 percent of aggregate OTC repo volume in the middle of our sample. Due to left and right censoring, relationships that are dissolved within 2 years of the start or that are established within 2 years of the end of our sample, are classified as short-term even though their actual duration could exceed two years. The censoring results in higher shares of short-term relationships at the two ends of our sample. Nonetheless, more than 90 percent of trades on any given trading day in our sample are over established long-term relationships.

The stability of the dealer-lender relationships allows us to treat the network of the OTC market as fixed in our theoretical and empirical analysis. In what follows, we use this assumption to characterize the wiring, demand, supply, and stability of the repo market.

3 A model of the repo market

Define the set of dealers as $D = \{d_1, \dots, d_n\}$, where $n = |D|$ is the number of dealers. Dealers lend cash in reverse repo transactions to a range of counterparties in the bilateral segment of the repo market, $\mathcal{B}$. The volume of bilateral reverse repo trades for dealer i is denoted by $q_{\mathcal{B}i}$. The aggregate cash lent by all dealers in bilateral repo is $\bar{q}_{\mathcal{B}} = \sum_{i=1}^{n} q_{\mathcal{B}i}$. Reverse repo transactions in the bilateral repo market determine dealers' cash demand in the tri-party repo market. We treat the dealers' lending commitments $\{q_{\mathcal{B}i}\}_{i \in D}$ as pre-determined. This assumption reflects obligations to satisfy demand for funding by hedge funds or other asset managers as well as obligations by primary dealers to participate in Treasury auctions.[5]

Dealers borrow cash from the two segments of the tri-party repo market to satisfy commitments in $\mathcal{B}$. Reflecting the repo wiring described in Section 2, the first segment is a decentralized over-the-counter (OTC) market denoted by $\mathcal{T}$, which corresponds

[4] There are limited counterparty credit risks in the repo market we are focusing on, as counterparty credit exposures are covered by government collateral and all trades are cleared by the tri-party (Bank of New York Mellon). In times of stress, trading relationships can fluctuate wildly if counterparty risks are of concern Beltran, Bolotnyy, and Klee [2019].

[5] While technically not part of the bilateral repo market, primary dealer participation in Treasury auctions is a determinant of dealers' demand for cash and is assumed to be pre-determined.

to the bipartite dealer-lender component in Figure 1, and the second segment is a centrally cleared interdealer market denoted by $\mathcal{C}$, which corresponds to the GCF market in Figure 1.

The set of cash lenders in $\mathcal{T}$ is denoted by $L = \{\ell_1, \ldots, \ell_m\}$, where $m = |L|$ is the number of lenders in $\mathcal{T}$. With this structure, the decentralized market is described by a bipartite graph $\mathcal{T} = (D \cup L, E)$, where E is the set of trading relationships (edges) from the set of lenders (L) to the set of dealers (D), with a slight abuse of notation of $\mathcal{T}$, denoting both the market and the graph.

For each lender $\ell_k \in L$, we define the set of counterparties $D_k = \{d_i \in D | ik \in E\}$, which is the set of dealers that borrow from lender ℓ_k and the number of dealers borrowing from k are $n_k = |D_k|$. Similarly, for each dealer $d_i \in D$, define the set of counterparties as $L_i = \{\ell_k \in L | ik \in E\}$, which is the set of lenders that lend to dealer d_i and $m_i = |L_i|$ is the number of lender counterparties of d_i.[6]

Dealers can either borrow or lend in $\mathcal{C}$ depending on whether they need or have additional cash at the market clearing rate $\rho_{\mathcal{C}}$. Dealers are price-takers, because the $\mathcal{C}$ market is blind-brokered. It is important to note that the $\mathcal{C}$ is a net zero supply funding market thatonly reallocates cash and collateral among dealers. We refer to the structure that combines the decentralized market and the centrally cleared market $\mathcal{W} = (\mathcal{T}, \mathcal{C})$ as the *"wiring"* of the repo market. We denote $\mathcal{W} = (\mathcal{T}, \varnothing)$, if there is no $\mathcal{C}$ market. We denote the ON RRP as $\mathcal{O}$ and the SRF facility as $\mathcal{S}$.

3.1 Cash lenders and funding supply

A lender k in $\mathcal{T}$ requires a spread s_k over the rate earned from depositing at the Fed's overnight reverse repo facility (ON RRP). This spread linearly increases in the quantity supplied to dealers according to the following inverse supply curve

$$s_k = \tilde{c}_k - \gamma_k \underline{q}_k + \gamma_k \sum_{j \in D_k} q_{jk} = c_k + \gamma_k \sum_{j \in D_k} q_{jk}, \ \forall k \in L. \tag{1}$$

We assume that each lender k has an exogenously given capacity to invest in repo markets $\underline{q}_k$.[7] All else equal, lenders with greater capacity charge lower spreads. Vari-

[6] Note that we use i or d_i as a generic label for a dealer and k or ℓ_k as a generic label for a lender. A generic trading relationship between d_i and ℓ_k is denoted as $ik \in E$.

[7] The supply capacity of a lender can be determined by a portfolio optimization problem or

ations in $c_k = \tilde{c}_k - \gamma_k \underline{q}_k$ are parallel shifts in the supply curve from the perspective of dealers borrowing from k. Lenders have some degree of market power encoded in a lender-specific supply elasticity $\gamma_k > 0$ for all $k \in L$.[8] For the rest of the analysis, we work with the spreads over the benchmark ON RRP rate and we assume that effects of the level of interest rates is encoded in variation in $\{c_k\}_{k \in L}$.

3.2 Cournot competition for funds

Dealers compete in quantities à la Cournot for funding in the $\mathcal{T}$ market.[9] Dealer i competes with other dealers for funding from common lenders and obtains total funding $q_{i\mathcal{T}} = \sum_{k \in L_i} q_{ik}$ from its lending counterparties. Dealers can also borrow from or lend to each other in the interdealer $\mathcal{C}$ market at the market clearing rate $\rho_{\mathcal{C}}$. Taken together, the total net cash borrowed by dealer i is $\bar{q}_i = q_{i\mathcal{C}} + q_{i\mathcal{T}}$, where $q_{i\mathcal{C}}$ is the net amount borrower or lent to the $\mathcal{C}$ market. Given a size of funding commitments $q_{\mathcal{B}i}$, each dealer i minimizes the total cost of funding defined as

$$V_i \equiv \sum_{k \in L_i} \left(c_k + \gamma_k \sum_{j \in D_k} q_{jk} \right) \times q_{ik} + \rho_{\mathcal{C}} q_{i\mathcal{C}} + \frac{\beta_i}{2} \left(\bar{q}_i - q_{\mathcal{B}i} \right)^2. \tag{2}$$

The first term is the cost of borrowing from counterparties in the $\mathcal{T}$ market. The second term is the cost of funds or income from lending in the $\mathcal{C}$ market. The last term is quadratic cost of not meeting the exogeneously given dealer demand $q_{\mathcal{B}i}$. If the dealer is unable to fund its pre-committed $q_{\mathcal{B}i}$, the dealer faces a quadratic cost proportional to the shortfall, with $\beta_i > 0$, $\forall i \in D$ is a dealer-specific shift of the cost of funding shortfalls. The cost can be interpreted either as the costs of failing to deliver promised reverse repo funding or the marginal cost of raising additional funds from internal or external unsecured funding sources to make up for the shortfall.[10]

stochastic variation in a lender's inflows of cash due to investor deposits or withdrawals of funds. In the empirical section, we proxy this capacity with the lenders' cash deposited at the ON RRP.

[8] Although we do not explicitly model the optimization of lenders or the bargaining game between lenders and dealers, shifts in funds supply could result from changes in the relative bargaining power of lenders. Huber [2023] and Beltran [2023] incorporate lender optimization frameworks.

[9] An alternative way of modeling dealer competition is Bertrand. However, Bertrand competition can be ruled out from the observed wiring of the tri-party repo markets and the observed rate dispersion.

[10] For example, the dealer affiliated with a bank holding company can obtain funding from its affiliated commercial bank or, alternatively, a dealer can issue commercial paper or other unsecured

The cost-minimization problem of dealer i is as follows

$$\mathcal{V}_i(q_{\mathcal{B}i}) \equiv \min_{q_{i\mathcal{C}}, \{q_{ik}\}_{k \in L_i}} V_i \tag{3}$$
$$\text{subject to:}$$
$$q_{ik} \geq 0, \qquad \forall k \in L_i$$
$$\bar{q}_i \geq 0,$$

where the first constraint is the non-negativity constraint for the individual amount of borrowing from $\mathcal{T}$ lenders, and the second constraint implies that dealers cannot borrow from the bilateral market to be net lenders in the $\mathcal{C}$ plus $\mathcal{T}$ market.

We focus on interior solutions first, and later provide conditions under which interior solutions consist of equilibrium by Lemma 1. The first-order condition for any dealer $i \in D$ borrowing from lender $k \in L$ with a trading relationship in the $\mathcal{T}$ market (i.e. $ik \in E$) is

$$q_{ik} = \frac{\beta_i q_{\mathcal{B}i} - \beta_i q_{i\mathcal{C}} - c_k}{2\gamma_k + \beta_i} - \frac{\beta_i}{2\gamma_k + \beta_i} \sum_{\substack{l \in L_i \\ l \neq k}} q_{il} - \frac{\gamma_k}{2\gamma_k + \beta_i} \sum_{\substack{j \in D_k \\ j \neq i}} q_{jk}. \tag{4}$$

Dealer i's amount of borrowing from lender k not only depends on dealer i's own demand conditions ($q_{\mathcal{B}i}$ and β_i) and the lender k's supply conditions (γ_k and c_k), but also depends on how the competing dealers $j \in D_k$ are borrowing from lender k and how much dealer i borrows from other lenders $l \in L_i$. Moreover, dealer i will reduce its borrowing amount from the $\mathcal{T}$ market when i borrows more from $\mathcal{C}$ market and vice versa. In other words, dealer i's decision on how much to borrow from lender k depends on Cournot competition with other connected dealers as well as dealer i's own optimization across other sources of funding.

The first-order condition for the net borrowing from the interdealer $\mathcal{C}$ market is

$$q_{i\mathcal{C}} = q_{\mathcal{B}i} - \sum_{k \in L_i} q_{ik} - \frac{1}{\beta_i} \rho_{\mathcal{C}}, \tag{5}$$

for any $i \in D$. A dealer lends in the $\mathcal{C}$ market, i.e. $q_{i\mathcal{C}} < 0$, when the dealer can fund the excess amount of cash from the $\mathcal{T}$ market at a rate lower than $\rho_{\mathcal{C}}$. A dealer borrows cash in the $\mathcal{C}$ market, i.e. $q_{i\mathcal{C}} > 0$, when the dealer's marginal cost of funds

wholesale funding to cover the shortfall.

in the $\mathcal{T}$ market is higher than the rate $\rho_{\mathcal{C}}$. The dealer net borrowing from the $\mathcal{C}$ market has an interest rate sensitivity determined by the inverse of the dealer's funding shortfall cost β_i, so that dealers with higher funding shortfall costs will be less price elastic. Thus, the inverse of β_i is a measure of the interest rate elasticity of dealers' repo demand.

Plugging (5) into (4) gives us the following expression for the optimal amount borrowed of dealer i from cash lender k for interior solutions

$$q_{ik} = \begin{cases} \frac{\beta_i q_{\mathcal{B}i} - c_k}{2\gamma_k + \beta_i} - \frac{\beta_i}{2\gamma_k + \beta_i} \sum_{l \in L_i, l \neq k} q_{il} - \frac{\gamma_k}{2\gamma_k + \beta_i} \sum_{j \in D_k, j \neq i} q_{jk} & \text{if } \mathcal{W} = (\mathcal{T}, \varnothing) \\ \frac{\rho_{\mathcal{C}} - c_k}{2\gamma_k} - \frac{1}{2} \sum_{j \in D_k, j \neq i} q_{jk}, & \text{if } \mathcal{W} = (\mathcal{T}, \mathcal{C}) \,. \end{cases} \tag{6}$$

The dealers' decisions to borrow from common lenders in the $\mathcal{T}$ market are strategic substitutes and the degree of substitution increases if dealers have access to the centrally cleared market, because $\frac{\gamma_k}{2\gamma_k + \beta_i} < \frac{1}{2}$ for all positive γ_k and β_i. We should note that the best response functions (6) reflect only the direct strategic interactions among dealers connected through common lenders. The equilibrium strategic interactions among dealers are more complex once higher-order interactions along the bipartite network are taken into account as we discuss in the next sections.

3.3 Market equilibrium without a $\mathcal{C}$ market

Suppose the wiring of the repo market does not include a $\mathcal{C}$ market. The market equilibrium can be defined as the solution to the system of equations (6) for the wiring $\mathcal{W} = (\mathcal{T}, \varnothing)$, which we formalize as follows.

Definition 1 *A market equilibrium without a $\mathcal{C}$ market is a vector $\{q^*_{ik}\}_{ik \in E}$ of transacted quantities that solves the system of first-order conditions (6) for all $ik \in E$.*

Define the $|E| \times 1$ vector of weights

$$\boldsymbol{\xi} = \left\{ \frac{1}{2\gamma_k + \beta_i} \right\}_{ik \in E} . \tag{7}$$

Then define the marginal surpluses of trade for any dealer-lender trading relationship $ik \in E$ as the $|E| \times 1$ vector

$$\phi(\mathbf{q}_{\mathcal{B}}) = \{\beta_i q_{\mathcal{B}i} - c_k\}_{ik \in E} , \tag{8}$$

where $\beta_i q_{\mathcal{B}i}$ is the marginal benefit of an additional dollar of funding and c_k is the marginal cost. In matrix notation, the system of first-order conditions can be written as

$$\mathbf{q} = \boldsymbol{\xi} \circ \phi(\mathbf{q}_{\mathcal{B}}) - \boldsymbol{\xi} \circ W\mathbf{q},$$

where $\mathbf{q} = \{q_{ik}\}_{ik\in E}$ is a $|E| \times 1$ vector of transacted quantities for each dealer-lender relationship, $\mathbf{q}_{\mathcal{B}} = \{q_{\mathcal{B}i}\}_{i=1}^{n}$ is the vector of dealer repo demand, the operator $\circ$ signifies the Hadamard (element-wise) product, and the matrix W is a $|E| \times |E|$ matrix with elements

$$W_{ik,j\ell} = \begin{cases} \beta_i & \text{if } i = j, k \neq \ell \\ \gamma_k & \text{if } i \neq j, k = \ell \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

The W matrix is the weighted adjacency matrix of the *line graph* of the connections between the dealer-lender pairs, where the *line graph* consists of every dealer-lender relationship $ik \in E$ as a node and an edge between two nodes exists, if the trading pairs share a counterparty.[11] For example, if two dealer-lender pairs are connected with a common dealer i, they are weighted by that dealer's marginal funding cost parameter β_i. If two dealer-lender pairs are connected with a common lender k, then the weight of their connection is the lender supply elasticity γ_k.

Under fairly general conditions discussed in the proof of Proposition 1 in the appendix, we show that there exists an inverse of the matrix $I + \boldsymbol{\xi} \circ W$, which we denote as the $|E| \times |E|$ matrix $\Psi \equiv (I + \boldsymbol{\xi} \circ W)^{-1}$. The equilibrium quantities are

$$\mathbf{q}^* = \Big[I + \boldsymbol{\xi} \circ W\Big]^{-1} (\boldsymbol{\xi} \circ \phi(\mathbf{q}_{\mathcal{B}})) = \Psi(\boldsymbol{\xi} \circ \phi(\mathbf{q}_{\mathcal{B}})). \tag{10}$$

3.4 Market equilibrium with a $\mathcal{C}$ market

Now consider a wiring $\mathcal{W} = (\mathcal{T}, \mathcal{C})$ that includes a $\mathcal{C}$ market. Introducing the $\mathcal{C}$ market results in a system of first-order conditions (4) and (5), that has $|E| + n$ equations with $|E| + n$ unknowns. The market equilibrium is the solution of this system of equations along with an equilibrium rate $\rho_{\mathcal{C}}^*$ that satisfies the $\mathcal{C}$ market

[11] We can formally define the line graph as the transformation from the original bi-partite network $\mathcal{T}$ to the graph $\mathcal{L}(\mathcal{T}) = (E, E^{\mathcal{L}})$. That is every edge in $\mathcal{T}$ is a node in $\mathcal{L}(\mathcal{T})$ and edges are connected if they share a common counterparty $E^{\mathcal{L}} = \{(ik, j\ell) : i = j, k \neq l \text{ or } i \neq j, k = \ell\}_{ik,i\ell\in E}$. See Figure 5 for an example of a line graph transformation of the networks in Figure 4.

clearing condition,

$$\sum_{i \in D} q_{i\mathcal{C}}(\rho^*_{\mathcal{C}}) = 0. \tag{11}$$

To solve for the market equilibrium, first note that (11) pins down the market clearing price $\rho^*_{\mathcal{C}}$, while n unknowns ($q_{i\mathcal{C}}$, $\forall\ i \in D$) are determined by n equations (first-order conditions with respect to $q_{i\mathcal{C}}$, $\forall\ i \in D$). Then, we examine the first-order conditions (6) in matrix form

$$\mathbf{q} = \tilde{\phi}(\rho_{\mathcal{C}}) - \frac{1}{2}\tilde{W}\mathbf{q}, \tag{12}$$

where $\tilde{\phi}(\rho_{\mathcal{C}})$ is a $|E| \times 1$ vector such that

$$\tilde{\phi}_{ik}(\rho_{\mathcal{C}}) = \frac{\rho_{\mathcal{C}} - c_k}{2\gamma_k}, \forall ik \in E, \tag{13}$$

and the $|E| \times |E|$ adjacency matrix $\tilde{W}$ is

$$\tilde{W}_{ik,j\ell} = \begin{cases} 1 & \text{if } i \neq j, k = l \\ 0 & \text{otherwise.} \end{cases} \tag{14}$$

Note that unlike the adjacency matrix (9) of the line-graph for a wiring without $\mathcal{C}$ market, the adjacency matrix of the line-graph of a wiring with a $\mathcal{C}$ market considers connections between two dealer-lender pairs only if they share a common lender. This is because all dealers compare marginal cost of borrowing from available lenders with $\rho_{\mathcal{C}}$, which dealers take as given. Hence, dealers only care about the borrowing quantities of their directly competing dealers that affect the marginal cost of funds from their direct lenders. The increase in the sparsity of the adjacency matrix results in a change in the propagation of supply and demand shocks, which we come back in more detail in the next sections.

Similar to the case without a $\mathcal{C}$ market, the matrix $\left(I + \frac{1}{2}\tilde{W}\right)$ is full rank and its inverse matrix, denoted as $\tilde{\Psi}$, exists.[12] Therefore, the equilibrium quantities for

[12]By construction, the diagonal elements of $\tilde{W}$ are zero and $\tilde{W}$ is symmetric, as $\tilde{W}_{ik,j\ell} = \tilde{W}_{j\ell,ik}$. Hence, $I + \frac{1}{2}\tilde{W}$ will have full rank with diagonal entries being 1 and other entries being either 1/2 or 0. This structure of $\tilde{W}$ guarantees that it is invertible.

the $|E| \times 1$ dealer-lender pairs can be solved as

$$\mathbf{q}(\rho_{\mathcal{C}}) = \left(I + \frac{1}{2}\tilde{W}\right)^{-1} \tilde{\phi}(\rho_{\mathcal{C}}) = \tilde{\Psi}\tilde{\phi}(\rho_{\mathcal{C}}). \tag{15}$$

The equilibrium quantity borrowed by dealer i from lender k is

$$q_{ik}(\rho_{\mathcal{C}}) = \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} \left(\rho_{\mathcal{C}} - c_\ell\right), \qquad \forall ik \in E. \tag{16}$$

Finally, the equilibrium rate $\rho^*_{\mathcal{C}}$ is determined by the market clearing condition

$$\sum_{i \in D} q_{i\mathcal{C}}(\rho^*_{\mathcal{C}}) = \sum_{i \in D} q_{\mathcal{B}i} - \sum_{i \in D} q_{i\mathcal{T}}(\rho^*_{\mathcal{C}}) - \left(\sum_{i \in D} \frac{1}{\beta_i}\right) \rho^*_{\mathcal{C}} = 0. \tag{17}$$

With the equilibrium conditions, we can formally define the market equilibrium with a $\mathcal{C}$ market.

Definition 2 *A market equilibrium with a $\mathcal{C}$ market is a vector $(\{q^*_{ik}\}_{ik \in E}, \{q^*_{iC}\}_{i \in D})$ of traded quantities and a rate for the centrally cleared market $\rho^*_{\mathcal{C}}$ that satisfy the system of equations* (5) *and* (15) *along with the market clearing condition* (17)*.*

3.5 Properties of market equilibria

We have examined interior solutions of the dealers' problems, where all edges are active in equilibrium (i.e. $q^*_{ik} > 0 \; \forall \; ik \in E$). The following lemma provides the necessary and sufficient condition for all edges to be active.

Lemma 1 *The quantity borrowed q_{ik} at any trading relationship $ik \in E$ is positive, if and only if the following condition holds*

$$\frac{\sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell}{\sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}} < \frac{\bar{q}_{\mathcal{B}} + \sum_{ab \in E} \sum_{i'k' \in E} \frac{\tilde{\psi}_{ab,i'k'}}{2\gamma_{k'}} c_{k'}}{\sum_{j \in D} \frac{1}{\beta_j} + \sum_{ab \in E} \sum_{i'k' \in E} \frac{\tilde{\psi}_{ab,i'k'}}{2\gamma_{k'}}}. \tag{18}$$

All proofs are summarized in Appendix A. As we derive in Proposition 1, the right-hand side of (18) is the equilibrium rate in the $\mathcal{C}$ market. The left-hand side defines the relative cost of borrowing of dealer i from lender k that takes into account the strategic reaction of other dealers, which depends on the connectedness of dealer i to all other dealers through its trading relationship with lender k. The equilibrium rate defines an upper bound on the acceptable relative cost of borrowing from lender k. If this bound is breached, dealer i is better off borrowing from the centrally cleared market.[13]

Although condition (18) appears restrictive, we can assume all edges to be active without loss of generality. In particular, we can solve for the equilibrium in which some trading relationships are inactive by removing those edges from the set of active edges E, focusing on a subset of active edges and solving the equilibrium for the trading relationships for which (18) holds.[14] We assume that (18) holds from now on, and we can prove the existence and uniqueness of the market equilibrium in the following proposition.

Proposition 1 *There exists a unique market equilibrium both with and without a centrally cleared market $\mathcal{C}$.*

1. *With a $\mathcal{C}$ market, the equilibrium quantities are*

$$
\begin{aligned}
q_{ik}^* &= \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} \left(\rho_{\mathcal{C}}^* - c_\ell\right), \ \forall ik \in E \\
q_{i\mathcal{C}}^* &= q_{\mathcal{B}i} + \sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \Big(\sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \frac{1}{\beta_i} \Big) \rho_{\mathcal{C}}^*, \ \forall i \in D,
\end{aligned}
\tag{19}
$$

   where $\rho_{\mathcal{C}}^*$ is the equilibrium rate in the $\mathcal{C}$ market equal to

$$
\rho_{\mathcal{C}}^* = \frac{\bar{q}_{\mathcal{B}} + \sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell}{\sum_{i \in D} \frac{1}{\beta_i} + \sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}}. \tag{20}
$$

[13] A similar condition can be derived for the wiring without $\mathcal{C}$ market, discussed in the appendix.

[14] This result is similar to the case without the $\mathcal{C}$ market examined in Bimpikis, Ehsani, and İlkılıç [2019]. In our setting, it is easy to show that removing inactive edges results in the same equilibrium quantities and market clearing rate $\rho_{\mathcal{C}}$. In general, solving for the equilibrium requires a finite number of steps to check that all the non-negativity constraints are satisfied.

2. Without a $\mathcal{C}$ market, the equilibrium quantities transacted in the $\mathcal{T}$ market are

$$q_{ik}^{*} = \sum_{j\ell \in E} \frac{\psi_{ik,j\ell}}{2\gamma_\ell + \beta_j} \left(\beta_j q_{\mathcal{B}j} - c_\ell\right), \ \forall ik \in E. \tag{21}$$

To understand the properties of the equilibrium with the $\mathcal{C}$ market, examine the term $\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}$. We refer to this term as the *strategic weight* of ik to $j\ell$ for any $ik, j\ell \in E$. The strategic weight captures how much q_{ik} is affected by $q_{j\ell}$, including its own supply elasticity for the case of $ik = j\ell$. We refer the term $\sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}$ as the *effective supply elasticity* of lender k to dealer i for any $ik \in E$ and the sum across all lender counterparties $\sum\limits_{k \in L_i} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}$ is dealer i specific effective supply elasticity.

The effective supply elasticity depends not only on the own supply elasticity $\frac{1}{\gamma_k}$ but also on all the other lenders' supply elasticities weighted by the strategic weights of other dealers to dealer i borrowing from k encoded in the $\tilde{\psi}_{ik,j\ell}$. The equilibrium quantity q_{ik}^{*} depends on the spread between the $\mathcal{C}$ market rate and the marginal cost c_ℓ weighted by the strategic weights. If the strategic weight is positive on a dealer-lender pair $j\ell$, dealer i borrows more from lender k as c_ℓ declines.

Next examine the equilibrium without $\mathcal{C}$ market. In this wiring, the strategic weight of ik to $j\ell$ is $\frac{\psi_{ik,j\ell}}{2\gamma_\ell+\beta_j}$, and the effective supply elasticity of lender k to dealer i is $\sum_{j\ell \in E} \frac{\psi_{ik,j\ell}}{2\gamma_\ell+\beta_j}$. Note that the strategic weights and effective supply elasticities involve also the dealers' demand elasticities. Without a centrally cleared market, which equalizes the marginal costs of funds across dealers, the strategic responses of dealers vary with each dealer's own demand elasticity. The equilibrium quantities are functions of the marginal surpluses $\beta_j q_{\mathcal{B}j} - c_\ell$ along all dealer-lender pairs with weights equal to the strategic weight.

To illustrate how the wiring of the market affects the effective supply elasticities and equilibrium quantities, examine the case of homogeneity in lender and dealer elasticities. We can express the equilibrium quantities as the following decomposition

$$q^{*} = \begin{cases} \left(\sum\limits_{z=0}^{\infty} \frac{1}{2}^{2z} \tilde{W}^{2z} - \sum\limits_{z=0}^{\infty} \frac{1}{2}^{2z+1} \tilde{W}^{2z+1}\right) \tilde{\phi}(\rho_{\mathcal{C}}) & \text{if } \mathcal{W} = (\mathcal{T}, \mathcal{C}) \\ \left(\sum\limits_{z=0}^{\infty} (\frac{1}{2\gamma+\beta})^{2z} W^{2z} - \sum\limits_{z=0}^{\infty} (\frac{1}{2\gamma+\beta})^{2z+1} W^{2z+1}\right) \frac{1}{2\gamma+\beta} \phi(\mathbf{q}_{\mathcal{B}}) & \text{if } \mathcal{W} = (\mathcal{T}, \varnothing) \end{cases} \tag{22}$$

The decomposition reveals that changes in demand and supply conditions at any dealer-lender trading relationship affect all the other dealer-lender relationships along the edges of the line graph with a rate of decay 1/2 for the wiring with $\mathcal{C}$ market, and a decay rate $\frac{1}{2\gamma+\beta}$ for the wiring without $\mathcal{C}$ market.[15] The powers of the adjacency matrices W^p and $\tilde{W}^p$ encode paths between any two edges of length p. The adjacency matrices are non-negative and the strategic quantity response of dealer j to changes in demand of dealer i would be a strategic complement, if the two edges $(ik, j\ell)$ are linked by a path of even length, and a strategic substitute, if the two edges are linked by a path of odd length.

The decomposition (22) allows us to express the equilibrium quantities as the Katz-Bonacich (KB) centrality of the dealer-lender trading relationship in the case without a $\mathcal{C}$ market

$$KB(-\xi, W) \equiv \left(\sum_{z=0}^{\infty}(-\xi W)^z\right)\mathbf{1}_{|E|} = \Psi\mathbf{1}_{|E|} = \left[\sum_{j\ell\in E}\psi_{ik,j\ell}\right]_{ik\in E}, \tag{23}$$

where the first equality is the definition of the KB centrality measure and $\mathbf{1}_{|E|}$ is a vector of ones of length $|E|$. The effective supply elasticity becomes the KB centrality measure in the homogeneous elasticities case. More central dealer-lender trading relationships have high effective supply elasticity, if they are part of more paths in the line graph network with ξ discounting the influence of longer paths. The equilibrium with a $\mathcal{C}$ market has a similar structure with the centrality $KB(-\frac{1}{2}, \tilde{W})$ defining the effective supply elasticity.

We next examine the properties of the aggregate equilibrium quantities in the case of wirings with a $\mathcal{C}$ market in the following two corollaries of Proposition 1.

Corollary 1 *For a fixed aggregate demand $\bar{q}_{\mathcal{B}}$, the gross volume of trades in the $\mathcal{C}$ market, $\sum_{i\in D}|q^*_{i\mathcal{C}}|$, is increasing in the heterogeneity of individual dealer-specific demand and dealer-specific supply scaled by the dealer-specific supply and demand elasticities*

$$\sum_{i\in D}\left|\frac{q_{\mathcal{B}i}+\sum_{k\in L_i}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{\gamma_\ell}c_\ell}{\frac{1}{\beta_i}+\sum_{k\in L_i}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{\gamma_\ell}} - \frac{\sum_{a\in D}q_{\mathcal{B}a}+\sum_{a\in D}\sum_{b\in D_a}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ab,j\ell}}{\gamma_\ell}c_\ell}{\sum_{a\in D}\frac{1}{\beta_a}+\sum_{ab\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ab,j\ell}}{\gamma_\ell}}\right|. \tag{24}$$

[15]The decomposition exists if the infinite sums are convergent, which is satisfied if the largest eigenvalue of ξW is less than 1 in absolute value.

Corollary 1 implies when there are no differences across dealers in their dealer-specific demand, demand elasticities, and in the effective supply elasticities, there will be no trades in the $\mathcal{C}$ market at the equilibrium rate $\rho^*_{\mathcal{C}}$. The effect of dealer-specific demand $q_{\mathcal{B}i}$ on gross trades in the $\mathcal{C}$ market is scaled by a factor that sums the dealer-specific demand elasticity $\frac{1}{\beta_i}$ and the dealer-specific effective supply elasticity $\sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}$. The second term in (24) is the average of those dealer characteristics.

All else equal, a dealer with a lower demand elasticity or a lower effective supply elasticity in the $\mathcal{T}$ market than the average dealer would be a net borrower in the $\mathcal{C}$ market, whereas a dealer with a higher demand elasticity or a higher effective supply elasticity in the $\mathcal{T}$ market would be a net lender in the $\mathcal{C}$ market.

Corollary 2 *The interest rate sensitivity with respect to $\rho^*_{\mathcal{C}}$ of the aggregate borrowing from the $\mathcal{T}$ market is smaller than the sensitivity of the aggregate borrowing from the $\mathcal{C}$ market.*

$$\left| \frac{\partial \left(\sum_{ik \in E} q^*_{ik} \right)}{\partial \rho^*_{\mathcal{C}}} \right| < \left| \frac{\partial \left(\sum_{i \in D} q^*_{i\mathcal{C}} \right)}{\partial \rho^*_{\mathcal{C}}} \right|$$

Corollary 2 highlights the difference in interest rate sensitivity between the aggregate borrowing from $\mathcal{T}$ market and the net borrowing in the $\mathcal{C}$ market. In response to an increase in $\rho^*_{\mathcal{C}}$, dealers reduce their net borrowing in the $\mathcal{C}$ market. Simultaneously, dealers also increase their borrowing from the $\mathcal{T}$ market. Therefore, the aggregate demand elasticity of the $\mathcal{T}$ market is less than the aggregate net demand elasticity of the $\mathcal{C}$ market.

3.6 Propagation of demand and supply shocks

As we have discussed in the previous section, the existence of a centrally cleared market affects the propagation of supply and demand shocks in a fundamental way. We further characterize the properties of the propagation of demand and supply shocks in the following proposition.

Proposition 2 *The existence of a centrally cleared market affects the propagation of demand and supply shocks.*

1. *With a $\mathcal{C}$ market, dealer demand shocks affect the equilibrium quantities only indirectly through their effect on the equilibrium rate $\rho^*_{\mathcal{C}}$, whereas supply shocks affect the equilibrium quantities both directly and indirectly as follows*

$$\begin{aligned}\frac{\partial q_{j\ell}}{\partial q_{\mathcal{B}i}} &= \frac{\partial \rho^*_{\mathcal{C}}}{\partial q_{\mathcal{B}i}} \sum_{ab\in E} \frac{\tilde{\psi}_{j\ell,ab}}{2\gamma_b} \\ \frac{\partial q_{j\ell}}{\partial c_k} &= \frac{\partial \rho^*_{\mathcal{C}}}{\partial c_k} \sum_{hz\in E} \frac{\tilde{\psi}_{j\ell,hz}}{2\gamma_z} - \sum_{a\in D_k} \frac{\tilde{\psi}_{j\ell,ak}}{2\gamma_k}\end{aligned} \tag{25}$$

for any $j\ell \in E$ and $i \in D, k \in L$. Finally, the derivatives of the equilibrium rate $\rho^*_{\mathcal{C}}$ is

$$\begin{aligned}\frac{\partial \rho^*_{\mathcal{C}}}{\partial q_{\mathcal{B}i}} &= \frac{1}{\sum\limits_{hz\in E}\sum\limits_{ab\in E} \frac{\tilde{\psi}_{hz,ab}}{2\gamma_b} + \sum\limits_{a\in D}\frac{1}{\beta_a}} \\ \frac{\partial \rho_{\mathcal{C}}}{\partial c_k} &= \frac{\sum\limits_{ab\in E}\sum\limits_{h\in D_k} \frac{\tilde{\psi}_{ab,hk}}{2\gamma_k}}{\sum\limits_{hz\in E}\sum\limits_{ab\in E} \frac{\tilde{\psi}_{hz,ab}}{2\gamma_b} + \sum\limits_{a\in D}\frac{1}{\beta_a}}.\end{aligned} \tag{26}$$

2. *Without a $\mathcal{C}$ market, demand shocks at any dealer $i \in D$ and supply shocks at any lender $k \in L$ influence the trades in all dealer-lender relationship $j\ell \in E$ according to*

$$\begin{aligned}\frac{\partial q_{j\ell}}{\partial q_{\mathcal{B}i}} &= \sum_{z\in L_i} \psi_{j\ell,iz} \frac{\beta_i}{2\gamma_z + \beta_i}, \\ \frac{\partial q_{j\ell}}{\partial c_k} &= -\sum_{d\in D_k} \psi_{j\ell,dk} \frac{1}{2\gamma_k + \beta_d}.\end{aligned} \tag{27}$$

For the wiring with a $\mathcal{C}$ market, idiosyncratic dealer demand shocks affect all dealers only through the change in equilibrium rate $\rho^*_{\mathcal{C}}$. All else equal, all dealers borrow more in response to a dealer-specific demand shock. However, supply shocks have both global effects through the equilibrium rate and local effects on an individual dealer's funding decisions. Therefore, with a $\mathcal{C}$ market, idiosyncratic lender supply shocks generate heterogeneous effects across dealers. Furthermore, local supply effects propagate to all dealer-lender pairs through all possible paths encoded in $\tilde{\Psi}$.

In the absence of a $\mathcal{C}$ market, the spillover effects of demand or supply shocks could affect the equilibrium trades of all dealer-lender pairs through all possible paths along the network encoded in the Ψ matrix. The sign of those coefficients determines whether the action of a dealer in a trading relationship is a strategic substitute or complement to the actions of other dealers in other relationships.

3.7 Dispersion in marginal borrowing costs and spreads

Define the marginal cost of dealer i of a dollar of additional funding from lender k evaluated at the equilibrium quantities as follows

$$\rho_{ik}^* \equiv \left.\frac{\partial q_{ik}(c_k + \gamma_k \sum_{j\in D_k} q_{jk})}{\partial q_{ik}}\right|_{q^*} = s_k^* + \gamma_k q_{ik}^*, \tag{28}$$

where the second equality indicates that the marginal cost always exceeds the repo rate or the average cost of funds.

Proposition 3 *The equilibrium dispersion in marginal costs of funding and in lender repo spreads depend on the market wiring.*

1. *Marginal costs:*

   (a) *With a $\mathcal{C}$ market, the marginal borrowing cost for all dealers across all lenders equals the equilibrium rate in the centrally cleared market $\rho_i^* = \rho_{\mathcal{C}}^*$, $\forall i \in D$, where $\rho_i^* = \rho_{ik}^*$, $\forall k \in L_i$.*

   (b) *Without a $\mathcal{C}$ market, the marginal borrowing cost can differ across dealers. Even if the dealer and lender parameters are homogeneous as $\beta_i = \beta, q_{\mathcal{B}i} = q_{\mathcal{B}}$, $\forall i \in D$, and $\gamma_\ell = \gamma, c_\ell = c$, $\forall \ell \in L$, the marginal borrowing costs across dealers are the same $\rho_i^* = \rho^*$ for all $i \in D$, if and only if*

$$\sum_{k\in L_i}\sum_{j\ell\in E}\psi_{ik,j\ell} = \bar{\psi} \tag{29}$$

   for all $i \in D$.

2. *Lender spreads:*

   (a) *With a $\mathcal{C}$ market, the equilibrium spreads depend on the number of lenders $(n_k)_{k\in L}$, where $n_k = |D_k|$, and the distribution of lender marginal costs*

$\{c_k\}_{k\in L}$ as

$$s_k^* = \frac{n_k}{n_k+1}\rho_{\mathcal{C}}^* + \frac{1}{n_k+1}c_k, \ \ k \in L. \tag{30}$$

(b) Without a $\mathcal{C}$ market, the equilibrium spreads are a function of the lender supply conditions and elasticities $(c_k, \gamma_k)_{k\in L}$, the dealer demand conditions and elasticities $(q_{\mathcal{B}i}, \beta_i)_{i\in D}$, as well as the wiring of the $\mathcal{T}$ market captured by the Ψ matrix as

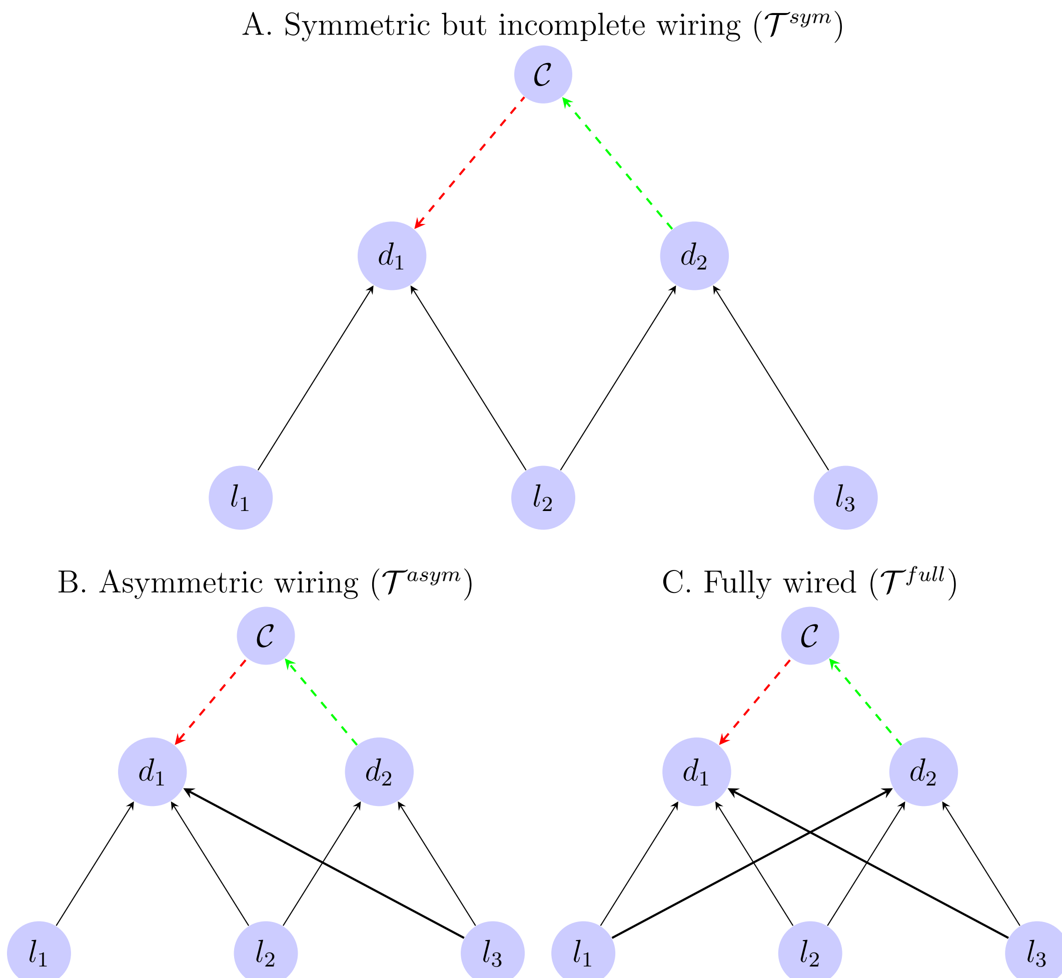
$$s_k^* = c_k + \gamma_k \sum_{i\in D_k}\sum_{j\ell\in E}\psi_{ik,j\ell}\frac{\beta_j q_{\mathcal{B}j} - c_\ell}{2\gamma_\ell + \beta_j}, \ \ k \in L. \tag{31}$$

The first part of the proposition states that in the presence of a centrally cleared market dealers equalize marginal costs not only across their lender counterparties but also among themselves, thus eliminating dispersion in marginal costs. This result is intuitive, because $\rho_{\mathcal{C}}^*$ is the common marginal borrowing cost for all dealers, and each dealer equalizes the marginal costs across all possible funding sources. Without a centrally cleared market (1b), marginal costs are equalized only if the dealer specific effective supply elasticities are equalized to a constant proportional to $\bar{\psi}$.

The second part of the proposition is somewhat unexpected. There is equilibrium dispersion in rates even when all cost parameters are homogeneous (2a), and the dispersion in rates is a function of the wiring of the market. Even if dealers equalize marginal costs, the existence of a centrally cleared market does not necessarily eliminate rate heterogeneity. It is only in situations when the market wiring is symmetric across counterparties that the "law of one price" holds. According to (30), when cost parameters are homogeneous, lenders with larger number of counterparties would charge higher rates than lenders with fewer counterparties, and their rates would be more sensitive to the equilibrium rate in the centrally cleared market. Finally, without $\mathcal{C}$ market, (2b) reveals that equilibrium rate dispersion depends on both the heterogeneity of supply and demand parameters but also on the wiring of the market. Similar to (1b), when such heterogeneity is removed, there is still rate dispersion if the there are differences in connectedness of lenders captured by differences in $\sum_{i\in D_k}\sum_{j\ell\in E}\psi_{ik,j\ell}$ for any $k \in L$.

3.8 Solving a simple closed-form example

Figure 4: Alternative wirings of a market with 2 dealers and 3 lenders



NOTE: Lines between a dealer and a lender represent an established relationship. Lines between dealers and the $\mathcal{C}$ market represent access to the centrally-cleared market, which could be either borrowing or lending. In this example, we assume that $q_{\mathcal{B}1} > q_{\mathcal{B}2}$ and that dealer d_1 needs additional cash and borrows from dealer d_2 through the $\mathcal{C}$ market.

We can gain intuition about the properties of the general model from solving a simple closed-form example. As shown in Figure 4, suppose there are two dealers $D = \{d_1, d_2\}$ and three lenders $L = \{\ell_1, \ell_2, \ell_3\}$ that interact in different $\mathcal{T}$ market wirings. There are three different configurations of the $\mathcal{T}$ market, and each configuration may include a $\mathcal{C}$ market. In panel A, the two dealers share a common lender ℓ_2, and each dealer has an exclusive lender, lender ℓ_1 for dealer d_1 and lender ℓ_3 for dealer d_2. Because dealers have the same number of counterparties, but not all dealers and lenders interact, the wiring is symmetric but incomplete.

Suppose that lenders share common cost parameters, $(c, \gamma) = (c_k, \gamma_k)$ for all $k = 1, 2, 3$, and dealers have the same balance sheet costs $\beta = \beta_1 = \beta_2$. To examine how demand imbalances are resolved, suppose that dealer d_1 has higher demand for borrowing than dealer d_2, that is, $q_{\mathcal{B}1} > q_{\mathcal{B}2}$. The equilibrium interdealer rate $\rho^*_{\mathcal{C}}$ in the $\mathcal{C}$-market is determined by the market clearing condition $q_{1\mathcal{C}}(\rho^*_{\mathcal{C}}) + q_{2\mathcal{C}}(\rho^*_{\mathcal{C}}) = 0$, which we can solve in closed form

$$\rho^*_{\mathcal{C}} = \frac{3\beta\gamma}{5\beta + 6\gamma}\bar{q}_{\mathcal{B}} + \frac{5\beta}{5\beta + 6\gamma}c,$$

where $\bar{q}_{\mathcal{B}} = q_{\mathcal{B}1} + q_{\mathcal{B}2}$ is total dealer demand. The equilibrium rate is the sum of dealer funding demand and the cost of funds in the $\mathcal{T}$ market, weighted by the supply and demand elasticities.

The total quantity borrowed from the $\mathcal{T}$ market is increasing in the demand for and decreasing in the cost of funding:[16]

$$\begin{aligned}
q^*_{11} = q^*_{23} &= \frac{3}{2}\frac{\beta\bar{q}_{\mathcal{B}} - 2c}{5\beta + 6\gamma} \\
q^*_{12} = q^*_{22} &= \frac{\beta\bar{q}_{\mathcal{B}} - 2c}{5\beta + 6\gamma} \\
q^*_{1\mathcal{C}} &= q_{\mathcal{B}1} - \frac{\bar{q}_{\mathcal{B}}}{2} \\
q^*_{2\mathcal{C}} &= q_{\mathcal{B}2} - \frac{\bar{q}_{\mathcal{B}}}{2}.
\end{aligned}$$

First note that in the presence of a centrally cleared market, individual dealer demand conditions affect the quantities traded only through their effect on aggregate dealer demand $\bar{q}_{\mathcal{B}}$. Second, note that because ℓ_2 is more central than ℓ_1 and ℓ_3, demand and supply shocks have higher impact on quantities traded with l_2. This also translates

[16]Note that the existence of an interior equilibrium requires $\bar{q}_{\mathcal{B}} > \frac{2c}{\beta}$. In other words, there is sufficient demand for funds from dealers relative to lenders' cost of supplying funds. This is a special case of the more general condition (18).

in higher sensitivity of equilibrium repo rates

$$s_1^* = s_3^* = \frac{3\beta\gamma}{2(5\beta+6\gamma)}\bar{q}_{\mathcal{B}} + \frac{5\beta+3\gamma}{5\beta+6\gamma}c$$
$$s_2^* = \frac{2\beta\gamma}{5\beta+6\gamma}\bar{q}_{\mathcal{B}} + \frac{5\beta+2\gamma}{5\beta+6\gamma}c.$$

Finally, the quantity borrowed by each dealer in the centrally-cleared market is half the differential in dealer demands

$$q_{i\mathcal{C}}^* = \frac{q_{\mathcal{B}i} - q_{\mathcal{B}j}}{2},\ i \neq j,\ i,j \in \{1,2\}.$$

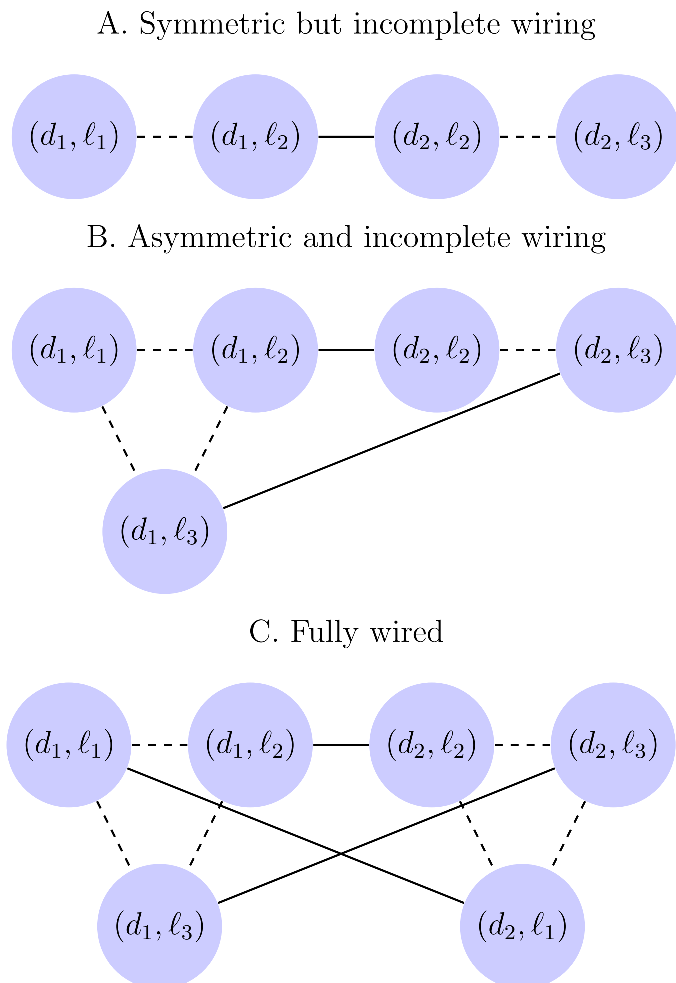
In this example, dealer 1 has higher demand than dealer 2 and will borrow $q_{1\mathcal{C}} = \frac{q_{\mathcal{B}1}-q_{\mathcal{B}2}}{2} > 0$, whereas dealer 2 will lend that same amount $q_{2\mathcal{C}} = \frac{q_{\mathcal{B}2}-q_{\mathcal{B}1}}{2} < 0$. The transacted amounts in the $\mathcal{C}$ market reflect the heterogeneity in dealers' demand conditions, and if demand conditions are the same, there are no equilibrium quantities traded at the equilibrium clearing rate. Note that this result is a special case to the derivations in Corollary 1.

The simple example also illustrates the findings in Proposition 3. In the presence of the $\mathcal{C}$ market, the optimal borrowing decisions of dealers is to equalize the marginal cost of funds across all sources of funds i.e. $\rho_{ik}^* \equiv \left.\frac{\partial q_{ik}(c+\gamma\sum_{j\in D_k} q_{jk})}{\partial q_{ik}}\right|_{\mathbf{q}^*} = \rho_{\mathcal{C}}^*$ at both dealers $i = d_1, d_2$ and across all lenders. However, because of differences in the quantities borrowed across lenders, the spread charged by the common lender ℓ_2 is higher than the spread charged by the exclusive lenders $s_2 > s_1 = s_3$. As a result, there is dispersion in rates $s_2 - s_1 = \gamma\frac{\beta\bar{q}_{\mathcal{B}}-2c}{2(6\gamma+5\beta)}$, which is positive because $\bar{q}_{\mathcal{B}} > \frac{2}{\beta}c$. This condition is equivalent to the general condition (18) and holds under any interior equilibrium. The dispersion in rates increases with the increase in overall dealer demand.

To illustrate the propagation of shocks, Figure 5 shows the line graphs for the three market wirings in Figure 4. A dashed line between two dealer-lender pairs indicates a common dealer; a solid line between pairs indicates a common lender. Panel A displays the symmetric case. Suppose that a supply shock hits ℓ_1, the exclusive lender for dealer d_1. Dealer d_1 would decrease its borrowing from ℓ_1 and increase its borrowing from the common lender ℓ_2. Dealer d_2 would then strategically respond by increasing its borrowing from lender ℓ_3. Because (d_1, ℓ_1) is connected to (d_2, ℓ_3)

by an odd length path, the decisions of dealers d_1 and d_2 are strategic complements. In contrast, dealer d_2 reacts by reducing borrowing from ℓ_2 as the actions of dealers along the two edges (d_1, ℓ_1) and (d_1, ℓ_2) are strategic substitutes.

Figure 5: Line graph of 3× 2 market wiring



NOTE: The line graph of the bipartite networks in Figure 4. Dashed lines connect edges with common dealers and thick lines connect edges with common lenders.

As the wiring of the decentralized market changes, so do the strategic interactions of dealers. For example, in the asymmetric and incomplete wiring in panel B, (d_1, ℓ_1) and (d_2, ℓ_3) are connected both by an odd and an even length path. The strategic interactions between the two dealers depends on the length of the paths, the supply and demand elasticities, and the decay factor as illustrated in equation (22). In this case, because the even length path $(d_1, \ell_1) - (d_1, \ell_3) - (d_2, \ell_3)$ is of length 2, whereas the odd-length path is of length 3, discounting places a higher weight on the even-length path. Finally, in the fully wired case in panel C, the two edges (d_1, ℓ_1) and (d_2, ℓ_3) are connected by additional odd and even length paths.

4 Empirical analysis

In this section, we apply the model to the data. We first provide a few important details on aggregate repo quantities and pricing, and summary statistics at the counterparty level.[17] We then present a decomposition of changes in quantities traded into supply and demand factors. Using this decomposition and other controls, we estimate the key model parameters and formally test the assumptions and mechanisms of the model.

The estimation of the model takes three steps. First, we characterize the marginal cost of lenders by estimating the parameters of the inverse supply function. Second, we evaluate dealers' strategic substitutability of funding. This evaluation includes funding from the decentralized market as well as net borrowing in the centrally cleared market. Third, we estimate the interest rate elasticity of dealer demand, controlling for the endogenous selection of dealers to be net borrowers or lenders in the centrally cleared market.

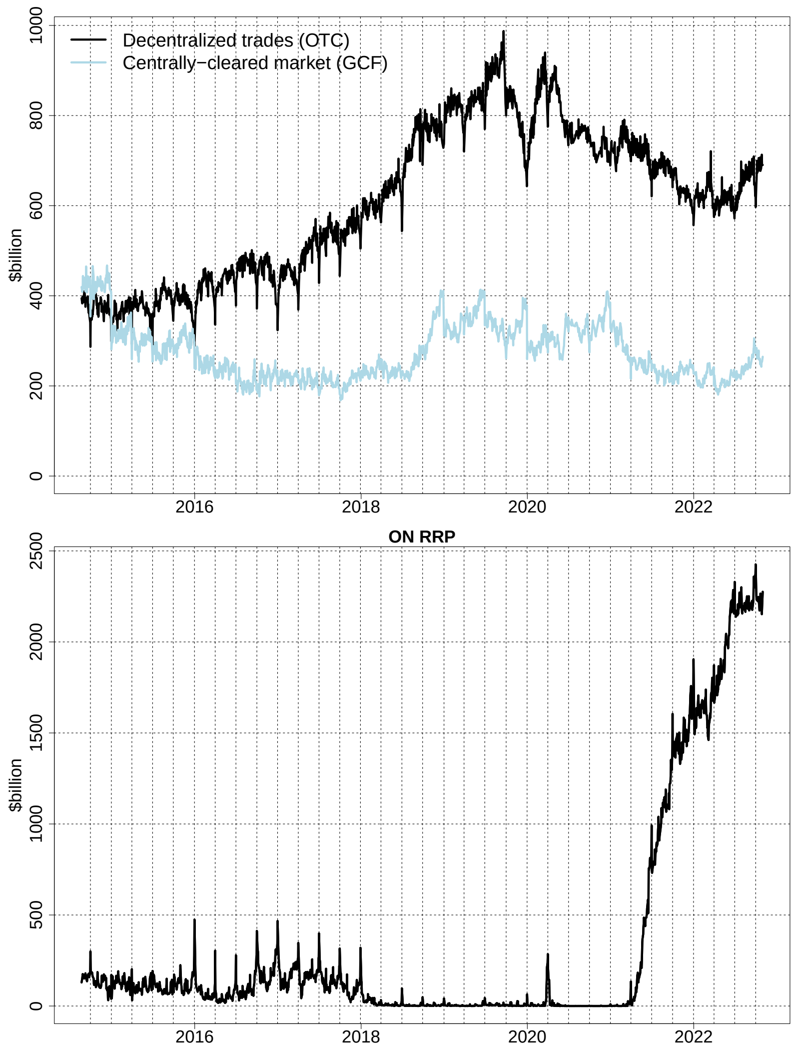
4.1 Aggregate quantities

As illustrated in the top panel of Figure 6, OTC repo volume hovered around \$400 billion at the beginning of our sample before it began to grow in 2016, peaked around \$1 trillion in 2019, and then declined to \$700 billion by end of our sample in October 2022. Centrally cleared GCF volume reached \$400 billion in 2019 before falling to \$200 billion in 2022. The GCF volume increased during the period from mid 2018 until the end of 2021. The volume of cash deposited by lenders with the Federal Reserve's ON RRP facility is plotted in the lower panel of Figure 6. ON RRP take-up averaged about \$200 billion in the period from 2014 through 2018 and was close

[17] Appendix C contains a detailed description of the data construction and additional institutional details.

to zero between 2019 and 2021. By the end of our sample, take-up reached levels in excess of $2 trillion.

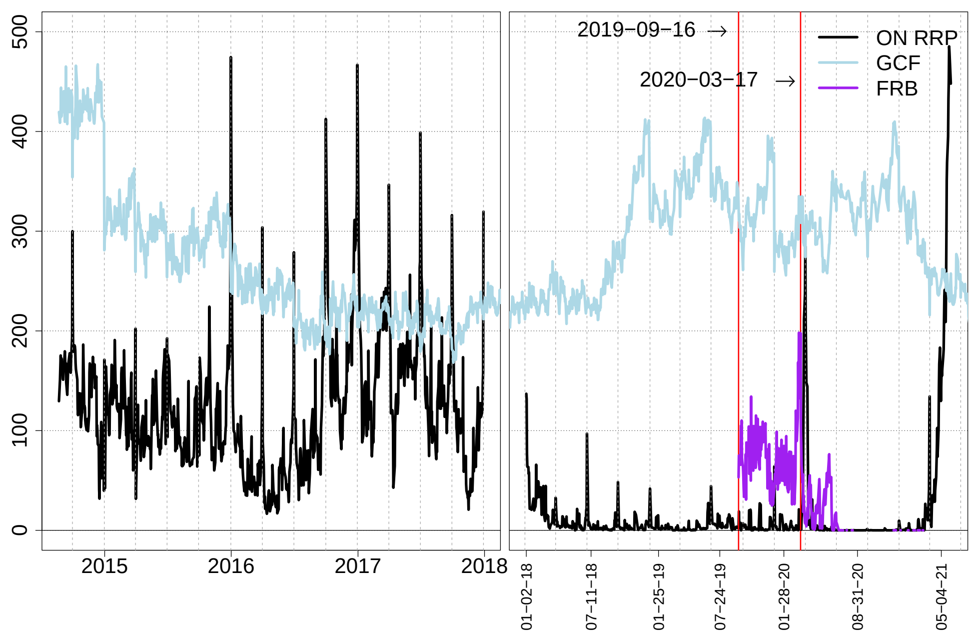
Figure 6: Repo volumes by market segment



NOTE: The black line is trading volume in the decentralized OTC segment of the tri-party repo market. The light blue line is trading volume in the centrally cleared GCF market. The full list of ON RRP counterparties can be found at the FRB NY website. Vertical dashed lines indicate quarter-ends. SOURCE: FRBNY Tri-party repo.

The repo market turmoil of September 17, 2019 was unusual as it did not involve a major financial crisis or default of a systemic player in the market. The episodes of market instability on September 17, 2019 prompted interventions by the Federal Reserve by executing a series of temporary repo operations that allowed dealers to access cash from the Federal Reserve at a pre-specified haircut and spread over the ON RRP rate.

Figure 7: Borrowing from FRB repo operations and the GCF



Note: The temporary FRB repo operations we considered started on September 18, 2019 and were completed in June 2020. Borrowing from the repo operations in purple is indicated as FRB in the chart's legend. The temporary repo operations were followed by the establishment of the permanent Standing Repo Facility (SRF) in July 2021. The SRF has not been actively used since its establishment. Source: FRBNY Tri-party repo.

Figure 7 plots the borrowing from the Fed's repo operations. Upon the commencement of the operations on September 18, 2019, dealers borrowed around \$70 billion and the amount quickly increased in subsequent months to above \$100 billion, which is close to the drop in supply, which we document in section 4.8. As the COVID-19 pandemic created pressure in Treasury markets, dealers tapped the operations again and the borrowing peaked at about \$200 billion before declining to zero by June 2020.

4.2 Summary statistics on repo counterparties

There are 159 lenders and 49 dealers in our sample with some entry and exits. As discussed in Figure 3, the entry and exit of counterparties are mostly smaller entities and the bulk of trades are over established long-term relationships. In addition, we drop very small lenders that provide less than $1 million in cash.

Table 1 provides summary statistics of the lenders in our sample. The average lender supplies around $4.5 billion of cash to dealer counterparties and there is significant heterogeneity in lender sizes. The 5th percentile lender provides about $6 million, the median lender provides more than $300 million, and the 95th percentile lender provides close to $30 billion.[18]

Table 1: Lenders' provision of cash

	mean	sd	5	25	50	75	95
Lending ($mln)	4,510	12,983	6	77	333	1,875	29,936
Number of dealers	5	6	1	1	3	7	20
Within-lender HHI	54	37	6	20	50	100	100
C1 concentration	60	34	12	29	55	100	100
C3 concentration	82	27	29	67	100	100	100
ON RRP ($mln)	2,528	18,143	0	0	0	0	6,500

NOTE: The sample period covers trading days from August 22, 2014 through October 31, 2022. C1 and C3 measure the shares of the top one and three dealer counterparty for each lender, respectively. HHI is the within-lender Herfindahl-Hirschman Index of concentration of dealer borrowing that is scaled to vary between 0 and 100. SOURCE: FRBNY Tri-party repo, SEC Form N-MFP, iMoneyNet, and authors' calculations.

Lenders also differ in the number and concentration of lending to dealer counterparties. The average lender has about 5 dealer counterparties and the median lender has 3 dealer counterparties. Finally, not all lenders have access to the ON RRP facility, or, if they have access, over certain periods of our sample lenders choose not to deposit cash at the ON RRP as shown in Figure 6.

Moving to dealers, there is significant heterogeneity in dealers' borrowing in the tri-party market reflecting heterogeneity in dealers' types, asset sizes, and connectedness

[18]We use information from the SEC's Form N-MFP and iMoneyNet to identify money market mutual funds (MMFs). Around a third of the volume of trades in government repo come from MMFs and the remainder are a diverse group of entities such as asset managers, insurance companies, pension funds, federal home loan banks, government sponsored enterprises, municipal treasurers, small commercial banks, credit unions, as well as nonfinancial corporations.

to the different market segments as summarized in Table 2. The average dealer is much larger and has a higher number of counterparties than an average lender. The average dealer borrows $13 billion from lenders and transacts with 13 lenders. Note that at least a quarter of mostly smaller dealers have one lender or do not maintain borrowing relationships with a lender in the decentralized market but instead mostly transact in the GCF market consistent with the market wiring in Figure 1. The within-dealer HHI of borrowing is about 23 percent. The average share of the largest lender is 29 percent of the borrowed amount and that share is 46 percent for the largest three lenders.

Table 2: Dealers balance sheet characteristics and repo borrowing

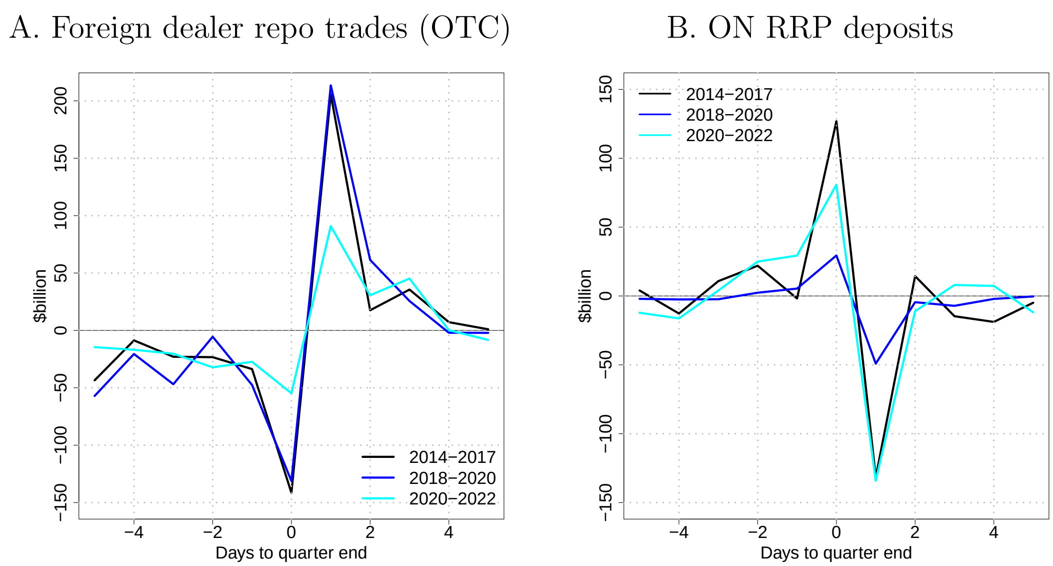
	mean	sd	5	25	50	75	95
	Decentralized dealer-lender OTC market						
Borrowing ($mln)	13,338	18,813	0	7	3,235	21,937	54,374
Number of lenders	13	16	0	1	6	26	44
Within-dealer HHI	31	33	4	6	14	49	100
C1 concentration	39	31	9	14	25	59	100
C3 concentration	61	30	24	33	53	100	100
Dealer demand growth δ, %	1.0	27.6	-22.6	-6.4	0	6.4	23.6
Average dealer supply growth, %	0.3	15.3	-8.2	-2.5	0.1	2.9	9.2
	Centrally cleared interdealer GCF market						
GCF borrowing ($mln)	7,480	9,524	0	600	4,100	11,450	24,350
GCF lending ($mln)	6,518	8,905	0	950	3,765	8,650	22,450
GCF net borrowing ($mln)	962	11,326	-14,904	-2,650	400	4,750	17,700
	Dealer balance sheet and credit risk information						
Consolidated assets ($bn)	1,267.9	780	305.9	643.8	1,134.9	1,775.2	2,680.1
Consolidated book leverage	6.4	2.4	3.7	4.6	5.8	7.9	11.2
EDF 1-year, bps	36.2	24.9	10.3	20.5	29.9	43.9	88.1
Market-to-book ratio	0.89	0.07	0.78	0.84	0.89	0.95	1.00

NOTE: The sample period covers data from August 22, 2014 through October 31, 2022. There are 49 unique dealers for which we observe information on tri-party repo trades over this period and 31 dealers for which we also have consolidated balance sheet and credit risk measures. C1 and C3 measure the shares of the top one and three lenders, respectively. The within-dealer HHI is the Herfindahl-Hirschman Index of concentration of dealer borrowing from lenders in the OTC market. GCF is the FICC centrally cleared market. SOURCE: FRB NY, Moody's CreditEdge (KMV), and and authors' calculations.

In the middle panel of Table 2, we examine dealers' transactions in the interdealer market. On average, larger dealers are net borrowers and the average amount borrowed is about $7.5 billion, which is smaller than the average amount lent $6.5 billion. As a result, the average dealer is a net lender in the GCF market, even though the aggregate net cash provided by the GCF market is exactly zero.

For a subset of the largest 31 dealers in our sample, we obtain information on their parent holding companies' consolidated balance sheets and credit risk from Moody's CreditEdge (KMV) database. The summary statistics of this information is summarized in the lower section of Table 2. The average dealer parent holding company has total consolidated assets exceeding $1.3 trillion and those include the assets not only of the dealer subsidiary but also affiliated entities including commercial banks, insurance companies, and other financial entities. The ratio of dealers' book equity to total assets is 6.4 percent for the average dealer and 5.8 for the median dealer. The average empirical default frequency over one year horizon (EDF1) is 36 basis points and the average market-to-book ratio is 0.89.

Figure 8: Foreign dealer trades at quarter-ends and ON RRP take-up



NOTE: The figures compute the average amounts over a 5-day window around the last trading date of the quarter. SOURCE: FRBNY Tri-party repo and authors' calculations.

Dealers can be categorized into three broad groups: bank-affiliated domestic dealers, which are typically part of a large domestic bank holding company subject to bank regulation in the U.S.; non-bank affiliated dealers, which are typically not affiliated with a regulated bank; and foreign dealers, which are typically part of large foreign banking organizations subject to bank regulation in the respective foreign country. Figure 8 illustrates an important feature of the repo market at quarter-ends.

Foreign dealers pull back from the repo market at quarter-ends to improve the regulatory leverage ratios of their parent bank holding company, which are calculated on quarter-end values. At the same time, domestic dealers affiliated with regulated banks do not exhibit such behavior, because U.S. bank holding companies' leverage ratios are based on quarterly average values.[19]

As foreign dealers pull from the repo market at quarter-ends, lenders with access to the ON RRP increase their deposits with the ON RRP with roughly the same magnitude. At the same time, foreign dealers borrow more from the GCF market inducing a spike in rates. Within a day following the end of the quarter, foreign dealers' repo trades revert back to their typical levels. Similarly, lenders withdraw cash from the ON RRP to fund the renewed trading activity of foreign dealers. The periodic inflows and outflows of cash in the repo market create demand and supply imbalances that can potentially result in rises in repo rates at quarter-ends.[20]

4.3 Pricing of repo trades and repo rate spikes

The time series variation of government repo rates is plotted in Figure 9 and summary statistics are provided in panel A of Table 3.[21] For most trading days, the dispersion of rates is very tight around the ON RRP rate with an average spread over the ON RRP rate of about 6 basis points and a standard deviation of 10 basis points. At quarter-ends, as foreign dealers exit the market, there are notable spikes in repo rates and significant increases in the levels and dispersion of rates. The average spread doubles to 12 basis points and the range of rates exceeds 60 basis points.

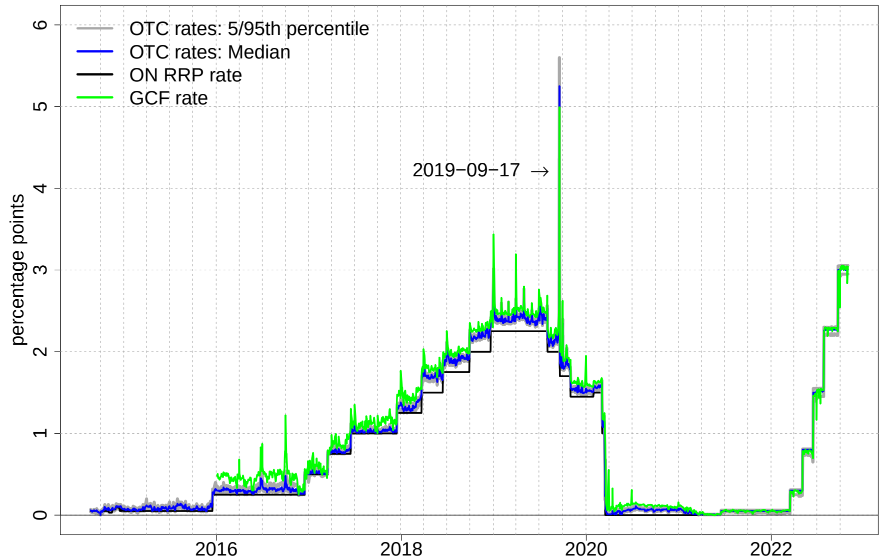
Panel B of Table 3 shows that a large fraction of the variation in tri-party repo rates is due to dealers facing different rates across lenders. Close to 70 percent of the variation in rates are within-dealer across lenders, and during the large spike in rates on September 17, 2019, 82 percent of the variation in rates could be attributed to within-dealer variation. This stylized fact allow us to significantly simplify the modeling of the price formation as coming from differences in market power and marginal costs of lenders as we discuss in section 3.1 and we verify this assumption in the empirical analysis of section 4.5.

[19] See Munyan [2015] for more detailed analysis on the regulatory arbitrage.

[20] Note that a similar plot for domestic dealers does not show seasonal patterns in their repo borrowing around quarter-ends.

[21] Government repo includes repo trades in Treasuries, agency debt, and agency MBS, which collateral that is eligible for pledging at the ON RRP and the FICC's GCF.

Figure 9: Distribution of government repo rates



NOTE: Spreads are expressed in percentage points. Government repo includes repo trades in Treasury securities, agency debt, and agency MBS. The sample period for rates on repo trades in the GCF market begins in 2016. SOURCE: FRBNY Tri-party repo and authors' calculations.

Panel C of Table 3 provides summary statistics of the borrowing rate in the GCF market. At 53 basis points, the average GCF spread is higher than the spread dealers face in the OTC market by about 15 basis points on within quarter trading days. At quarter-ends, the difference increases by 41 basis points indicating that the disbalances in supply and demand from the pullback of foreign dealers are cleared through higher rates at the GCF market. Finally, there is also notable spike in the GCF spreads on September 17, 2019. Even though the GCF spread was lower for the average and median dealer as compared to the OTC market, the upper percentiles the GCF rates were significantly higher. These differences likely reflect the timing of the execution of the trades within the trading day. Our data do not provide a timestamp of a within day execution and we abstract from this high frequency information both in our empirical and theoretical analysis.[22]

There is a substantial increase in the level of spreads observed on September 17, 2019 from the typical 6 basis points to around 315 basis points and this spike in rates

[22] See Paddrik, Young, Kahn, McCormick, and Nguyen [2023] for analysis using high-frequency intra-day repo data collected by the Office of Financial Research (OFR).

Table 3: Summary statistics on government repo pricing

	mean	sd	5	25	50	75	95
	A. OTC market spreads over ON RRP (basis points)						
Within quarter	6	10	-3	1	4	10	20
Quarter-end	12	19	-5	0	6	19	62
Sept. 17, 2019	315	62	230	3	325	350	357
	B. Variance decomposition of OTC spreads						
Within-dealer (within quarter)	0.68	0.12	0.48	0.60	0.69	0.76	0.86
Within-dealer (quarter-end)	0.61	0.13	0.41	0.50	0.63	0.71	0.80
Within-lender (within quarter)	0.42	0.14	0.15	0.35	0.45	0.52	0.59
Within-lender (quarter-end)	0.37	0.12	0.17	0.29	0.37	0.44	0.56
	C. GCF market spreads over ON RRP (basis points)						
Within quarter	21	13	6	14	21	27	35
Quarter-end	53	45	8	24	43	66	135
Sept. 17, 2019	293	172	73	194	282	350	634

NOTE: The variance decomposition of rates is computed as a decomposition of the share in total variation in rates from within-dealer and across-dealer variation as well as an equivalent decomposition into within-lender and across-lender variation. The identity can be expressed as $\sum_i \sum_k (r_{ikt} - \bar{r}_t)^2 = \sum_i \sum_k (r_{ikt} - \bar{r}_{it})^2 + m_t \sum_i (\bar{r}_{it} - \bar{r}_t)^2 = \sum_i \sum_k (r_{ikt} - \bar{r}_{kt})^2 + n_t \sum_i (\bar{r}_{kt} - \bar{r}_t)^2$, where $\bar{r}_t$ is the average rate across all dealers and lenders, $\bar{r}_{it}$ is the average rate of dealer i, $\bar{r}_{kt}$ is the average rate of lender k, and n_t and m_t are the number of dealers and lenders, respectively.

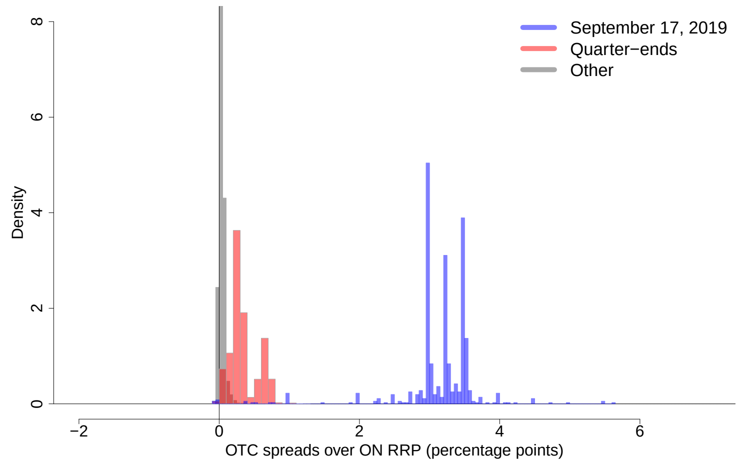
was also associated with a significant increase in the dispersion of spreads across dealer-lender trading relationships as illustrated in Figure 10. In normal times, the cross-sectional dispersion in spreads is within 10 basis points, and at quarter-ends, the dispersion almost doubles to 19 basis points. However, on September 17, 2019, the standard deviation of the cross-sectional distribution of spreads increased to more than 60 basis points with the 5th percentile lender charging 230 basis points and the 95th percentile lender charging over 350 basis points.

4.4 Decomposition of supply and demand factors

Proposition 2 illustrates the complex relationship of supply and demand conditions in a networked market. However, to a first-order approximation and under a set of assumptions, the incomplete connectedness of the $\mathcal{T}$ market allows us to decompose movements in quantities into changes in the relative supply and demand conditions of lenders and dealers. Such decomposition allows us to estimate demand and supply elasticities by controlling for endogeneity or simultaneity biases.

We begin with a decomposition of movements in quantities in the $\mathcal{T}$ market into

Figure 10: Dispersion in spreads over the ON RRP rate



NOTE: Quarter-ends are the last trading day for the quarter. Other includes all trading days outside quarter-ends and the September 2019 spikes. SOURCE: FRBNY Tri-party repo and authors' calculations.

dealer-specific demand and lender-specific supply factors, which we use as a set of instruments to estimate the supply and demand elasticities. First, we assume that the first-order effects of changes in dealer demand (lender supply) result in changes in quantities borrowed (lent) across lender (dealer) counterparties proportional to the lagged lender (dealer) shares. This assumption is common in the network propagation literature [Greenwood, Landier, and Thesmar, 2015; Duarte and Eisenbach, 2021; Cetorelli, Landoni, and Lu, 2023] and resembles the concept of a Bartik instrument (e.g. Goldsmith-Pinkham, Sorkin, and Swift [2020]). Second, we assume that higher-order effects of demand shocks are mean zero in expectation. Under these assumptions, we can decompose the effects of demand and supply as in the following proposition.

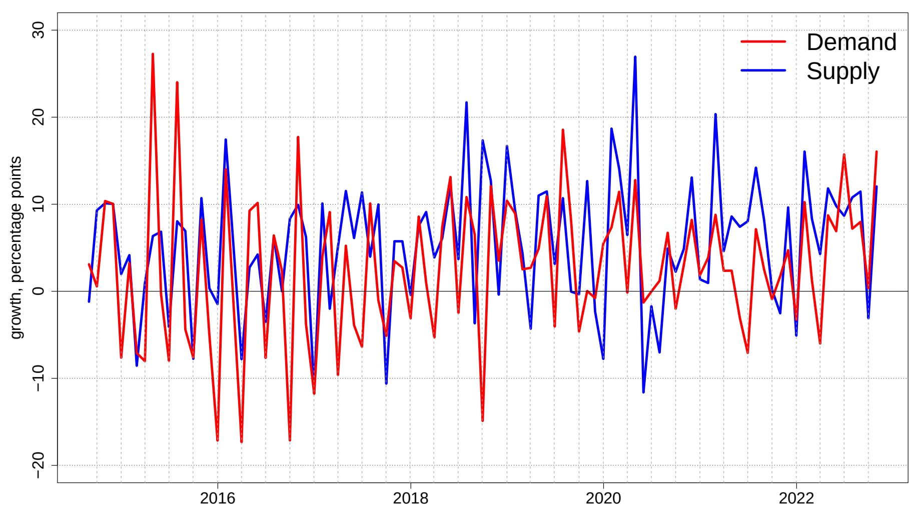
Proposition 4 *For any dealer-lender pair $ik \in E$ the growth rate in the quantity traded Δq_{ikt}, can be decomposed into the change due to dealer i specific shock δ_{it} and the change due to a lender k specific supply shock λ_{kt}*

$$\Delta q_{ikt} = \delta_{it} + \lambda_{kt} + \epsilon_{ikt}, \ \forall ik \in E, \tag{32}$$

where $\delta_{it} \propto dq_{\mathcal{B}it}$ and $\lambda_{kt} \propto \frac{1}{\gamma_k} dc_{kt}$. The error term ϵ_{ikt} contains remaining variation *related to higher-order interactions that is dealer-lender specific.*

The decomposition is similar to that proposed by Amiti and Weinstein [2018], hence we refer to it as the AW decomposition. The AW decomposition works for most trading relationships except for the cases in which a lender has an exclusive relationship with a single dealer. In those cases, similar to the fixed-effects methodology of Khwaja and Mian [2008], the supply factor is not identified. Therefore, we drop lenders with only one dealer, and such lenders form a small fraction of the overall trading volume. In addition, the decomposition takes into account the entry and exit of counterparties, as well as the establishment and dissolution of trading relationships. While these changes are not large in our data and provide the support in our theoretical model to assume the network is static, we control for the small changes in participation and relationships, as neglecting these transitions could bias our estimates.

Figure 11: Decomposition of supply and demand factors



NOTE: The figure shows the monthly weighted averages of the daily supply and demand factors based on the solution of the system of equations. See appendix for details on the construction. SOURCE: FRBNY Tri-party repo and authors' calculations.

Figure 11 plots the time series of the decomposition of supply and demand factors aggregated and averaged at a monthly frequency. The figure reveals significant variation in supply and demand conditions over our sample period. Of note, supply and demand exhibit seasonal patterns. For example, from the start of our sample period through 2018, demand at quarter-ends declines, reflecting the pull back from repo markets by foreign dealers. Lenders deposit the freed up cash at the ON RRP. Foreign dealer demand usually bounces back following the end of the quarter with lenders increasing supply by reducing balances held at the ON RRP. However, this pattern is disrupted in 2018. Beginning in 2018, the magnitude of demand shocks declines, while the magnitude of supply shocks increases. This pattern is consistent with the dry up of excess cash deposited with the Federal Reserve's ON RRP. The dry-up of excess lending capacity increased the participation of dealers in the centrally cleared GCF market as we illustrated in Figure 7.

4.5 Lender marginal costs

We estimate the lender marginal cost curve (1) using the following regression equation

$$\begin{aligned} s_{kt} =& \gamma(q_{k,t} - q_{\mathcal{O},k,t}) \\ & \tilde{c}_k + c^{\mathcal{Q}}\mathbb{I}\{\text{Quarter-end}\} + c^{\mathcal{O}}\mathbb{I}\{q_{\mathcal{O},k,t} = 0\} + c^{2019}\mathbb{I}\{\text{Sept.16-18,2019}\} + \epsilon_{kt}, \end{aligned} \tag{33}$$

where $s_{kt} = r_{kt} - r_{\mathcal{O},t}$ is the spread over the ON RRP rate, $q_{k,t}$ is lender k total repo lending to dealers in the decentralized market. We assume a common supply elasticity γ across lenders and proxy for the lender available excess cash with the balance held at the ON RRP $q_{\mathcal{O},k,t}$. The time-invariant lender opportunity costs, $\tilde{c}_k$ parameters, are estimated as lender fixed effects. We also control for the last trading day of the quarter and we add a dummy for the days surrounding September 17, 2019.

Table 4 reports the results from this estimation with repo spreads expressed in basis points and quantities expressed in $billions. Column (1) shows the simple pooled OLS regression. Turning first to quantities supplied, the results reveal that greater lending in excess of cash deposited at the ON RRP leads to a higher spread over the ON RRP rate. The estimate of γ implies that, on average, an increase in lending of about $100 billion leads to an average increase in the spread of the repo rate over the ON RRP rate of about 5.2 basis points. Lenders that do not have deposits with the ON RRP ($q_{\mathcal{O},k,t} = 0$), which is a proxy for lack of excess cash, charge on average about 5 basis points higher spreads.

Turning next to calendar effects, there is an average 6.1 basis point increase in the

Table 4: Estimates of lender supply coefficients

	Dependent variable:				
	Spread over ON RRP $s_{kt} = r_{k,t} - r_{\mathcal{O},t}$				
	(1)	(2)	(3)	(4)	(5)
$q_{k,t} - q_{\mathcal{O},k,t}$, ($\hat{\gamma}^1$)	0.054***	0.039***			
	(0.017)	(0.013)			
$q^{\delta}_{k,t} - q^{\delta}_{\mathcal{O},k,t}$, ($\hat{\gamma}^2$)			0.154***		
			(0.045)		
$q^{\delta}_{k,t}$, ($\hat{\gamma}^3$)				0.220***	
				(0.064)	
$q^{\delta}_{\mathcal{O},k,t}$, ($\hat{\gamma}^4$)				−0.139***	
				(0.044)	
$q^{\lambda}_{k,t} - q^{\lambda}_{\mathcal{O},k,t}$, ($\frac{1}{\hat{\beta}}$)					−0.021
					(0.019)
$\mathcal{I}\{q_{\mathcal{O},k,t} = 0\}$	4.072***	6.516***			
	(0.904)	(0.347)			
$\mathcal{I}\{q^{\delta}_{\mathcal{O},k,t} == 0\}$			7.600***	7.600***	
			(0.304)	(0.304)	
$\mathcal{I}\{q^{\lambda}_{\mathcal{O},k,t} == 0\}$					7.607***
					(0.305)
$\mathcal{I}$\{Quarter-end\}	6.091***	6.175***	5.930***	5.945***	5.917***
	(0.201)	(0.187)	(0.171)	(0.170)	(0.170)
$\mathcal{I}$\{2019-09-16\}	34.092***	33.867***	33.988***	33.988***	33.995***
	(0.858)	(0.756)	(0.750)	(0.750)	(0.750)
$\mathcal{I}$\{2019-09-17\}	291.146***	290.860***	290.992***	290.993***	290.938***
	(5.457)	(5.392)	(5.394)	(5.394)	(5.395)
$\mathcal{I}$\{2019-09-18\}	41.660***	41.407***	41.432***	41.414***	41.471***
	(1.253)	(1.155)	(1.116)	(1.117)	(1.114)
Constant	3.187***				
	(0.310)				
Observations	167,546	167,546	167,546	167,546	167,546
R^2	0.305	0.628	0.624	0.624	0.624
Adjusted R^2	0.305	0.627	0.624	0.624	0.624

NOTE: The data consist of an unbalanced panel of 159 lenders and 1925 trading dates over the period 2014-08-27 to 2022-10-31. Spreads are measured in basis points. The quantity variables $q_{k,t}$ and $q^{\mathcal{O}}_{k,t}$ are the lender-level repo transaction volumes expressed in \$billion in the decentralized tri-party repo market and the ON RRP facility, respectively. The predicted values from the supply and demand decomposition are computed as $q^{\lambda}_{kt} \equiv \lambda_{kt} \times q_{kt-1}$ and $q^{\delta}_{k,t} \equiv \bar{\delta}_{kt} \times q_{kt-1}$, where $\bar{\delta}_{kt}$ is the weighted average of lender k dealers' demand factors. A Wald test on the null hypothesis of different signs but equality of the magnitudes of the coefficient estimates in specification (4) for $q^{\delta}_{k,t}$ and $q^{\delta}_{\mathcal{O},k,t}$ (i.e. $H_0 : \hat{\gamma}^3 + \hat{\gamma}^4 = 0$) has a Chi-squared value of 1.26 and a p-value of 26 percent, thus failing to reject the null hypothesis. Heteroscedasticity consistent standard errors are clustered at the lender level. Significant at *p<0.1; **p<0.05; ***p<0.01.

cost of funds at quarter-ends. In addition, during the market turmoil on September 17, 2019, the average funding cost increased by about 291 basis points. Those estimates indicate that lender supply experiences large time series variation. The constant term provides an estimate of the lender-specific cost parameter $\tilde{c}$. The estimate for the average lender of $\tilde{c}$ is about 3 basis points, which accounts for roughly 60 percent of the average repo spread variation outside the quarter-end periods. In columns (2) through (5), we add lender fixed effects $\{\tilde{c}_k\}_{k \in L}$ to identify the unobserved lender-specific variation in the marginal cost curves. With this addition, other parameter estimates are quantitatively similar to those in column (1). Of note, there is a slight attenuation in our estimate estimate of γ at 0.04, implying an increase in spread of about 4 bps for every \$100 billion increase in aggregate lending.

Our estimated rate elasticities in columns (1) and (2) have a positive sign indicative of an upward sloping supply curve with the quantities traded. However, the standard endogeneity problem of this regression holds as the spread charged is co-determined with the quantities transacted. The parameter estimates are biased downward, because we are not controlling for changes in dealer demand. Therefore, in columns (3) and (4), we report results from empirical specifications that use the AW decomposition to predict the changes in the quantities transacted for each lender k as coming from the average change in dealer demand conditions $q^{\delta}_{k,t} \equiv \bar{\delta}_{k,t} q_{k,t-1}$, where $\bar{\delta}_{k,t} = \sum_{j \in D_{k,t-1}} \frac{q_{jk,t-1}}{q_{k,t-1}} \delta_{j,t}$ is the weighted change in dealer demand faced by lender k, weighted by the lagged shares of lender k dealer counterparties. Similarly, in column (5), we use the change in quantities due to the changes in the lender supply conditions, which are constructed as $q^{\lambda}_{k,t} \equiv \lambda_{k,t} q_{k,t-1}$. The change in quantities $q^{\lambda}_{k,t}$ and $q^{\delta}_{k,t}$ are parallel shifts in the quantities supplied and demanded that allow us to condition on movements along demand and supply curves and identify supply and demand elasticities.

In column (3), the estimate of γ is higher than the estimates in columns (1) and (2), which is consistent with correcting for the downward bias of estimates in columns (1) and (2) by conditioning on changes in dealer demand. It implies that in the aggregate the funding costs for dealers increase by about 15 basis points for every additional \$100 billion in funding. All else equal, lenders without excess cash deposited with the Fed's ON RRP charge on average around 7.6 basis points higher spreads. Note that the rest of the parameter estimates are roughly unchanged indicating that the quarter-end effects and the effects around September 17, 2019 are likely driven by supply factors not related to changes in supply elasticities.

In column (4), we test our two assumptions embedded in equation (1) that excess cash deposited at the ON RRP reduces the opportunity cost of supplying funds to dealers and that the inverse supply elasticity is the same as the inverse elasticity of the cash provided to dealers. First, the coefficient estimate for the ON RRP balance $\hat{\gamma}^4$ is statistically significant and negative at -0.139 validating the first assumption. Second, the coefficient estimate $\hat{\gamma}^3$ is 0.220, which is higher than the estimate in specification (3). However, a Wald test for the equality of the magnitudes of the two coefficients fails to reject the null hypothesis of equality with a p-value exceeding 26 percent.[23]

The estimates in columns (3) and (4) give us some range of estimates of the supply elasticity. Based on estimates from column (3), the implied lender supply elasticity is \$6.5 billion for every 1 basis point increase in interest rates. The estimate in column (4) is lower and implies that funds with excess cash are willing to supply an additional \$4.5 billion for every 1 basis point increase in interest rates.[24]

Finally, the analysis in column (5) examines a test for the validity of the supply and demand decomposition. The previous three specifications were conditioning on movements in dealer repo demand tracing an upward sloping lender marginal cost curves. In specification (5), we examine movements in repo supply tracing a downward sloping demand curve. Therefore, the coefficient estimate on the term $(q^{\lambda}_{k,t} - q^{\lambda}_{\mathcal{O},k,t})$ is expected to be negative consistent with movements along a downward-sloping demand curve and its magnitude inversely proportional to dealers' inverse elasticity parameter β. The coefficient estimate is indeed negative and its magnitude is both economically small and statistically not significant. This estimate indicates that dealer repo demand is relatively inelastic. We return to a more in-depth estimation of dealer demand in the next section.

We have assumed a common interest rate elasticity of lender supply and, thus, the estimate for the supply elasticities should be interpreted as an aggregate supply elasticity. At the individual lender level, there are capacity constraints that would make the supply elasticity much lower especially for smaller lenders in our sample. It

[23]Note that if we estimate the regression in specification (4) without the AW decomposition, we obtain qualitatively similar results to specification (1) with the Wald test also failing to reject the null hypothesis.

[24]In unreported estimation, we also run a weighted regression to underscore that larger funds are more likely to be unconstrained and have impact on the aggregate supply of funds. The estimates are in line with the unweighted regressions.

should be noted that while we assumed supply elasticities to be fixed, we let lender marginal cost intercepts $\{\tilde{c}_k\}_{k\in L}$ to differ across lenders and in part capture variation in capacity constraints and excess cash as discussed in Section 3.1. Table 5 shows the cross-sectional distribution of those estimates, which reveals that there is significant heterogeneity in the average marginal costs across lenders with a right tail of high cost lenders with marginal costs exceeding 20 basis points and a notable mass of low cost lenders, which are, all else equal, willing to supply funds to dealers at low rates with more than 10 basis point discount relative to the ON RRP rate. On average lenders with access to the Fed's ON RRP have higher marginal costs than those lenders that do not have access. The median lender with access to the ON RRP charges 1.1 basis points spread over the ON RRP rate, whereas the median lender without access to the ON RRP charges 2.4 basis points lower spread over the ON RRP rate.

Table 5: Estimates of the average lender marginal cost parameters $\tilde{c}$

	mean	w.mean	sd	5	25	50	75	95
All lenders	0.2	3.15	9.6	-10.5	-4.3	-1.5	2.5	20.0
No access to ON RRP	-1.2	2.12	8.9	-11.9	-5.4	-2.3	-0.2	20.7
Access to ON RRP	3.3	3.89	10.4	-2.5	-0.6	1.1	3.8	7.1

NOTE: The estimates of the lender fixed effects from regression Table 4 column (3). The units are basis points. w.mean is the volume-weighted mean. There are 159 lenders in our sample. Of those, 43 have access to the ON RRP with the Fed and 116 do not have access.

4.6 Dealers' strategic substitutability of funding

Before we estimate the repo demand elasticities, we first test whether dealers' borrowing actions are strategic substitutes in the decentralized market. The system of first-order conditions (6) implies that dealer i reduces its own borrowing in response to higher borrowing by other dealers with whom dealer i shares a set of common lenders. The degree of substitution depends on on the relative supply and demand elasticities. To quantify the degree of substitution of dealer actions, we examine the following reduced-form empirical specification

$$\Delta q_{ik,t} = \alpha_1 \sum_{j \in D_k, j \neq i} \Delta q_{jk,t} + \alpha_2 \sum_{l \in L_i, \ell \neq k} \Delta q_{il,t} + \alpha_3 \rho_{\mathcal{C},t} + \delta_{i,t} + \lambda_{k,t} + u_{ik,t}, \tag{34}$$

where $\Delta q_{ik,t}$ is the growth rate in repo volume between dealer i and lender k between trading days $t-1$ and t. The term $\sum_{j \in D_k, j \neq i} \Delta q_{jk,t}$ captures the growth rate in repo volume by lender k from all of its dealer counterparties excluding dealer i. Similarly, the term $\sum_{l \in L_i, \ell \neq k} \Delta q_{il,t}$ captures the growth rate in repo volume of all lender counterparties of dealer i excluding lender k.

The sign and magnitude of the coefficient estimates of α_1 and α_2 are of importance. Both coefficients should be negative reflecting substitutions of dealers across different lenders in the OTC market as a response to other dealers' funding decisions. Finally, all else equal, higher cost of borrowing from the GCF market should increase the borrowing from the decentralized market, implying that α_3 should be positive. This coefficient captures the degree of substitution between the decentralized and the centrally cleared GCF market.

To control for the endogeneity of the equilibrium quantities, we condition on changes in dealer demand captured by $\delta_{i,t}$ and changes in lender supply captured by $\lambda_{k,t}$. We also control for unobservable dealer and lender characteristics with a set of dealer and lender fixed effects. The indicator function $\mathcal{I}\{q_{i\mathcal{C}t} = 0\}$ takes the value of 1 for the case when a dealer does not transact in the interdealer market, and $\mathcal{I}\{q_{i\mathcal{C}t} \neq 0\}$ takes the value of 1 for the case when a dealer borrows or lends in the decentralized market.

Estimates of (34) are reported in Table 6. In the first column, we present the regression without the demand and supply controls but with a full set of dealer and lender fixed effects. The terms that capture the strategic interactions among dealers and the substitutions across lenders in column (1) are both positive, which contradicts the predictions of the model. However, this is expected, because the growth in repo trades are determined by common variation in demand and supply conditions among dealers and lenders.

Table 6: An estimate of dealers' substitutability of funding

	Dependent variable:		
	Growth in dealer-lender repo trades $\Delta q_{ik,t}$		
	(1)	(2)	(3)
GCF spread $\rho_{\mathcal{C}}$			1.510**
			(0.610)
$\sum_{l\in L_i,\ell\neq k}\Delta q_{i\ell}$			−0.305***
			(0.056)
$\sum_{j\in D_k,j\neq i}\Delta q_{jk}$			−0.306***
			(0.038)
GCF spread $\rho_{\mathcal{C}}\lvert\mathbb{I}\{q_{i\mathcal{C}}\neq 0\}$	2.225***	1.646**	
	(0.733)	(0.675)	
GCF spread $\rho_{\mathcal{C}}\lvert\mathbb{I}\{q_{i\mathcal{C}}=0\}$	0.879	0.907	
	(0.718)	(0.696)	
$\sum_{l\in L_i,\ell\neq k}\Delta q_{i\ell}\lvert\mathbb{I}\{q_{i\mathcal{C}}=0\}$	0.230***	−0.291***	
	(0.058)	(0.060)	
$\sum_{l\in L_i,\ell\neq k}\Delta q_{i\ell}\lvert\mathbb{I}\{q_{i\mathcal{C}}\neq 0\}$	0.075***	−0.363***	
	(0.024)	(0.057)	
$\sum_{j\in D_k,j\neq i}\Delta q_{jk}\lvert\mathbb{I}\{q_{i\mathcal{C}}=0\}$	0.088***	−0.306***	
	(0.015)	(0.039)	
$\sum_{j\in D_k,j\neq i}\Delta q_{jk}\lvert\mathbb{I}\{q_{i\mathcal{C}}\neq 0\}$	0.105***	−0.304***	
	(0.029)	(0.045)	
$\lambda_{k,t}$		0.966***	0.966***
		(0.074)	(0.074)
$\delta_{i,t}$		0.891***	0.895***
		(0.064)	(0.064)
Observations	1,049,713	1,049,713	1,049,713
R^2	0.016	0.135	0.135
Adjusted R^2	0.015	0.135	0.134
Residual Std. Error	35.8	33.6	33.6
Degrees of freedom	1,049,506	1,049,504	1,049,507

NOTE: The data consist of an unbalanced panel of 159 lenders, 49 dealers, 1261 trading relationships, and 1926 trading dates over the period 2014-08-27 to 2022-10-31. The growth rates and the GCF repo spread are expressed in percentage points. Therefore, a percentage point increase in the GCF spread over the ON RRP spread leads to a 1.5 percentage points increase in the growth of repo trades in the OTC market. All regressions include a full set of dealer and lender fixed effects. Heteroscedasticity consistent standard errors are clustered at the lender level. Significant at *p<0.1; **p<0.05; ***p<0.01.

In columns (2) and (3), we control for demand and supply conditions of dealer i and lender k. With these controls, the two terms switch signs to being negative as predicted by the model. The estimates imply that for every percentage point increase in the borrowing of competing dealers, a dealer reduces its own borrowing by about 30 basis points. Similarly, a percentage point increase in the borrowing from lenders other than k in dealer i's counterparties, results in about 30 basis points decline in the borrowing from lender k. The degree of substitution among lenders is smaller for dealers that access the interdealer market as revealed in column (2) that conditions on whether the dealer participates in the interdealer market.

Finally, the sign on the GCF spread $\rho_{\mathcal{C}}$ is positive, indicating that dealers are more likely to borrow more from their counterparties in the decentralized market, when the cost of borrowing from the centrally-cleared market is higher. The dealers, that do not participate in the interdealer market, do not respond to changes in the GCF spread. The coefficient estimate for dealers that do not transact in the interdealer market is both smaller and statistically not significant. This substitution between the decentralized and the centrally cleared market is predicted by the model and the magnitude of the interest rate sensitivity is inversely related to the dealers' balance sheet cost parameter.

We can extract an estimate of dealers' demand elasticities from the estimate of α_3, which is related to the dealer demand elasticity $\frac{1}{\beta}$. The estimate implies that for every 100 basis points increase in the GCF spread, dealers increase borrowing from the decentralized market by about 1.5 percent. This estimate implies a very low demand elasticity relative to the estimated lender supply elasticity in the previous section. However, this estimate is likely to be biased as it ignores the endogeneity in the choice of participating in the GCF market. We examine empirically the endogenous selection of dealers into net borrowers and net lenders in the centrally cleared market along the extensive and intensive margins in more detail in the next section and provide additional estimates of dealers' demand elasticity.

4.7 Dealers' participation in the interdealer market

We next examine the extensive and intensive margins of dealers' participation in the centrally-cleared interdealer market (FICC GCF). Equation (19) predicts that dealers with more costly access to the decentralized market would be net borrowers, whereas dealers with lower cost of accessing the decentralized market would be net lenders. In addition, dealers with low β or low funding shortfall costs are more elastic to interest rates. All else equal, those dealers are more likely to switch roles between being net borrowers in the GCF market to being net lenders. To estimate β, we design the following empirical specification

$$q_{i\mathcal{C},t} = \alpha_1 q^{\delta}_{i,t} + \alpha_2 \sum_{\substack{k\in L_i \\ j\ell\in E}} \tilde{\psi}_{ik,j\ell,t} q^{\lambda}_{l,t} + \alpha_3 (\sum_{\substack{k\in L_i \\ j\ell\in E}} \tilde{\psi}_{ik,j\ell,t}) \times \rho_{\mathcal{C},t} + \alpha_4 \rho_{\mathcal{C},t} + \epsilon_{it}. \quad (35)$$

We estimate equation (35) as a selection model with the main object of interest the estimate of $\alpha_4 = \frac{1}{\beta}$. The model implies that conditional on demand dealers with higher funding cost and balance sheet costs β are more likely to select to be net borrowers.

Table 7: Probit regression for the participation in the GCF market

	Dependent variable: Participation in the GCF market	
	Net borrower $\mathcal{I}\{q_{i\mathcal{C},t} > 0\}$	Net lender $\mathcal{I}\{q_{i\mathcal{C},t} < 0\}$
	(1)	(2)
EDF 1-year, it	-0.716^{***}	1.092^{***}
	(0.041)	(0.041)
Book leverage, it	13.822^{***}	-5.821^{***}
	(0.334)	(0.325)
Market-to-book, it	-4.512^{***}	3.715^{***}
	(0.152)	(0.147)
log(Assets), it	0.131^{***}	0.715^{***}
	(0.010)	(0.011)
Constant	1.085^{***}	-13.282^{***}
	(0.207)	(0.219)
Observations	43,811	43,811
Obs. $\mathcal{I}\{q_{i\mathcal{C}} > 0\}$	13,108	13,108
Obs. $\mathcal{I}\{q_{i\mathcal{C}} < 0\}$	21,047	21,047
Log Likelihood	−25,704.680	−27,643.660
Akaike Inf. Crit.	51,419.370	55,297.320

NOTE: The data consist of an unbalanced panel of 31 dealers for which we observe EDF 1-year, book leverage, market-to-book ratios, and total assets over the period 2014-08-27 to 2022-10-31. Significant at *p<0.1; **p<0.05; ***p<0.01.

The first stage of the estimation is a probit model that examines the determinants of the dealer's choice to participate in the GCF market as either a net borrower $\mathcal{I}\{q_{i\mathcal{C}} > 0\}$ or as a net lender $\mathcal{I}\{q_{i\mathcal{C}} < 0\}$. We introduce dealer-specific variables that are determined outside the tri-party repo market and relate to the dealers' cost of access to unsecured credit markets as well as regulatory balance sheet constraints. In particular, we proxy for the cost of funds from external unsecured markets with measures of the default risk, leverage, asset size, and market valuation of the dealers' parent holding company. For leverage constraints on bank affiliated dealers, we use measures of book leverage again measured at the parent holding company. We use the one-year empirical default frequency (EDF 1-year) constructed by the Moody's KMV Merton-style default model as well as the book leverage of the dealer's parent holding company. To condition on the parent's alternative use of funds, we also include the parent holding company market-to-book ratio. Finally, we also control for the size of the parent holding company with the log of the market value of total assets.

Results of the probit regression are reported in Table 7. Column (1) examines the choice to be a net borrower in the GCF market relative to being a net lender or not participating, and column (2) examines the choice to be a net lender relative to being a net borrower or not participating. Higher EDF 1-year predicts lower probability to be a net borrower and higher probability to be a net lender, whereas higher book leverage predicts higher participation as a net borrower and lower participation as a net lender. A lower market-to-book ratio, which could be an indicator for market distress or the lack of good investment opportunities, is associated with higher participation as a net lender and a lower participation as a net borrower.

The estimates of second stage of the selection model are presented in Table 8. In columns (1) and (2), we estimate the interest sensitivity of the amount borrowed or the amount lent, conditioning on the dealer selection to be net borrower or net lender, respectively. The quantities are expressed in billions of dollars and the GCF spread is expressed in basis points. Therefore, the amount borrowed decreases by about $28 million following a 1 basis point increase in spreads, whereas a similar increase in the spreads results in a $42 million increase in lending. This implies that dealers that select to provide funding in the GCF market have lower β as compared to those that demand funding. The estimate of the inverse demand elasticity β for dealers, that are net borrowers in the GCF market, implies that those dealers are willing to pay 36 basis points for every additional billion of dollars of funding, whereas the estimated β for dealers, that are net lenders in the GCF market, implies that those dealers are willing to supply additional \$1 billion in funding if compensated by additional 24 basis points in spreads. Compared with estimates for the inverse loan supply elasticities in Table 4, dealer demand is significantly less interest rate elastic.

Table 8: Net borrowing and lending in the GCF market

	Dependent variable: Net amount, \$billions	
	Borrowed $q_{i\mathcal{C}} \mid q_{i\mathcal{C}} > 0$	Lent $q_{i\mathcal{C}} \mid q_{i\mathcal{C}} < 0$
	(1)	(2)
GCF spread $\rho_{\mathcal{C},t}$	-0.028^{***}	-0.042^{***}
	(0.010)	(0.007)
$(\sum_{k \in L_i} \sum_{j\ell \in E} \tilde{\psi}_{ik,j\ell}) \times \rho_{\mathcal{C},t}$	-0.007^{***}	0.011^{***}
	(0.002)	(0.001)
Lender supply $\sum_{k \in L_i} \sum_{j\ell \in E} \tilde{\psi}_{ik,j\ell} q^{\lambda}_{\ell,t}$	-4.934^{***}	3.087^{***}
	(0.282)	(0.159)
Dealer demand $q^{\delta}_{i,t}$	0.046^{***}	-0.199^{***}
	(0.008)	(0.004)
Constant	18.426^{***}	-5.783^{***}
	(0.412)	(0.171)
Observations	43,566	43,486
Log Likelihood	−76,611.180	−102,358.700
ρ	-0.428^{***} (0.019)	0.295^{***} (0.015)

NOTE: The data consist of an unbalanced panel of 31 dealers for which we observe EDF 1-year, market value of assets, equity, and book leverage. The GCF spread over the ON RRP rate is expressed in basis points. The supply and demand factors are computed as $q^{\lambda}_{\ell t} \equiv (1 + \lambda_{\ell t}) \times q_{\ell t-1}$ and $q^{\delta}_{k,t} \equiv (1 + \delta_{it}) \times q_{it-1}$. The weights $\tilde{\psi}_{ik,j\ell}$ are elements of the matrix $\tilde{\Psi} = \left(I + \frac{1}{2}\tilde{W}\right)^{-1}$, where $\tilde{W}$ is defined in (14). All quantities are expressed in billions of dollars. Column 1 and 2 estimate regression equation (35) using maximum likelihood conditioning on a dealer being a net borrower or a net lender according to selection model in Table 7. Significant at *p<0.1; **p<0.05; ***p<0.01.

Finally, the empirical specification controls for the effects of dealer demand and the weighted cost of borrowing from the decentralized market and the strategic interactions of dealers in that market. As predicted by the model higher dealer demand increases the amount borrowed in the centrally cleared market, whereas higher supply of funds or lower cost of funds in the decentralized OTC market decreases the amount borrowed. The last row in Table 8 gives the estimate of the correlation ρ between the unobserved determinants of the choice to borrow or lend in the GCF market with the unobserved components of the determinants of the amount borrowed or lent. The statistical significance of the ρ coefficient indicates that the selection into borrowing or lending in the GCF market is non-random.

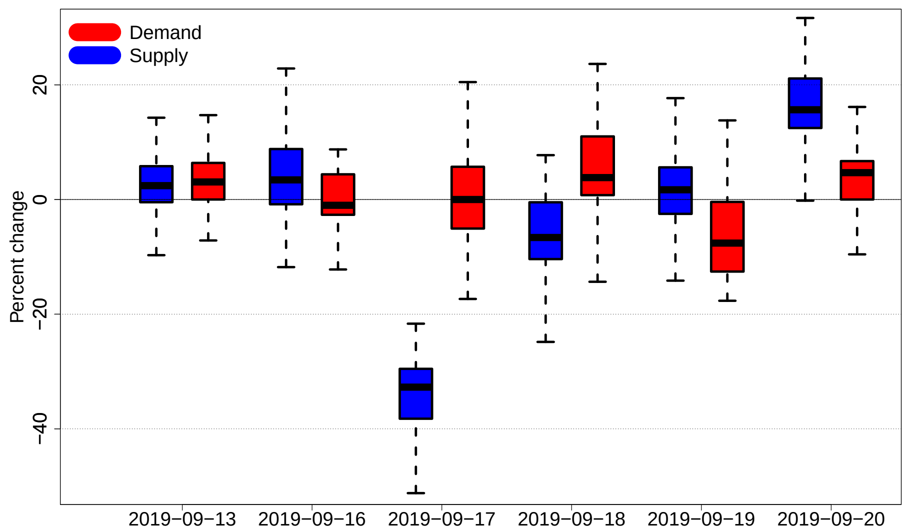
4.8 Supply shocks and rate spikes in September 2019

The previous sections established that the repo market is characterized by significantly lower dealer demand elasticity as compared to the lender supply elasticity. This implies that the repo market would experience significant increases in spreads over the ON RRP rate, when there are significant reductions in lender supply of cash. Indeed, when we examine the daily decomposition of supply and demand around September 17, 2019 in Figure 12, we can see that the market experienced a large negative supply shock. The supply shock resulted in a 30 percent decline in supply at the median lender and some lenders experienced even larger declines in supplied quantities. At the same time, there was no notable change in aggregate demand with the change in demand at the median dealer hovering around zero. The volume-weighted supply declined by about 22 percent, which represents a reduction of about $160 billion, whereas the volume-weighted demand increased slightly by about 1 percent. Therefore, because of the large supply decline and the steady and inelastic demand, the repo spreads spiked as shown in Figure 10.

Based on our estimates of the demand elasticities, we can do a simple back-of-the-envelope calculation that such a large supply shock could result in a spike in repo spreads far exceeding the actual observed average spike of 315 basis points on September 17, 2019 documented in Table 3. Based on the estimates of the demand elasticity from Table 6, we can project that that repo rates would have increased by more than 14 percentage points, whereas the estimates in Table 8, which account for the selection into borrowing from the GCF market, imply an even larger spike in rates that exceeds 25 percentage points.

Those back-of-the-envelope estimates are several orders of magnitude higher than those observed during this period, mainly because they ignore the substitutions dealers do across lenders and the centrally-cleared market as well as other factors that determine the equilibrium repo spread not captured by the model. However, the extrapolation is indicative that the model estimates of the elasticities and movements in supply and demand could match the volatility in repo spreads. Furthermore, as we document next, the magnitudes of declines in supply are consistent with the observed borrowing of dealers from the temporary repo operations by the Federal Reserve.

Figure 12: Supply and demand factors around September 19, 2019



NOTE: The boxplots represent the interquartile ranges of the percent changes in supply and demand across lender and dealers, respectively. The solid black lines are the medians and the interquartile ranges are represented in the colored boxes. The whiskers represent the 5th and 95th percentiles of the distribution. SOURCE: FRBNY Tri-party repo and authors' calculations.

5 Counterfactual and policy analysis

We examine two counterfactuals related to potential and actual policy changes. First, we quantify the importance of the centrally-cleared market for the availability and cost of dealer funding, holding fixed the connectedness in the decentralized market. This exercise illustrates how the introduction of central clearing in decentralized financial markets could affect those markets. Second, we evaluate the role of the Standing Repo Facility (SRF) for market efficiency.

5.1 Welfare and market wiring

To be able to conduct policy evaluations, we need to first define welfare. Define market welfare as the sum of the dealer and lender surpluses. The total funding cost of dealers is the sum of individual dealer funding costs

$$V(\mathcal{W}) = \sum_{i \in D} \mathcal{V}_i(q_{\mathcal{B}i}|\mathcal{W}). \tag{36}$$

All else equal, a market wiring with lower dealer funding costs is more efficient.

Lender surplus is defined as the area under the lenders' marginal cost curves $Z_k = \frac{(r_k - c_k)^2}{2\gamma_k} = \frac{\gamma_k}{2} q_k^2$, where $q_k = \sum\limits_{i \in D_k} q_{ik}$. The sum of all lenders' surpluses is

$$Z(\mathcal{W}) = \sum_{k \in L} \frac{\gamma_k}{2} q_k^2. \tag{37}$$

Lender surplus increases with the quantities traded at lenders with higher monopoly power as captured by the interest rate elasticity parameter γ. The total welfare in the market is the sum of the dealer and lender surpluses

$$U(\mathcal{W}) = -V(\mathcal{W}) + Z(\mathcal{W}), \tag{38}$$

where the negative of the total dealer funding costs ensures that lower funding costs increases overall welfare.

5.2 Introduction of a centrally-cleared market

We illustrate the main intuition of the analysis through our simple example, introduced in Section 3.8, which we can solve in closed form. The changes in the total dealer funding costs, the lender surplus, and the total market welfare can also be computed in closed form for the case of symmetric wiring as follows

$$
\begin{aligned}
V(\mathcal{C},\mathcal{T}^{sym}) - V(\varnothing,\mathcal{T}^{sym}) &= -\frac{\beta\gamma(\beta+2\gamma)}{2(3\beta+2\gamma)^2}(q_{\mathcal{B}1}-q_{\mathcal{B}2})^2 \\
L(\mathcal{C},\mathcal{T}^{sym}) - L(\varnothing,\mathcal{T}^{sym}) &= -\frac{\beta^2\gamma}{4(3\beta+2\gamma)^2}(q_{\mathcal{B}1}-q_{\mathcal{B}2})^2 \\
W(\mathcal{C},\mathcal{T}^{sym}) - W(\varnothing,\mathcal{T}^{sym}) &= \frac{\beta\gamma(\beta+4\gamma)}{4(3\beta+2\gamma)^2}(q_{\mathcal{B}1}-q_{\mathcal{B}2})^2
\end{aligned} \tag{39}
$$

The total funding cost differential is always lower when a centrally-cleared market exists. Furthermore, the improvements in funding costs increase with the square of the demand differentials between the two dealers $q_{B1} - q_{B2}$. This is not a very surprising result, because the centrally cleared market allows for the excess demand conditions of dealers to be resolved at a marginal cost that is equalized across all funding sources for both dealers. This allows for dealers to better coordinate on their borrowing decisions to achieve lower funding costs. Such improvements in funding costs of dealers are in part at the expense of lender surplus, which decreases in proportion to the square of the demand differentials. The existence of a centrally cleared market effectively reduces the overall market power of lenders. The equalization of marginal cost of funds with the centrally cleared market results in higher strategic substitutability of borrowing of dealers from their common lender. However, the reduction in lender surplus is dominated by the increases in dealer welfare and, as a result, the total market welfare increases.

Now examine the situation in which the decentralized market is fully wired as in panel C of Figure 4. Following the steps outlined above, one can similarly solve for the differentials in equilibrium welfare in closed form as follows[25]

$$
\begin{aligned}
V(\mathcal{C},\mathcal{T}^{full}) - V(\varnothing,\mathcal{T}^{full}) &= -\frac{\beta\gamma^2}{4(3\beta+\gamma)^2}(q_{\mathcal{B}1}-q_{\mathcal{B}2})^2 \\
L(\mathcal{C},\mathcal{T}^{full}) - L(\varnothing,\mathcal{T}^{full}) &= 0 \\
W(\mathcal{C},\mathcal{T}^{full}) - W(\varnothing,\mathcal{T}^{full}) &= \frac{\beta\gamma^2}{4(3\beta+\gamma)^2}(q_{\mathcal{B}1}-q_{\mathcal{B}2})^2.
\end{aligned} \tag{40}
$$

Dealers' funding costs are lower in the presence of a centrally cleared market. This result is somewhat counter intuitive. To understand how the reduction in funding costs occurs, examine the dealer marginal costs in the fully wired $\mathcal{T}$ market. Without the centrally cleared market dealer's funding costs are equalized across lenders but

[25] See the appendix for all the derivations.

not across dealers. In contrast, with a centrally cleared market, all dealers' marginal costs are equalized to the equilibrium rate in the centrally cleared market. We can calculate how marginal costs differ between a wiring with and a wiring without a centrally cleared market

$$\rho_{\mathcal{C}}(\mathcal{C}, \mathcal{T}^{full}) - \rho_{ik}(\varnothing, \mathcal{T}^{full}) = \frac{\beta\gamma}{3\beta+\gamma}\frac{q_{\mathcal{B}j} - q_{\mathcal{B}i}}{2}.$$

Differences in dealer demand $q_{\mathcal{B}1} > q_{\mathcal{B}2}$ result in lower marginal costs for the dealer with higher demand and higher marginal costs for the dealer with the low demand in the presence of a centrally cleared market as compared to a wiring without. This difference is needed to induce dealer d_2 with low demand to borrow an additional amount $\frac{q_{\mathcal{B}1}-q_{\mathcal{B}2}}{2}$ from cash lenders and lend it to the centrally cleared market to meet dealer d_1 with high demand. In equilibrium, lenders provide exactly the same amount of cash, charge the same rates, and receive the same surplus. However, because of the higher substitutability of dealer actions, the overall market welfare is increased by the reduction in dealer funding costs for the dealer with high repo demand.

5.3 Introduction of the Standing Repo Facility

In July 2021, the Federal Reserve established the Standing Repo Facility (SRF) as a liquidity backstop in the repo market to support monetary policy implementation. In the context of our model, the SRF introduces an alternative source of funding for the set of dealers, $D_{\mathcal{S}}$, who are authorized SRF counterparties. The SRF would charge a minimum bid spread of $\underline{\rho_{\mathcal{S}}}$ over the ON RRP rate $r^{\mathcal{O}}$. Furthermore, the SRF imposes an individual participant cap $\bar{q}^{\mathcal{S}}$ and an aggregate cap $\bar{\bar{q}}^{\mathcal{S}}$. Denote the effective aggregate cap as $\tilde{q}^{\mathcal{S}} \equiv \min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}$, which is the effectively binding constraint between the sum of individual caps and the aggregate cap.[26]

To characterize the usage of the facility, we assume that the equilibrium bid rate of a participating dealer is determined by the equilibrium market clearing rate of the

[26] There are 37 SRF counterparties as of December 2024 (see FRB NY website). The minimum bid spread is set by the FOMC and is currently set at 25 basis points over the ON RRP rate. The caps are \$20 billion and \$550 billion for the individual dealer and the aggregate, respectively. The settlement of SRF is integrated with the tri-party repo platform with pre-specified haircuts for Treasuries and Agency MBS. See Ennis and Huther [2021] and FRB NY website for additional institutional details of the Standing Repo Facility.

$\mathcal{C}$ market, and every participating dealer takes the equilibrium bid rate as given. We follow the convention in the general equilibrium literature (Walrasian tâtonnement) and how we model the $\mathcal{C}$ market.[27] Because of the centrally cleared market, dealers face a common marginal funding cost and their equilibrium bidding rates should equal that marginal funding cost $\rho_{\mathcal{C}}$.

First, consider the case in which the minimum bid rate exceeds the equilibrium $\mathcal{C}$ market funding rate $\underline{\rho_{\mathcal{S}}} > \rho^*_{\mathcal{C}}$. Then, dealers find it optimal not to borrow from the SRF, because it is cheaper to borrow from the $\mathcal{C}$ market. Second, consider the case in which $\rho^*_{\mathcal{C}}$ exceeds the minimum bid rate, i.e., $\rho^*_{\mathcal{C}} > \underline{\rho_{\mathcal{S}}}$. Then, every dealer with access to the SRF will borrow from the SRF as dealers in $D_{\mathcal{S}}$ make profit from the arbitrage between the SRF rate and the market rate by borrowing from the SRF and lending in the $\mathcal{C}$ market. All dealers in $D_{\mathcal{S}}$ submit the auction bid $\rho_{\mathcal{S}}$. The new equilibrium $\mathcal{C}$ market rate must equal the equilibrium bid rate, i.e., $\rho^*_{\mathcal{C},\mathcal{S}} = \rho_{\mathcal{S}}$.

Denote the SRF borrowing amount of dealer $i \in D_{\mathcal{S}}$ as $q_{i\mathcal{S}}$. If the total SRF borrowing amount $\sum_{i \in D_{\mathcal{S}}} q_{i\mathcal{S}}$ does not reach its effective cap $\tilde{q}^{\mathcal{S}}$ with the equilibrium market rate at the minimum bid rate, then the market rate will stay at the minimum bid rate, i.e. $\rho^*_{\mathcal{C},\mathcal{S}} = \rho_{\mathcal{S}} = \underline{\rho_{\mathcal{S}}}$. The last equality is again coming from the same mechanism as in Proposition 3, as dealers would equalize their marginal cost of funding from all possible sources. The last case is when the effective cap is binding at the minimum bid rate $\underline{\rho_{\mathcal{S}}}$. In this case, dealers will bid at a new equilibrium $\mathcal{C}$ market rate $\rho^*_{\mathcal{C},\mathcal{S}} > \underline{\rho_{\mathcal{S}}}$. The new market rate $\rho^*_{\mathcal{C},\mathcal{S}}$ is determined by the following market clearing condition

$$\sum_{i \in D} q^{\mathcal{S}}_{i\mathcal{C}}(\rho^*_{\mathcal{C},\mathcal{S}}) = \sum_{i \in D} q_{i\mathcal{C}}(\rho^*_{\mathcal{C},\mathcal{S}}) - \tilde{q}^{\mathcal{S}} = 0, \tag{41}$$

where $q^{\mathcal{S}}_{i\mathcal{C}}(\rho^*_{\mathcal{C},\mathcal{S}})$ is the net $\mathcal{C}$ market demand of dealer i when there is SRF facility. The first equality relates the equilibrium with SRF to the equilibrium without SRF.

To derive the new equilibrium, one can use the individual net cash demand functions $q_{i\mathcal{C}}$ as the ones in the equilibrium without the SRF and subtract the aggregate cash obtained from the SRF. However, under conditions described below high-cost dealer-lender trading relationships become inactive after the introduction of the SRF.

[27] We can provide a formal microfoundation to this assumption with a strategic interaction through a discriminatory ascending auction.

Define the set of trading relationships that remain active after the introduction of the SRF as $E^{\mathcal{S}} \subseteq E$. The corresponding matrix $\tilde{\Psi}^{\mathcal{S}}$ is then derived for the new set of active trading relationships $E^{\mathcal{S}}$ in the same way as in the previous sections. We can derive the aggregate demand for SRF funding as

$$\sum_{i \in D^S} q_{i\mathcal{S}}(\rho_{\mathcal{S}}) = \bar{q}_{\mathcal{B}} + \sum_{ik \in E^{\mathcal{S}}} \sum_{j\ell \in E^{\mathcal{S}}} \frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \left(\sum_{ik \in E^{\mathcal{S}}} \sum_{j\ell \in E^{\mathcal{S}}} \frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i \in D} \frac{1}{\beta_i} \right) \rho_{\mathcal{S}} \tag{42}$$

The next proposition summarizes the equilibrium of the market in the presence of an SRF facility.

Proposition 5 *Let $\rho^*_{\mathcal{C}}$ and $\rho^*_{\mathcal{C},\mathcal{S}}$ be the equilibrium $\mathcal{C}$ market rate without and with the SRF, respectively. When the SRF is introduced, the following statements are true.*

1. *If $\rho^*_{\mathcal{C}} \leq \underline{\rho_{\mathcal{S}}}$, then no dealer borrows from the SRF, $q_{i\mathcal{S}} = 0$, for all $i \in D_{\mathcal{S}}$.*

2. *If $\rho^*_{\mathcal{C}} > \underline{\rho_{\mathcal{S}}}$, a trading relationship $ik \in E$ becomes inactive in the equilibrium with the SRF if and only if*

$$\frac{\sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell}{\sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}} > \rho^*_{\mathcal{C},\mathcal{S}}. \tag{43}$$

3. *If $\rho^*_{\mathcal{C}} > \underline{\rho_{\mathcal{S}}}$ and $\sum_{i \in D^S} q_{i\mathcal{S}}(\underline{\rho_{\mathcal{S}}}) \leq \tilde{q}^{\mathcal{S}}$ hold, then $\rho^*_{\mathcal{S}} = \rho^*_{\mathcal{C},\mathcal{S}} = \underline{\rho_{\mathcal{S}}}$ and dealers borrow from the SRF in the aggregate amount of $\sum_{i \in D^S} q_{i\mathcal{S}}(\underline{\rho_{\mathcal{S}}})$.*

4. *If $\rho^*_{\mathcal{C}} > \underline{\rho_{\mathcal{S}}}$ and $\sum_{i \in D^S} q_{i\mathcal{S}}(\underline{\rho_{\mathcal{S}}}) > \tilde{q}^{\mathcal{S}}$ hold, then the borrowed amount from the SRF is the cap amount and the new equilibrium rate is*

$$\rho^*_{\mathcal{C},\mathcal{S}} = \frac{\bar{q}_{\mathcal{B}} + \sum_{ik \in E^{\mathcal{S}}} \sum_{j\ell \in E^{\mathcal{S}}} \frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \tilde{q}^{\mathcal{S}}}{\sum_{ik \in E^{\mathcal{S}}} \sum_{j\ell \in E^{\mathcal{S}}} \frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i \in D} \frac{1}{\beta_i}}, \tag{44}$$

and the equilibrium SRF bid rate is $\rho^*_{\mathcal{S}} = \rho^*_{\mathcal{C},\mathcal{S}} > \underline{\rho_{\mathcal{S}}}$.

The first statement of Proposition 5 implies that the SRF is not used when the $\mathcal{C}$ market rate is below the minimum bid rate. The second statement examines which trading relationships in the $\mathcal{T}$ market become inactive when dealers borrow from the SRF, which is condition similar to (18) of Lemma 1. The third statement proves that the $\mathcal{C}$ market rate stays at the SRF minimum bid rate when the SRF cap is not binding. The fourth statement examines the $\mathcal{C}$ market rate when borrowing from the SRF reaches the cap. In this situation, the equilibrium rate exceeds the minimum bid rate.

Proposition 5 implies that the SRF lowers the marginal cost of funds in the repo market, as it can be easily shown that (44) in Proposition 5 is lower than (20) in Proposition 1. Therefore, the SRF provides a conditional funding buffer, which mitigates fluctuations of the $\mathcal{C}$ market rate due to supply and demand shocks. It is easy to see that the effect of the SRF on the repo market is equivalent to reducing the aggregate dealer demand up to the aggregate cap i.e. we can redefine dealer demand as $\bar{q}_{\mathcal{B}}^{\mathcal{S}} = \bar{q}_{\mathcal{B}} - \tilde{q}^{\mathcal{S}}$.

The market clearing condition pins down a unique aggregate demand for the SRF funding. However, individual dealer demand schedules $q_{i\mathcal{S}}(\rho_{\mathcal{S}})$ are not well defined and there is multiplicity of equilibria with respect to the individual dealer borrowing from the SRF. This is because each dealer is indifferent between borrowing from the SRF and borrowing from the centrally-cleared market.

Proposition 5 also illustrates a trade-off between the size of the cap on available SRF funding and the level of the minimum bid rate $\underline{\rho_{\mathcal{S}}}$ and their impact on the market. Lower SRF caps or a higher minimum bid rate provide smaller liquidity buffer against supply and demand shocks, limiting the effectiveness of the facility as a liquidity backstop. However, higher SRF caps or lower minimum bid rate reduce the incentives of dealers to maintain relationships with lenders. Moreover, expanded participation in the SRF through higher caps, larger set of counterparties $|D_{\mathcal{S}}|$ or lower minimum bid rates could also result in no equilibrium trades in the $\mathcal{C}$ market.

While this section illustrates how the market equilibrium is affected by the introduction of the SRF, deriving an optimal design of the SRF facility is beyond the scope of this paper. Such analysis requires a substantial extension of our model including examining issues of moral hazard and the cost of funding the SRF facility. We leave such extensions for future research.

6 Conclusion

We have provided a novel framework to examine the efficiency with which the tri-party repo market allocates cash and collateral between lenders and dealers in the decentralized OTC market, and among dealers in the anonymous centrally-cleared GCF market. Unlike existing literature on repo markets, we emphasized the role of the wiring of the two segments of the market and the strategic interaction among dealers resulting from competition in quantities. This allowed us to decompose movements in quantities into supply and demand factors and estimate the supply and demand elasticities.

The model allows us to evaluate policy interventions in repo markets and the effects of different wirings for market efficiency. We have evaluated the role of the centrally cleared market for market efficiency as well as the density of connections in the decentralized market. The introduction of a standing repo facility was shown to be equivalent to absorbing some of the dealer demand and we have characterized its impact on the pricing of the centrally cleared market. The model also allows us to examine the necessary conditions for disbalances in supply and demand to result in the use of the standing repo facility. These conditions give policy makers tools to evaluate the capacity of the market to absorb supply and demand shocks before the need for market participants to use the government supplied liquidity backstops.

Finally, even though we have assumed the market wiring to be exogenously given, we view our work as a first step in understanding the market in a structural way that opens the possibility to model and characterize the endogenous responses of the market wiring to policy interventions. Incorporating endogenous changes to the wiring of the market would allow for the evaluation of optimal design of liquidity backstops. We leave these extensions of our framework for future research.

References

Acharya, V. V., V. R. Anshuman, and S. V. Viswanathan (2024): "Bankruptcy Exemption of Repo Markets: Too Much Today for Too Little Tomorrow?," Working Paper 32027, National Bureau of Economic Research.

Afonso, G., M. Cipriani, A. M. Copeland, A. Kovner, G. La Spada, and

A. Martin (2020): "The Market Events of Mid-September 2019," *FRB of New York Staff Report*, (918).

Allen, F., A. Babus, and E. Carletti (2012): "Asset Commonality, Debt Maturity and Systemic Risk," *Journal of Financial Economics*, 104(3), 519–534.

Allen, J., and M. Wittwer (2023): "Centralizing Over-The-Counter Markets?," *Journal of Political Economy*, 131(12), 3310–3351.

Amiti, M., and D. E. Weinstein (2018): "How Much Do Idiosyncratic Bank Shocks Affect Investment? Evidence from Matched Bank-Firm Loan Data," *Journal of Political Economy*, 126(2), 525–587.

Anbil, S., A. Anderson, and Z. Senyuz (2020): "Are Repo Markets Fragile? Evidence from September 2019," *The Board of Governors of the Federal Reserve*.

Anderson, A. G., and J. Kandrac (2017): "Monetary Policy Implementation and Financial Vulnerability: Evidence from the Overnight Reverse Repurchase Facility," *The Review of Financial Studies*.

Baklanova, V., C. Caglio, M. Cipriani, and A. Copeland (2019): "The Use of Collateral in Bilateral Repurchase and Securities Lending Agreements," *Review of Economic Dynamics*, 33, 228 – 249, Fragmented Financial Markets.

Ballester, C., A. Calvó-Armengol, and Y. Zenou (2006): "Who's Who in Networks. Wanted: The Key Player," *Econometrica*, 74(5), 1403–1417.

Banegas, A., and P. Monin (2023): "Hedge Fund Treasury Exposures, Repo, and Margining," *FEDS Notes*.

Bech, M. L., and E. Klee (2011): "The Mechanics of a Graceful Exit: Interest on Reserves and Segmentation in the Federal Funds Market," *Journal of Monetary Economics*, 58(5), 415–431.

Beltran, D. O., V. Bolotnyy, and E. Klee (2019): "The Federal Funds Network and Monetary Policy Transmission: Evidence from the 2007–2009 Financial Crisis," *Journal of Monetary Economics*.

Beltran, P. (2023): "A Lending Network under Stress: A Structural Analysis of the Money Market Funds Industry," *"Working Paper, UCLA"*.

Bimpikis, K., S. Ehsani, and R. İlkiliç (2019): "Cournot Competition in Networked Markets," *Management Science*, 65(6), 2467–2481.

Blume, L. E., D. Easley, J. Kleinberg, and Éva Tardos (2009): "Trading networks with price-setting agents," *Games and Economic Behavior*, 67(1), 36 – 50.

Brunnermeier, M. K., and L. H. Pedersen (2009): "Funding Liquidity and Market Liquidity," *Review of Financial Studies*, 22(2201-2238), 6.

Bulow, J., J. Geanakoplos, and P. Klemperer (1985): "Multimarket Oligopoly: Strategic Substitutes and Complements," *Journal of Political Economy*, 93(3), 488–511.

Cetorelli, N., and L. S. Goldberg (2012): "Banking Globalization and Monetary Transmission," *The Journal of Finance*, 67(5), 1811–1843.

Cetorelli, N., M. Landoni, and L. Lu (2023): "Non-Bank Financial Institutions and Banks' Fire-Sale Vulnerabilities," *FRB Boston Risk and Policy Analysis Unit Paper No. SRA*, pp. 23–01.

Chang, J.-W. (2019): "Collateralized Debt Networks with Lender Default," *Available at SSRN 3468267*.

Chang, J.-W., and G. Chuan (2024): "Contagion in debt and collateral markets," *Journal of Monetary Economics*, 148, 103600.

Cocco, J. F., F. J. Gomes, and N. C. Martins (2009): "Lending Relationships in the Interbank Market," *Journal of Financial Intermediation*, 18(1), 24 – 48.

Copeland, A., I. Davis, and A. Martin (2014): "A Primer on the GCF Repo Service: An Empirical Analysis of the GCF Repo Service," *Federal Reserve Bank of New York, Staff Report*, (671), 36–54.

Copeland, A., D. Duffie, and Y. Yang (2025): "Reserves Were Not So Ample After All," *The Quarterly Journal of Economics*, 140(1), 239–281.

Copeland, A., A. Martin, and M. Walker (2014): "Repo Runs: Evidence from the Tri-Party Repo Market," *The Journal of Finance*, 69(6), 2343–2380.

COPELAND, A. M., A. MARTIN, AND M. WALKER (2010): "The Tri-party Repo Market Before the 2010 Reforms," *FRB of New York Staff Report*, (477).

CORREA, R., W. DU, AND G. LIAO (2020): "U.S. Banks and Global Liquidity," *The Board of Governors of the Federal Reserve.*

DIELER, T., L. MANCINI, AND N. SCHÜRHOFF (2021): "(In) Efficient Repo Markets," *CEPR Discussion Paper No. DP15782.*

DUARTE, F., AND T. M. EISENBACH (2021): "Fire-Sale Spillovers and Systemic Risk," *The Journal of Finance*, 76(3), 1251–1294.

DUFFIE, D. (1996): "Special Repo Rates," *The Journal of Finance*, 51(2), 493–526.

——— (2020): "Still the World's Safe Haven? Redesigning the U.S. Treasury Market After the COVID-19 Crisis," *Brookings Hutchins Center Working Paper No. 62.*

ELLIOTT, M. (2015): "Inefficiencies in Networked Markets," *American Economic Journal: Microeconomics*, 7(4), 43–82.

ENNIS, H., AND J. W. HUTHER (2021): "The Fed's Evolving Involvement in the Repo Markets," *Richmond Fed Economic Brief*, 21(31).

ENNIS, H. M. (2011): "Strategic Behavior in the Tri-Party Repo Market," *FRB Richmond Economic Quarterly*, 97(4), 389–413.

GÂRLEANU, N., AND L. H. PEDERSEN (2013): "Dynamic Trading with Predictable Returns and Transaction Costs," *The Journal of Finance*, 68(6), 2309–2340.

GOLDSMITH-PINKHAM, P., I. SORKIN, AND H. SWIFT (2020): "Bartik Instruments: What, When, Why, and How," *American Economic Review*, 110(8), 2586–2624.

GORTON, G., T. LAARITS, AND A. METRICK (2020): "The Run on Repo and The Fed's Response," *Journal of Financial Stability*, 48, 100744.

GORTON, G., AND A. METRICK (2012): "Securitized Banking and the Run on Repo," *Journal of Financial Economics*, 104(3), 425–451.

GREENWOOD, R., A. LANDIER, AND D. THESMAR (2015): "Vulnerable Banks," *Journal of Financial Economics*, 115(3), 471–485.

Han, S., and K. Nikolaou (2016): "Trading Relationships in the OTC Market for Secured Claims: Evidence from Triparty Repos," *Federal Reserve Board, Finance and Economics Discussion Series 2016-064*.

Han, Y. (2020): "Money Market Segmentation and the Transmission of Post-crisis Monetary Policy," *Available at SSRN 3663512*.

Hu, G. X., J. Pan, and J. Wang (2020): "Tri-Party Repo Pricing," *Journal of Financial and Quantitative Analysis*, p. 1–50.

Huber, A. W. (2023): "Market Power in Wholesale Funding: A Structural Perspective from the Triparty Repo Market," *Journal of Financial Economics*, 149(2), 235–259.

Infante, S., and A. P. Vardoulakis (2020): "Collateral Runs," *The Review of Financial Studies*, 34(6), 2949–2992.

Khwaja, A. I., and A. Mian (2008): "Tracing the Impact of Bank Liquidity Shocks: Evidence from an Emerging Market," *The American Economic Review*, 98(4), 1413–1442.

Kranton, R. E., and D. F. Minehart (2001): "A Theory of Buyer-Seller Networks," *American economic review*, 91(3), 485–508.

Krishnamurthy, A., S. Nagel, and D. Orlov (2014): "Sizing Up Repo," *The Journal of Finance*, 69(6), 2381–2417.

Malamud, S., and M. Rostek (2017): "Decentralized Exchange," *American Economic Review*, 107(11), 3320–62.

Manea, M. (2011): "Bargaining in Stationary Networks," *American Economic Review*, 101(5), 2042–2080.

Martin, A., D. Skeie, and E.-L. Von Thadden (2014): "Repo Runs," *Review of Financial Studies*, 27(4), 957–989.

Munyan, B. (2015): "Regulatory Arbitrage in Repo Markets," *Office of Financial Research Working Paper*.

Nava, F. (2015): "Efficiency in decentralized oligopolistic markets," *Journal of Economic Theory*, 157, 315–348.

Paddrik, M. E., H. P. Young, R. J. Kahn, M. McCormick, and V. Nguyen (2023): "Anatomy of The Repo Rate Spikes in September 2019," *Journal of Financial Crises*, 5(4).

Peña, J. M. (2001): "A Class of P-Matrices with Applications to the Localization of the Eigenvalues of a Real Matrix," *SIAM Journal on Matrix Analysis and Applications*, 22(4), 1027–1037.

Rosen, J. B. (1965): "Existence and Uniqueness of Equilibrium Points for Concave N-Person Games," *Econometrica*, 33(3), 520–534.

Rostek, M., and J. J. Yoon (2023): "Imperfect Competition in Financial Markets: Recent Developments," *University of Wisconsin-Madison and UCL Working paper*.

Schmidt, L., A. Timmermann, and R. Wermers (2016): "Runs on Money Market Mutual Funds," *American Economic Review*, 106(9), 2625–57.

Üslü, S. (2019): "Pricing and Liquidity in Decentralized Asset Markets," *Econometrica*, 87(6), 2079–2140.

Vives, X. (2002): "Private Information, Strategic Behavior, and Efficiency in Cournot Markets," *RAND Journal of Economics*, pp. 361–376.

——— (2011): "Strategic Supply Function Competition with Private Information," *Econometrica*, 79(6), 1919–1966.

Wittwer, M. (2021): "Connecting Disconnected Financial Markets?," *American Economic Journal: Microeconomics*, 13(1), 252–82.

"Rewiring repo"

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A Proofs

Proof of Proposition 1.

The proof of the second case without the $\mathcal{C}$ market is based on a variation of arguments in Rosen [1965] and Bimpikis, Ehsani, and İlkılıç [2019]. The proof of the first case with the $\mathcal{C}$ market utilizes the fact that equation (17) is monotonically decreasing in $\rho_{\mathcal{C}}$.

Step 1. (Existence of a unique equilibrium for a fixed $\rho_{\mathcal{C}}$)

First, we show that there exists a unique equilibrium quantities for a fixed $\rho_{\mathcal{C}}$. The proof is based on derivations in Rosen [1965] and Bimpikis, Ehsani, and İlkılıç [2019] applied to a convex n-person game with cost minimization by changing the conditions for concavity to convexity. Therefore, the sufficient condition for the existence of unique equilibrium is to show that each dealer's strategy space is convex and compact, and each dealer's objective function

$$V_i = \rho_{\mathcal{C}} q_{i\mathcal{C}} + \sum_{k \in L_i} q_{ik} \times \left(c_k + \gamma_k \sum_{j \in D_k} q_{jk} \right) + \frac{\beta_i}{2} \left(\bar{q}_i - q_{\mathcal{B}i} \right)^2 \tag{A.1}$$

is convex in the dealer's own strategy $(q_i, q_{i\mathcal{C}})$ given other dealers' strategies $(q_j, q_{j\mathcal{C}})_{j \neq i}$.

Step 1.1. (Existence of an equilibrium for a fixed $\rho_{\mathcal{C}}$) To prove existence, we need to show that the Hessian matrix of any dealer $i \in D$ is positive semi-definite. The Hessian is defined as the matrix of second-order derivatives of V_i

$$H_i = \begin{bmatrix} \frac{\partial^2 V_i}{\partial q_{i1} \partial q_{i1}} & \frac{\partial^2 V_i}{\partial q_{i1} \partial q_{i2}} & \cdots & \frac{\partial^2 V_i}{\partial q_{i1} \partial q_{im_i}} & \frac{\partial^2 V_i}{\partial q_{i1} \partial q_{i\mathcal{C}}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial^2 V_i}{\partial q_{im_i} \partial q_{i1}} & \frac{\partial^2 V_i}{\partial q_{im_i} \partial q_{i2}} & \cdots & \frac{\partial^2 V_i}{\partial q_{im_i} \partial q_{im_i}} & \frac{\partial^2 V_i}{\partial q_{im_i} \partial q_{i\mathcal{C}}} \\ \frac{\partial^2 V_i}{\partial q_{i\mathcal{C}} \partial q_{i1}} & \frac{\partial^2 V_i}{\partial q_{i\mathcal{C}} \partial q_{i2}} & \cdots & \frac{\partial^2 V_i}{\partial q_{i\mathcal{C}} \partial q_{im_i}} & \frac{\partial^2 V_i}{\partial q_{i\mathcal{C}} \partial q_{i\mathcal{C}}} \end{bmatrix}, \tag{A.2}$$

which is a $(m_i+1)\times(m_i+1)$ matrix, where $m_i \equiv |L_i|$ is the number of lenders dealer i is connected to. Note that the second-order derivatives of V_i are

$$\frac{\partial^2 V_i}{\partial q_{ik}\partial q_{jl}} = \begin{cases} 2\gamma_k + \beta_i & \text{if } i=j, k=l\neq\mathcal{C} \\ \beta_i & \text{if } i=j, k=l=\mathcal{C} \\ \beta_i & \text{if } i=j, k\neq l \\ \gamma_k & \text{if } i\neq j, k=l\neq\mathcal{C} \\ 0 & \text{otherwise} \end{cases}. \tag{A.3}$$

Define a $(m_i+1)\times(m_i+2)$ full-rank matrix R as

$$R_{ik,l} = \begin{cases} \sqrt{2\gamma_k} & \text{if } l=k\neq\mathcal{C} \\ \sqrt{\beta_i} & \text{if } l=m_i+2 \\ 0 & \text{otherwise} \end{cases}, \tag{A.4}$$

which is

$$R = \begin{bmatrix} \sqrt{2\gamma_k} & 0 & 0 & \cdots & 0 & \sqrt{\beta_i} \\ 0 & \sqrt{2\gamma_k} & 0 & \cdots & 0 & \sqrt{\beta_i} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \sqrt{2\gamma_k} & 0 & \sqrt{\beta_i} \\ 0 & 0 & \cdots & 0 & 0 & \sqrt{\beta_i} \end{bmatrix}, \tag{A.5}$$

Then, $H_i = RR^T$, implying H_i is positive semi-definite. Therefore, according to Rosen [1965], there exists an equilibrium.

Step 1.2. (Uniqueness of equilibrium for a fixed $\rho_{\mathcal{C}}$) Next, we prove uniqueness of equilibrium for a fixed $\rho_{\mathcal{C}}$. Denote the vector of all quantities by dealers as $\mathbf{q} = \left(q_1^T, q_{1\mathcal{C}}, q_2^T, q_{2\mathcal{C}}, \ldots, q_n^T, q_{n\mathcal{C}}\right)^T$, where $q_i = (q_{il_{i1}}, q_{il_{i2}}, \ldots, q_{il_{im_i}})$ for any $i \in D$ and $l_{ik} \in L_i$ for any $k = 1, \ldots, m_i$. Theorems 2 and 6 in Rosen [1965] imply that the equilibrium is unique if the $(|E|+n)\times(|E|+n)$ matrix $\left[G(\mathbf{q}) + G(\mathbf{q})^T\right]$ is positive definite for any $\mathbf{q}$ with

$$G(\mathbf{q}) = \begin{bmatrix} \frac{\partial^2 V_1}{\partial q_{11} \partial q_{11}} & \frac{\partial^2 V_1}{\partial q_{11} \partial q_{12}} & \cdots & \frac{\partial^2 V_1}{\partial q_{11} \partial q_{nm_n}} & \frac{\partial^2 V_1}{\partial q_{11} \partial q_{n\mathcal{C}}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial^2 V_n}{\partial q_{nm_n} \partial q_{11}} & \frac{\partial^2 V_n}{\partial q_{nm_n} \partial q_{12}} & \cdots & \frac{\partial^2 V_n}{\partial q_{nm_n} \partial q_{nm_n}} & \frac{\partial^2 V_n}{\partial q_{nm_n} \partial q_{n\mathcal{C}}} \\ \frac{\partial^2 V_n}{\partial q_{n\mathcal{C}} \partial q_{11}} & \frac{\partial^2 V_n}{\partial q_{n\mathcal{C}} \partial q_{12}} & \cdots & \frac{\partial^2 V_n}{\partial q_{n\mathcal{C}} \partial q_{nm_n}} & \frac{\partial^2 V_n}{\partial q_{n\mathcal{C}} \partial q_{n\mathcal{C}}} \end{bmatrix}. \tag{A.6}$$

Again, we are applying the theorems in Rosen [1965] to the cost minimization problem, so the signs are reversed.[28] We take the fixed vector r to be a vector of 1s for the $G(x, r)$ in the original theorems of Rosen [1965].

The matrix can be represented as $2\Gamma \equiv \left[G(\mathbf{q}) + G(\mathbf{q})^T\right]$, where

$$\Gamma_{ik,jl} = \begin{cases} 2\gamma_k + \beta_i & \text{if } i = j, k = l \neq \mathcal{C} \\ \beta_i & \text{if } i = j, k = l = \mathcal{C} \\ \beta_i & \text{if } i = j, k \neq l \\ \gamma_k & \text{if } i \neq j, k = l \neq \mathcal{C} \\ 0 & \text{otherwise} \end{cases}. \tag{A.7}$$

Then, it is sufficient to show that there exists R with full rank of $|E| + n$ such that $\Gamma = RR^T$. We find the matrix R as a $(|E| + n) \times (|E| + 2n + m)$ matrix, which can be arranged as a block matrix of

$$R = [A,\ B], \tag{A.8}$$

where A is a $(|E| + n) \times (|E| + n)$ diagonal matrix such that

$$A_{ik,jl} = \begin{cases} \sqrt{\gamma_k} & \text{if } i = j, k = l \neq \mathcal{C} \\ \sqrt{\beta_i} & \text{if } i = j, k = l = \mathcal{C} \\ 0 & \text{otherwise} \end{cases}, \tag{A.9}$$

[28] Instead of the sufficient condition for uniqueness of payoff maximization games, diagonal strict concavity, we use diagonal strict convexity to show uniqueness of equilibrium for the cost minimization game.

and B is a $(|E| + n) \times (n + m)$ matrix such that

$$B_{ik,t} = \begin{cases} \sqrt{\gamma_k} & \text{if } t = n + k, k \neq \mathcal{C} \\ \sqrt{\beta_i} & \text{if } t = i, k \neq \mathcal{C} \\ 0 & \text{otherwise} \end{cases}. \tag{A.10}$$

Because A is a diagonal matrix with non-zero entries, R is full rank, and Γ is positive definite, implying $\left[G(\mathbf{q}) + G(\mathbf{q})^T\right]$ is positive definite. Therefore, the equilibrium is unique for a fixed $\rho_{\mathcal{C}}$.

Step 2. (Uniqueness of the market clearing price $\rho_{\mathcal{C}}$) Finally, we show that the market clearing price $\rho_{\mathcal{C}}$ with resulting equilibrium quantities $\mathbf{q}$ that satisfies the market clearing condition (17) is unique. The first-order condition (6) can be represented in a matrix equation

$$\tilde{\mathbf{q}} = \tilde{\phi}(\rho_{\mathcal{C}}) - \frac{1}{2} W \tilde{\mathbf{q}}, \tag{A.11}$$

where $\tilde{\mathbf{q}} = (q_{11}, \ldots q_{1m_1}, q_{21}, \ldots, q_{nm_n})^T$, $\tilde{\phi}$ is a $|E| \times 1$ vector such that

$$\tilde{\phi}_{ik}(\rho_{\mathcal{C}}) = \frac{\rho_{\mathcal{C}} - c_k}{2\gamma_k}, \tag{A.12}$$

and W is a $|E| \times |E|$ matrix such that

$$W_{ik,jl} = \begin{cases} 1 & \text{if } i \neq j, k = l \\ 0 & \text{otherwise.} \end{cases} \tag{A.13}$$

Thus, the equilibrium quantities in $\mathcal{T}$ market in (A.11) can be rearranged as

$$\left(I + \frac{1}{2} W\right) \tilde{\mathbf{q}} = \tilde{\phi}(\rho_{\mathcal{C}}). \tag{A.14}$$

The left-hand side of (A.14) is a linear function of $\tilde{\mathbf{q}}$, which is strictly increasing in $\tilde{\mathbf{q}}$. Also, the right-hand side of (A.14) is a linear function of $\rho_{\mathcal{C}}$, which is also strictly increasing in $\rho_{\mathcal{C}}$ for $\gamma_k > 0, \forall k \in L$. Hence, in equilibrium, the quantities funded in the $\mathcal{T}$ market are strictly and continuously increasing in $\rho_{\mathcal{C}}$. From (5), we can also easily see that for $\beta_i > 0, \forall i \in D$, the excess net demand $\sum_{i \in D} q_{i\mathcal{C}}(\rho_{\mathcal{C}})$ in the interdealer market is a strictly decreasing continuous function in $\rho_{\mathcal{C}}$. Therefore, the aggregate market clearing condition has a unique solution $\rho_{\mathcal{C}}^*$ such that

$$\sum_{i\in D} q_{i\mathcal{C}}(\rho_{\mathcal{C}}^*) = \sum_{i\in D} q_{\mathcal{B}i} - \sum_{i\in D}\sum_{k\in L_i} q_{ik}(\rho_{\mathcal{C}}^*) - \sum_{i\in D}\frac{1}{\beta_i}\rho_{\mathcal{C}}^* = 0. \tag{A.15}$$

Step 3. (Closed-form representations of the equilibrium) The market clearing condition is linear in $\rho_{\mathcal{C}}$ and we can solve for the equilibrium $\rho_{\mathcal{C}}^*$ in a closed-form as follows

$$\rho_{\mathcal{C}}^* = \frac{\sum_{i\in D} q_{\mathcal{B}i} + \sum_{ik\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}c_\ell}{\sum_{ik\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i\in D}\frac{1}{\beta_i}} \tag{A.16}$$

$$q_{ik}^* = \sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}(\rho_{\mathcal{C}}^* - c_\ell),\ \forall ik\in E. \tag{A.17}$$

Plugging the expression for $\rho_{\mathcal{C}}^*$, in (5), we obtain

$$q_{a\mathcal{C}}^* = q_{\mathcal{B}a} + \sum_{k\in L_a}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ak,j\ell}}{2\gamma_\ell}c_\ell - \left(\sum_{k\in L_a}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ak,j\ell}}{2\gamma_\ell} + \frac{1}{\beta_a}\right)\rho_{\mathcal{C}}^*,\ \forall a\in D, \tag{A.18}$$

Finally, it is easy to verify that under the condition for Lemma 1, all equilibrium quantities q_{ik}^* are positive $\forall ik\in E$. ■

Proof of Lemma 1. From (A.17), we can derive the following condition for positivity of equilibrium quantities along any dealer-lender pair $ab \in E$

$$\sum_{j\ell \in E} \left(\frac{\sum\limits_{i \in D} q_{\mathcal{B}i} + \sum\limits_{ik \in E} \sum\limits_{i'k' \in E} \frac{\tilde{\psi}_{ik,i'k'}}{2\gamma_{k'}} c_{k'}}{\sum\limits_{i \in D} \frac{1}{\beta_i} + \sum\limits_{ik \in E} \sum\limits_{i'k' \in E} \frac{\tilde{\psi}_{ik,i'k'}}{2\gamma_{k'}}} - c_\ell \right) \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell} > 0$$

$$\sum_{j\ell \in E} \left(\frac{\sum\limits_{i \in D} q_{\mathcal{B}i} + \sum\limits_{ik \in E} \sum\limits_{i'k' \in E} \frac{\tilde{\psi}_{ik,i'k'}}{2\gamma_{k'}} c_{k'}}{\sum\limits_{i \in D} \frac{1}{\beta_i} + \sum\limits_{ik \in E} \sum\limits_{i'k' \in E} \frac{\tilde{\psi}_{ik,i'k'}}{2\gamma_{k'}}} \right) \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell} > \sum_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell} c_\ell$$

$$\underbrace{\frac{\sum\limits_{i \in D} q_{\mathcal{B}i} + \sum\limits_{ik \in E} \sum\limits_{i'k' \in E} \frac{\tilde{\psi}_{ik,i'k'}}{2\gamma_{k'}} c_{k'}}{\sum\limits_{i \in D} \frac{1}{\beta_i} + \sum\limits_{ik \in E} \sum\limits_{i'k' \in E} \frac{\tilde{\psi}_{ik,i'k'}}{2\gamma_{k'}}}}_{\rho^*_{\mathcal{C}}} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell} > \sum_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell} c_\ell$$

Finally, rearranging the term on the left-hand side to equal the equilibrium $\mathcal{C}$ market rate $\rho^*_{\mathcal{C}}$, we arrive at the following condition

$$\rho^*_{\mathcal{C}} > \frac{\sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell} c_\ell}{\sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell}}, \tag{A.19}$$

The inequality (A.19) is the sufficient and necessary condition for $q^*_{ab} > 0$ for all dealer-lender pairs $ab \in E$. ■

Proof of Corollary 1. Plugging in (20) into (19) results in

$$q^*_{i\mathcal{C}} = q_{\mathcal{B}i} + \sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{\gamma_\ell} c_\ell - \frac{\sum\limits_{k \in L_i} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{\gamma_\ell} + \frac{1}{\beta_i}}{\sum\limits_{ab \in E} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{\gamma_\ell} + \sum\limits_{a \in D} \frac{1}{\beta_a}} \left(\sum_{a \in D} q_{\mathcal{B}a} + \sum_{a \in D} \sum_{b \in D_a} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{\gamma_\ell} c_\ell \right).$$

The absolute value of the equilibrium quantities for dealer $i \in D$ can be written as

$$|q^*_{i\mathcal{C}}| = \left| \left[\frac{q_{\mathcal{B}i} + \sum\limits_{k \in L_i} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{\gamma_\ell} c_\ell}{\sum\limits_{k \in L_i} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{\gamma_\ell} + \frac{1}{\beta_i}} - \frac{\sum\limits_{a \in D} q_{\mathcal{B}a} + \sum\limits_{a \in D} \sum\limits_{b \in D_a} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{\gamma_\ell} c_\ell}{\sum\limits_{ab \in E} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ab,j\ell}}{\gamma_\ell} + \sum\limits_{a \in D} \frac{1}{\beta_a}} \right] \left(\sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{\gamma_\ell} + \frac{1}{\beta_i} \right) \right|.$$

Hence, the gross volume of trades in the $\mathcal{C}$ market, $\sum\limits_{i \in D} |q^*_{i\mathcal{C}}|$, is increasing in (24). ■

Proof of Corollary 2. From (19), the coefficient of $\rho^*_{\mathcal{C}}$ for $\sum\limits_{ik \in E} q^*_{ik}$ is $\sum\limits_{ik \in E} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}$, while the coefficient of $\rho^*_{\mathcal{C}}$ for $-\sum\limits_{i \in D} q^*_{i\mathcal{C}}$ is $\sum\limits_{ik \in E} \sum\limits_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum\limits_{i \in D} \frac{1}{\beta_i}$. Because $\sum\limits_{i \in D} \frac{1}{\beta_i}$ is always positive,

$$\begin{aligned} \frac{\partial \left(\sum\limits_{ik \in E} q^*_{ik} \right)}{\partial \rho^*_{\mathcal{C}}} &= \sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} \\ < -\frac{\partial \left(\sum\limits_{i \in D} q^*_{i\mathcal{C}} \right)}{\partial \rho^*_{\mathcal{C}}} &= \sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i \in D} \frac{1}{\beta_i}. \end{aligned}$$

Hence, the interest rate sensitivity of the aggregate borrowing from $\mathcal{T}$ market is lower than the interest rate sensitivity of the aggregate borrowing from $\mathcal{C}$ market. ■

Proof of Proposition 2.

1. With a $\mathcal{C}$ market, individual dealer demand shocks affect the equilibrium quantities through their indirect effects on the equilibrium rate $\rho^*_{\mathcal{C}}$, and lender supply shocks affect equilibrium quantities both through their direct effects and their indirect effects on the equilibrium rate $\rho^*_{\mathcal{C}}$. The partial derivatives of the equi-

librium rate with respect to demand shocks and supply shocks are

$$\frac{\partial \rho_{\mathcal{C}}^*}{\partial q_{\mathcal{B}h}} = \frac{1}{\sum\limits_{ik\in E}\sum\limits_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}+\sum\limits_{i\in D}\frac{1}{\beta_i}}, \qquad \forall h\in D \tag{A.20}$$

$$\frac{\partial \rho_{\mathcal{C}}^*}{\partial c_z} = \frac{\sum\limits_{ik\in E}\sum\limits_{h\in D_z}\frac{\tilde{\psi}_{ik,hz}}{2\gamma_z}}{\sum\limits_{ik\in E}\sum\limits_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}+\sum\limits_{i\in D}\frac{1}{\beta_i}}, \qquad \forall z\in L. \tag{A.21}$$

$$\tag{A.22}$$

From (19), the partial derivative with respect to $q_{\mathcal{B}h}$ for any $h \in D$ is

$$\frac{\partial q_{ik}^*}{\partial q_{\mathcal{B}h}} = \sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}\frac{\partial \rho_{\mathcal{C}}^*}{\partial q_{\mathcal{B}h}} = \frac{\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}}{\sum\limits_{ik\in E}\sum\limits_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}+\sum\limits_{i\in D}\frac{1}{\beta_i}},\ \forall ik\in E. \tag{A.23}$$

Finally, the partial derivative with respect to a shock to any lender $z \in L$ and plugging in the partial derivative of $\rho_{\mathcal{C}}^*$ is

$$\frac{\partial q_{ik}^*}{\partial c_z} = \frac{\partial \rho_{\mathcal{C}}^*}{\partial c_z}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} - \sum_{j\in D_z}\frac{\tilde{\psi}_{ik,jz}}{2\gamma_z} \tag{A.24}$$

$$= \frac{\sum\limits_{j\in D_z}\sum\limits_{ab\in E}\frac{\tilde{\psi}_{ab,jz}}{2\gamma_z}}{\sum\limits_{ab\in E}\sum\limits_{j\ell\in E}\frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell}+\sum\limits_{j\in D}\frac{1}{\beta_j}}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} - \sum_{j\in D_z}\frac{\tilde{\psi}_{ik,jz}}{2\gamma_z},\ \forall ik\in E. \tag{A.25}$$

2. The partial derivatives of the equilibrium quantities (21), result in the following sensitivity of quantities along any dealer-lender trading relationship jl and shocks to any dealer i or lender k

$$\begin{aligned} \frac{\partial q_{j\ell}^*}{\partial q_{\mathcal{B}i}} &= \sum_{z\in L_i}\psi_{j\ell,iz}\frac{\beta_i}{2\gamma_z+\beta_i} && \forall i\in D,\\ \frac{\partial q_{j\ell}^*}{\partial c_k} &= -\sum_{d\in D_k}\psi_{j\ell,dk}\frac{1}{2\gamma_k+\beta_d} && \forall k\in L, \end{aligned} \tag{A.26}$$

■

Proof of Proposition 3.

1. Marginal costs: We defined marginal costs of funds of borrowing of any dealer-lender trading pair ik as

$$\rho_{ik}^* \equiv \left. \frac{\partial q_{ik}(c_k + \gamma_k \sum_{j \in D_k} q_{jk})}{\partial q_{ik}} \right|_{q^*} = s_k^* + \gamma_k q_{ik}^*, \tag{A.27}$$

   (a) With a $\mathcal{C}$ market, equation (5) results in

$$\rho_{ik}^* = -\beta_i \left(q_{\mathcal{B}i} - \sum_{l \in L_i} q_{il}^* - \frac{1}{\beta_i} \rho_{\mathcal{C}}^* + \sum_{l \in L_i} q_{il}^* - q_{\mathcal{B}i} \right) = \rho_{\mathcal{C}}^*$$

   for any $i \in D$ and $k \in L_i$. Therefore, all dealers borrow from counterparties in the decentralized market so that to equalize their marginal costs to $\rho_{\mathcal{C}}^*$.

   (b) Without a $\mathcal{C}$ market, the marginal cost (A.27) becomes

$$\rho_i^* = \beta_i \left(q_{\mathcal{B}i} - \sum_{l \in L_i} q_{il}^* \right),$$

   where $\rho_i^* = \rho_{ik}^*$ for all $k \in L_i$ comes directly from the optimality condition across all q_{ik}^*. Plugging (21) into the above equation implies

$$\rho_i^* = \beta_i \left(q_{\mathcal{B}i} - \sum_{k \in L_i} \sum_{j\ell \in E} \psi_{ik,j\ell} \frac{\beta_j q_{\mathcal{B}j} - c_\ell}{2\gamma_\ell + \beta_j} \right).$$

   Thus, the marginal cost of funding for dealer i depends on the interconnectedness of dealer i through Ψ and may differ from ρ_j^* for $j \neq i$ even if all the parameters are homogeneous as $\beta_i = \beta$ and $q_{\mathcal{B}i} = q_{\mathcal{B}}$, $\forall i \in D$, and $\gamma_\ell = \gamma, c_\ell = c$, $\forall \ell \in L$. The only case that $\rho_i^* = \rho^*$ for all $i \in D$ is when

$$\sum_{k \in L_i} \sum_{j\ell \in E} \psi_{ik,j\ell} = \bar{\psi}$$

   for all $i \in D$.

2. Lender spreads:

   (a) If there is a $\mathcal{C}$ market, dealers have homogeneous marginal cost of funding as shown in the first part of the proposition. Recall that the equilibrium rate (spread) of borrowing from lender k is

$$s_k^* = c_k + \gamma_k \sum_{i \in D_k} q_{ik}^*, \tag{A.28}$$

and the equilibrium marginal cost of funding of dealer i for borrowing from lender k is

$$\rho_{\mathcal{C}}^* = \rho_{ik}^* = s_k^* + \gamma_k q_{ik}^* \tag{A.29}$$

for any $i \in D_k$. Thus, in equilibrium, $q_{ik}^* = q_{jk}^*$ for any $i, j \in D_k$. Thus, using this property and (A.28), (A.29) can be expressed as

$$\rho_{\mathcal{C}}^* = c_k + \gamma_k (n_k + 1) q_{ik}^*, \tag{A.30}$$

where $n_k = |D_k|$ and $i \in D_k$. Rearranging (A.30) yields

$$q_{ik}^* = \frac{\rho_{\mathcal{C}}^* - c_k}{\gamma_k (n_k + 1)}, \tag{A.31}$$

and plugging this expression in (A.28) results in

$$s_k^* = \frac{1}{n_k + 1} c_k + \frac{n_k}{n_k + 1} \rho_{\mathcal{C}}^*. \tag{A.32}$$

Thus, differences in rates across lenders do not depend on individual dealer demand conditions or interest rate sensitivity $(\beta_i, q_{\mathcal{B}i})_{i \in D}$. Furthermore, the wiring of the $\mathcal{T}$ market affects equilibrium rates only through the number of trading counterparties of lender $k \in L$ i.e. $n_k = |D_k|$.

Now consider the case without a $\mathcal{C}$ market. Plugging (21) into (A.28) results in

$$s_k^* = c_k + \gamma_k \sum_{i \in D_k} \sum_{j\ell \in E} \psi_{ik,j\ell} \frac{\beta_j q_{\mathcal{B}j} - c_\ell}{2\gamma_\ell + \beta_j},$$

for any $k \in L$. Hence, all dealer parameters $(\beta_i, q_{\mathcal{B}i})_{i \in D}$ and lender parameters $(c_k, \gamma_k)_{k \in L}$ as well as individual entries in the Ψ matrix affect the equilibrium rates and rate dispersion.

■

Proof of Proposition 4. Using the derivations of Proposition 2, we can write the change in equilibrium quantities following changes in demand and supply as follows

$$dq^*_{ik} = \frac{\partial q^*_{ik}}{\partial q_{\mathcal{B}i}} dq_{\mathcal{B}i} + \frac{\partial q^*_{ik}}{\partial c_k} dc_k + \sum_{\substack{j \in D \\ j \neq i}} \frac{\partial q^*_{ik}}{\partial q_{\mathcal{B}j}} dq_{\mathcal{B}j} + \sum_{\substack{k' \in L \\ k' \neq k}} \frac{\partial q^*_{ik}}{\partial c_{k'}} dc_{k'},$$

where dx denotes an infinitesimal change in the variable x between two periods. Next, define the percent changes in quantity demanded by dealer i as $\tilde{\delta}_{it} \equiv dq_{\mathcal{B}i}$ and the changes in quantity supplied by lender k as $\tilde{\lambda}_{kt} \equiv \frac{1}{\gamma_k} dc_k$, where $\frac{1}{\gamma_k}$ converts the change in the lender spreads to changes in quantities supplied. We can approximate the total change in the quantity traded between period t and $t-1$ as follows

$$\Delta q_{ikt} = \phi^{\delta}_i(\gamma,\beta)\tilde{\delta}_{it} + \phi^{\lambda}_k(\gamma,\beta)\tilde{\lambda}_{kt} + \tilde{\epsilon}_{ikt}, \tag{A.33}$$

where $\phi^{\delta}_i(\gamma,\beta)$ and $\phi^{\lambda}_k(\gamma,\beta)$ are dealer and lender specific constants that are functions of the supply and demand elasticities as shown in Proposition 2. To disentangle the dealer specific variation from the lender specific variation, we need additive separability of the marginal demand effects, which comes from (25) in Proposition 2. In other words, the constants can be written as $\phi^{\delta}_i(\gamma,\beta) = \phi^{\delta}_i + \phi^{\delta}_{ik}$ and $\phi^{\lambda}_k(\gamma,\beta) = \phi^{\lambda}_k + \phi^{\lambda}_{ik}$. We can redefine the dealer specific variation in quantities as $\delta_{i,t} = \phi^{\delta}_i \tilde{\delta}_{i,t}$ and the lender specific variation in quantities as $\lambda_{k,t} = \phi^{\lambda}_k \tilde{\lambda}_{k,t}$. The error term ϵ_{ikt} contains remaining variation that is dealer-lender specific .

Next, note that $\mathbb{E}\epsilon_{ikt} = 0$ should hold, as these are any errors that are not captured by the fundamental changes in the parameters. This allows us to express the changes in quantities at the dealer and lender level as follows

$$\begin{aligned} \Delta q_{i,t} =& \delta_{i,t} + \sum_{\ell \in L_{i,t-1}} \phi_{il,t-1} \lambda_{\ell,t}, \ \forall i \in D, \\ \Delta q_{k,t} =& \lambda_{k,t} + \sum_{j \in D_{k,t-1}} \theta_{kj,t-1} \delta_{j,t} \ \forall k \in L, \end{aligned} \tag{A.34}$$

where we define $\phi_{ik,t-1} = \frac{q_{ik,t-1}}{\sum_{l \in L_i} q_{il,t-1}}$, the share of dealer i borrowing from lender k across all lender counterparties L_i at time $t-1$. Similarly, we define $\theta_{ki,t-1} = \frac{q_{ik,t-1}}{\sum_{j \in D_k} q_{jk,t-1}}$ as the share of lender k lending to dealer i across all dealer counterparties

D_k at time $t-1$. The system of equations contains $n+m$ unknowns and the rank of the system is $n+m-2$. Therefore, the supply and demand factors are identified up to a scalar. We follow Amiti and Weinstein [2018] and normalize all the equations with a randomly selected reference entity and then re-normalize the factors with the median entity to eliminate the influence of the reference entity. ■

Proof of Proposition 5.

Recall that the effective SRF cap is $\tilde{q}^{\mathcal{S}} \equiv \min\left\{|\mathcal{D}_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}$.

Step 1. (Dealer's optimization problem) Dealers will take the equilibrium $\mathcal{C}$ market rate and SRF bid rate as given, i.e. $\rho_{\mathcal{C}}$ and $\rho_{\mathcal{S}}$ are macro variables.

For each dealer $i \in D_{\mathcal{S}}$, the dealers' cost minimization problem in the presence of the SRF facility is

$$\begin{aligned}
\min_{\substack{q_{i\mathcal{C}}, q_{i\mathcal{S}},\\ \{q_{ik}\}_{k\in L_i}}} \; & \rho_{\mathcal{C}} q_{i\mathcal{C}} + \rho_{\mathcal{S}} q_{i\mathcal{S}} + \sum_{k\in L_i} q_{ik}\left(c_k + \gamma_k \sum_{j\in D_k} q_{jk}\right) + \frac{\beta_i}{2}\left(q_{i\mathcal{C}} + q_{i\mathcal{S}} + \sum_{k\in L_i} q_{ik} - q_{\mathcal{B}i}\right)^2 \\
\text{s.t. } & q_{i\mathcal{S}} \le \bar{q}^{\mathcal{S}} \\
& q_{i\mathcal{S}} \ge 0 \\
& q_{ik} \ge 0, \qquad \forall k \in L_i,
\end{aligned} \tag{A.35}$$

where the first constraint is the individual SRF cap, the second constraint is the non-negativity for the SRF borrowing amount, and the third constraint is the non-negativity for $\mathcal{T}$ market borrowing amounts. The first-order conditions are

$$\rho_{\mathcal{C}} + \beta_i\left(q_{i\mathcal{C}} + q_{i\mathcal{S}} + \sum_{k\in L_i} q_{ik} - q_{\mathcal{B}i}\right) = 0 \tag{A.36}$$

$$\rho_{\mathcal{S}} + \beta_i\left(q_{i\mathcal{C}} + q_{i\mathcal{S}} + \sum_{k\in L_i} q_{ik} - q_{\mathcal{B}i}\right) + \bar{\xi} - \underline{\xi} = 0 \tag{A.37}$$

$$c_k + \gamma_k \sum_{j\in D_k} q_{jk} + q_{ik} + \beta_i\left(q_{i\mathcal{C}} + q_{i\mathcal{S}} + \sum_{k\in L_i} q_{ik} - q_{\mathcal{B}i}\right) = 0 \qquad \forall k \in L_i, \tag{A.38}$$

where $\bar{\xi}$ and $\underline{\xi}$ denote the Lagrangian multipliers for the individual cap constraint and the non-negativity constraint for $q_{i\mathcal{S}}$, respectively.

Step 2. (Equilibrium quantities for given rates)

Case 1. Suppose that $\rho_{\mathcal{C}} < \rho_{\mathcal{S}}$. Then, the individual cap constraint (upper bound) cannot be binding, because otherwise $\bar{\xi} > 0$ due to the complementarity slackness condition of $\bar{\xi}(\bar{q}^{\mathcal{S}} - q_{i\mathcal{S}}) = 0$ (and automatically $\underline{\xi} = 0$, as $q_{i\mathcal{S}} > 0$), and it would make the left-hand side of (A.37) strictly greater than the left-hand side of (A.36). If $q_{i\mathcal{S}} > 0$, then (A.36) and (A.37) imply

$$\rho_{\mathcal{C}} = \rho_{\mathcal{S}},$$

which contradicts the initial assumption $\rho_{\mathcal{C}} < \rho_{\mathcal{S}}$. Therefore, the optimal decision should be $q_{i\mathcal{S}} = 0$ with $\underline{\xi} > 0$ to make both (A.36) and (A.37) hold. Then, with $q_{i\mathcal{S}} = 0$ for all $i \in D_{\mathcal{S}}$, the equilibrium quantities will be the same as the equilibrium quantities without the SRF. Therefore, the equilibrium rate will be $\rho^*_{\mathcal{C}}$ in this case. The initial assumption of $\rho_{\mathcal{C}} < \rho_{\mathcal{S}}$ is satisfied only if the $\mathcal{C}$ market rate is lower than the lowest possible bid rate, which is the minimum bid rate. Hence, if $\rho^*_{\mathcal{C}} < \underline{\rho}_{\mathcal{S}}$, then $q_{i\mathcal{S}} = 0$ for all $i \in D_{\mathcal{S}}$.

Case 2. Suppose that $\rho_{\mathcal{C}} > \rho_{\mathcal{S}}$. Then, (A.36) and (A.37) imply that the upper bound for the SRF borrowing amount is binding with $q_{i\mathcal{S}} = \bar{q}^{\mathcal{S}}$ and $\bar{\xi} > 0$. This implies that the SRF participating dealers have incentives to bid a higher rate and still willing to reach the upper bound, i.e. excess demand. Therefore, competition for funds with the given $\mathcal{C}$ market rate will increase the market clearing bid rate $\rho_{\mathcal{S}}$ until it reaches indifference between borrowing from the SRF and the $\mathcal{C}$ market at $\rho_{\mathcal{S}} = \rho_{\mathcal{C}}$. Hence, there is no equilibrium in this case of $\rho_{\mathcal{S}} < \rho_{\mathcal{C}}$.

Case 3. Suppose that $\rho_{\mathcal{C}} = \rho_{\mathcal{S}}$. Then, (A.36) and (A.37) imply that dealer i is indifferent between any combination of $q_{i\mathcal{C}}$ and $q_{i\mathcal{S}}$ with a fixed $q_{i\mathcal{C}} + q_{i\mathcal{S}}$ that satisfies the first-order condition subject to quantity constraints.

Rearranging (A.36) and (A.37) implies

$$q_{i\mathcal{C}} = q_{\mathcal{B}i} - \sum_{k \in L_i} q_{ik} - q_{i\mathcal{S}} - \frac{\rho_{\mathcal{C}}}{\beta_i} \tag{A.39}$$

$$q_{i\mathcal{S}} = q_{\mathcal{B}i} - \sum_{k \in L_i} q_{ik} - q_{i\mathcal{C}} - \frac{\rho_{\mathcal{C}}}{\beta_i}, \tag{A.40}$$

and combining (A.39) with (A.38) results in

$$q^*_{ik} = \frac{\rho_{\mathcal{C}} - c_k}{2\gamma_k} - \frac{1}{2} \sum_{j \in D_k, j \neq i} q_{jk}, \tag{A.41}$$

which is exactly the same as the second case of (6). Also, for each dealer $i \notin D_{\mathcal{S}}$, the optimal quantities $\{q_{ik}\}_{k \in L_i}$ and $q_{i\mathcal{C}}$ are the same as in the case. Therefore, the equilibrium $\mathcal{T}$ market quantities for fixed $\rho_{\mathcal{C}} = \rho_{\mathcal{S}}$ are the same as in Proposition 1:

$$q_{ik}^* = \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}(\rho_{\mathcal{C}} - c_\ell) \tag{A.42}$$

$$q_{i\mathcal{C}}^{\mathcal{S}\,*} = \begin{cases} q_{\mathcal{B}i} + \sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \left(\sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \frac{1}{\beta_i} \right) \rho_{\mathcal{C}} & \text{if } i \notin D_{\mathcal{S}} \\ q_{\mathcal{B}i} + \sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \left(\sum_{k \in L_i} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \frac{1}{\beta_i} \right) \rho_{\mathcal{C}} - q_{i\mathcal{S}} & \text{if } i \in D_{\mathcal{S}}. \end{cases} \tag{A.43}$$

The $\mathcal{C}$ market clearing condition is

$$\sum_{i \in D} q_{i\mathcal{C}}^{\mathcal{S}\,*} = \bar{q}_{\mathcal{B}} + \sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \left(\sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i \in D} \frac{1}{\beta_i} \right) \rho_{\mathcal{C}} - \sum_{i \in D_{\mathcal{S}}} q_{i\mathcal{S}} = 0. \tag{A.44}$$

Hence, the market clearing rate with the SRF, $\rho_{\mathcal{C},\mathcal{S}}^*$ is

$$\rho_{\mathcal{C},\mathcal{S}}^* = \frac{\bar{q}_{\mathcal{B}} + \sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \sum_{i \in D_{\mathcal{S}}} q_{i\mathcal{S}}}{\sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i \in D} \frac{1}{\beta_i}}, \tag{A.45}$$

and $\rho_{\mathcal{S}}^* = \rho_{\mathcal{C},\mathcal{S}}^*$ by the initial assumption of this case. Then, for the fixed $\rho_{\mathcal{S}}^*$, the aggregate amount of the SRF borrowing, $\sum_{i \in D_{\mathcal{S}}} q_{i\mathcal{S}}$ is uniquely determined by (A.45) as

$$\sum_{i \in D_{\mathcal{S}}} q_{i\mathcal{S}} = \bar{q}_{\mathcal{B}} + \sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \left(\sum_{ik \in E} \sum_{j\ell \in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i \in D} \frac{1}{\beta_i} \right) \rho_{\mathcal{S}}^*. \tag{A.46}$$

Step 3. (Determination of the market clearing rates) The final step is to pin down the market clearing rates for $\mathcal{C}$ market and the SRF auction.

Case 1. Suppose that $\rho_{\mathcal{C}}^* \leq \underline{\rho_{\mathcal{S}}}$. Then, the equilibrium bid rate is bounded below by the minimum bid rate spread, $\rho_{\mathcal{S}}^* \geq \underline{\rho_{\mathcal{S}}}$, and the equilibrium is in the situation of Case 1 in Step 2. Therefore, the equilibrium SRF amount is $q_{i\mathcal{S}} = 0$ for any $i \in D_{\mathcal{S}}$, and the equilibrium rate is the same as in the equilibrium without the SRF $\rho^*_{\mathcal{C},\mathcal{S}} = \rho^*_{\mathcal{C}}$ and the equilibrium quantities are the same as in the equilibrium without the SRF as well.

Case 2. Suppose that $\rho^*_{\mathcal{C}} > \underline{\rho_{\mathcal{S}}}$. Then, the $\mathcal{C}$ market rate without the SRF exceeds the minimum SRF bid rate spread, so there will be positive demand for the SRF borrowing—i.e. $q_{i\mathcal{S}} > 0$ for some $i \in D_{\mathcal{S}}$. Since Case 2 of Step 2 is not possible, it should be Case 3 in Step 2 with $\rho^*_{\mathcal{C},\mathcal{S}} = \rho^*_{\mathcal{S}}$. Then, the equilibrium aggregate SRF borrowing amount is determined by (A.46).

Case 2.1. Suppose that for all the active links without the SRF, $\forall ab \in E$, the following condition holds

$$\frac{\sum_{j\ell\in E} \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell} c_\ell}{\sum_{j\ell\in E} \frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell}} < \frac{\bar{q}_{\mathcal{B}} + \sum_{ik\in E}\sum_{j\ell\in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}}{\sum_{ik\in E}\sum_{j\ell\in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i\in D} \frac{1}{\beta_i}}. \tag{A.47}$$

The condition (A.47) implies that all the equilibrium quantities are positive—i.e., $q^*_{ab} > 0$ for all $ab \in E$—even when dealers borrow from the SRF as much as possible.[29]

Case 2.1.1. Suppose that

$$\sum_{i\in D_{\mathcal{S}}} q_{i\mathcal{S}} = \bar{q}_{\mathcal{B}} + \sum_{ik\in E}\sum_{j\ell\in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \left(\sum_{ik\in E}\sum_{j\ell\in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i\in D}\frac{1}{\beta_i}\right)\underline{\rho_{\mathcal{S}}} \tag{A.48}$$

$$\leq \min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}, \tag{A.49}$$

which implies the equilibrium aggregate SRF amount is below the minimum between the sum of individual caps or the aggregate cap even when the dealers bid the minimum bid rate spread. Then, by (A.44) and (A.45), the equilibrium $\mathcal{C}$ market rate is $\rho^*_{\mathcal{C},\mathcal{S}} = \underline{\rho_{\mathcal{S}}} = \rho^*_{\mathcal{S}}$, and the equilibrium aggregate SRF amount is (A.48).

Case 2.1.2. Suppose that

$$\sum_{i\in D_{\mathcal{S}}} q_{i\mathcal{S}} = \bar{q}_{\mathcal{B}} + \sum_{ik\in E}\sum_{j\ell\in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} c_\ell - \left(\sum_{ik\in E}\sum_{j\ell\in E} \frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i\in D}\frac{1}{\beta_i}\right)\underline{\rho_{\mathcal{S}}}$$

$$> \min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}, \tag{A.50}$$

[29]This condition corresponds to the condition for Lemma 1 that makes all links to be active for the market equilibrium without the SRF.

which implies that the equilibrium aggregate SRF amount will reach its upper bound if the SRF participants bid the minimum bid rate spread. In other words, dealers' marginal cost of borrowing from other sources are greater than the minimum bid rate $\underline{\rho_{\mathcal{S}}}$. Then, by the same logic as in Case 2 of Step 2, the equilibrium SRF bid rate should increase to match the $\mathcal{C}$ market rate, i.e. $\rho_{\mathcal{S}} = \rho_{\mathcal{C},\mathcal{S}}$, and the SRF participants will borrow from the SRF up to the aggregate upper bound—the minimum between the sum of individual caps or the aggregate cap. Then, the equilibrium $\mathcal{C}$ market rate is determined by (A.45) as

$$\rho^*_{\mathcal{C},\mathcal{S}} = \frac{\bar{q}_{\mathcal{B}} + \sum_{ik\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}c_\ell - \min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}}{\sum_{ik\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i\in D}\frac{1}{\beta_i}}, \tag{A.51}$$

the equilibrium SRF bid rate is $\rho^*_{\mathcal{S}} = \rho^*_{\mathcal{C},\mathcal{S}}$, and the equilibrium aggregate SRF borrowing amount is $\sum_{i\in D_{\mathcal{S}}} q^*_{i\mathcal{S}} = \min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}$.

Case 2.2. Finally, suppose that for there exists a link $ab \in E$, which is active without the SRF but inactive in the equilibrium with the SRF as

$$\frac{\sum_{j\ell\in E}\frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell}c_\ell}{\sum_{j\ell\in E}\frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell}} > \frac{\bar{q}_{\mathcal{B}} + \sum_{ik\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}c_\ell - \sum_{i\in D_{\mathcal{S}}} q^*_{i\mathcal{S}}}{\sum_{ik\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i\in D}\frac{1}{\beta_i}}, \tag{A.52}$$

where the equilibrium SRF quantities are determined below. Under this case, we can redefine the set of active edges with the SRF as $E^{\mathcal{S}} \subset E$, and the corresponding $\tilde{\psi}^{\mathcal{S}}$, which is the inverse of $\left(I + \frac{1}{2}\tilde{W}^{\mathcal{S}}\right)$, where $\tilde{W}^{\mathcal{S}}$ is defined by 14 for $E^{\mathcal{S}}$ instead of E.

Case 2.2.1.

$$\begin{aligned}\sum_{i\in D_{\mathcal{S}}} q_{i\mathcal{S}} =& \bar{q}_{\mathcal{B}} + \sum_{ik\in E^{\mathcal{S}}}\sum_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}c_\ell - \left(\sum_{ik\in E^{\mathcal{S}}}\sum_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell} + \sum_{i\in D}\frac{1}{\beta_i}\right)\underline{\rho_{\mathcal{S}}} && \text{(A.53)}\\ \le& \min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}, && \text{(A.54)}\end{aligned}$$

then, this case is similar to Case 2.1.1. Therefore, the equilibrium $\mathcal{C}$ market rate is $\rho^*_{\mathcal{C},\mathcal{S}} = \underline{\rho_{\mathcal{S}}} = \rho^*_{\mathcal{S}}$, and the equilibrium aggregate SRF amount is (A.53).

This will be an equilibrium, only if, for any $ab \in E$ such that $ab \notin E^{\mathcal{S}}$, the following condition holds

$$\frac{\sum\limits_{j\ell\in E}\frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell}c_\ell}{\sum\limits_{j\ell\in E}\frac{\tilde{\psi}_{ab,j\ell}}{2\gamma_\ell}} > \frac{\bar{q}_{\mathcal{B}}+\sum\limits_{ik\in E}\sum\limits_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}c_\ell-\left(\bar{q}_{\mathcal{B}}+\sum\limits_{ik\in E^{\mathcal{S}}}\sum\limits_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}c_\ell-\left(\sum\limits_{ik\in E^{\mathcal{S}}}\sum\limits_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}+\sum_{i\in D}\frac{1}{\beta_i}\right)\underline{\rho_{\mathcal{S}}}\right)}{\sum_{ik\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}+\sum_{i\in D}\frac{1}{\beta_i}},$$

$$=\frac{\sum\limits_{ik\in E}\sum\limits_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}c_\ell-\left(\sum\limits_{ik\in E^{\mathcal{S}}}\sum\limits_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}c_\ell-\left(\sum\limits_{ik\in E^{\mathcal{S}}}\sum\limits_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}+\sum_{i\in D}\frac{1}{\beta_i}\right)\underline{\rho_{\mathcal{S}}}\right)}{\sum_{ik\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}+\sum_{i\in D}\frac{1}{\beta_i}}, \tag{A.55}$$

which implies the link becoming inactive after the equilibrium SRF borrowing amount lowers the equilibrium marginal cost of funds.

Case 2.2.2. Suppose that

$$\begin{aligned}\sum_{i\in D_{\mathcal{S}}} q_{i\mathcal{S}} =&\bar{q}_{\mathcal{B}}+\sum_{ik\in E^{\mathcal{S}}}\sum_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}c_\ell-\left(\sum_{ik\in E^{\mathcal{S}}}\sum_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}+\sum_{i\in D}\frac{1}{\beta_i}\right)\underline{\rho_{\mathcal{S}}}\\ >&\min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}},\bar{\bar{q}}^{\mathcal{S}}\right\},\end{aligned} \tag{A.56}$$

which implies that the equilibrium aggregate SRF amount will reach its upper bound if the SRF participants bid the minimum bid rate spread. As in Case 2.1.2, the equilibrium $\mathcal{C}$ market rate is

$$\rho^*_{\mathcal{C},\mathcal{S}}=\frac{\bar{q}_{\mathcal{B}}+\sum_{ik\in E^{\mathcal{S}}}\sum_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}c_\ell-\min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}},\bar{\bar{q}}^{\mathcal{S}}\right\}}{\sum_{ik\in E^{\mathcal{S}}}\sum_{j\ell\in E^{\mathcal{S}}}\frac{\tilde{\psi}^{\mathcal{S}}_{ik,j\ell}}{2\gamma_\ell}+\sum_{i\in D}\frac{1}{\beta_i}}, \tag{A.57}$$

the equilibrium SRF bid rate is $\rho^*_{\mathcal{S}}=\rho^*_{\mathcal{C},\mathcal{S}}$, and the equilibrium aggregate SRF borrowing amount is $\sum_{i\in D_{\mathcal{S}}} q^*_{i\mathcal{S}}=\min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}},\bar{\bar{q}}^{\mathcal{S}}\right\}$.

This will be an equilibrium, only if, for any $ik\in E$ such that $ik\notin E^{\mathcal{S}}$, the following condition holds

$$\frac{\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}c_\ell}{\sum_{j\ell\in E}\frac{\tilde{\psi}_{ik,j\ell}}{2\gamma_\ell}} > \frac{\bar{q}_{\mathcal{B}} + \sum_{i'k'\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{i'k',j\ell}}{2\gamma_\ell}c_\ell - \min\left\{|D_{\mathcal{S}}|\bar{q}^{\mathcal{S}}, \bar{\bar{q}}^{\mathcal{S}}\right\}}{\sum_{i'k'\in E}\sum_{j\ell\in E}\frac{\tilde{\psi}_{i'k',j\ell}}{2\gamma_\ell} + \sum_{i\in D}\frac{1}{\beta_i}}. \tag{A.58}$$

■

B Derivations of the simple example

Here we detail the algebra needed to to solve the simple example in section 3.8 for different wirings of the repo market illustrated in Figures 4 and 5.

B.1 Symmetric but incomplete wiring

Starting with the wiring in panel A of Figure 4, the first-order conditions for quantities borrowed in the decentralized market are:

$$\begin{aligned}
q_{11}(\rho_{\mathcal{C}}) &= \frac{1}{2\gamma}(\rho_{\mathcal{C}} - c) \\
q_{12}(\rho_{\mathcal{C}}) &= \frac{1}{2\gamma}(\rho_{\mathcal{C}} - c) - \frac{1}{2}q_{22} \\
q_{22}(\rho_{\mathcal{C}}) &= \frac{1}{2\gamma}(\rho_{\mathcal{C}} - c) - \frac{1}{2}q_{12} \\
q_{23}(\rho_{\mathcal{C}}) &= \frac{1}{2\gamma}(\rho_{\mathcal{C}} - c).
\end{aligned}$$

Given these first order conditions, the equilibrium quantities borrowed from the decentralized market along each dealer-lender pair are $q_{11} = q_{23} = \frac{1}{2\gamma}(\rho_{\mathcal{C}} - c)$ and $q_{12} = q_{22} = \frac{1}{3\gamma}(\rho_{\mathcal{C}} - c)$. It is easy to verify that for any $\rho_{\mathcal{C}} > c$ each dealer borrows less from their common lender ℓ_2 than their exclusive lenders ℓ_1 and ℓ_3; that is, $q_{11} > q_{12}$ and $q_{23} > q_{22}$. We briefly provide intuition behind the quantities. Recall that the borrowing spread is determined by

$$s_k = c + \gamma \sum_{j\in D_k} q_{jk}, \text{for each } k \in L.$$

If a dealer is borrowing from a lender exclusively, then the dealer exerts monopsony power and the sensitivity to lender supply is $1/2\gamma$. However, if a dealer is competing with another dealer for funding from the same lender, then the Cournot competition decreases the sensitivity to lender supply to $1/3\gamma$. This is because dealers do not internalize the increase in marginal cost of funding for their competitors. Therefore, Cournot competition results in a rate higher than the rate at each dealer's exclusive lender, because the total amount borrowed from the common lender $\frac{2}{3\gamma}(\rho_{\mathcal{C}}-c)$ exceeds the total amount borrowed from an exclusive lender $\frac{1}{2\gamma}(\rho_{\mathcal{C}}-c)$.

The total amount borrowed by each dealer is $q_{i\mathcal{T}} = \frac{5}{6\gamma}(\rho_{\mathcal{C}}-c)$ for $i = 1, 2$. The total amount borrowed from the decentralized market is a function of the borrowing rate in the interdealer market:

$$q_{\mathcal{T}}(\rho_{\mathcal{C}}) \equiv \sum_{j\in\{1,2\}} q_{j\mathcal{T}}(\rho_{\mathcal{C}}) = \frac{5}{3\gamma}(\rho_{\mathcal{C}}-c).$$

The demand for net funding from the interdealer market is

$$q_{i\mathcal{C}}(\rho_{\mathcal{C}}) = q_{\mathcal{B}i} - q_{i\mathcal{T}}(\rho_{\mathcal{C}}) - \frac{\rho_{\mathcal{C}}}{\beta},\ i \in \{d_1, d_2\}.$$

The market clearing condition for $\mathcal{C}$ market is

$$q_{1\mathcal{C}}(\rho_{\mathcal{C}}) + q_{2\mathcal{C}}(\rho_{\mathcal{C}}) = 0,$$

and plugging in the $\mathcal{T}$ market quantities allows us to solve for the equilibrium rate

$$\begin{aligned} &\bar{q}_{\mathcal{B}} - \frac{5}{3\gamma}(\rho_{\mathcal{C}}-c) - \frac{2\rho_{\mathcal{C}}}{\beta} = 0 \\ &\qquad\qquad\qquad \Rightarrow \rho_{\mathcal{C}} = \frac{3\beta\gamma}{6\gamma+5\beta}\bar{q}_{\mathcal{B}} + \frac{3\beta\gamma}{6\gamma+5\beta}\frac{5}{3\gamma}c. \end{aligned}$$

To summarize, the equilibrium with $\mathcal{C}$ market in closed form is

$$\begin{aligned} \rho^*_{\mathcal{C}} &= \frac{3\beta\gamma}{6\gamma+5\beta}\bar{q}_{\mathcal{B}} + \frac{5\beta}{6\gamma+5\beta}c \\ q_{\mathcal{T}} &= \frac{5\beta}{6\gamma+5\beta}\bar{q}_{\mathcal{B}} - \frac{10}{6\gamma+5\beta}c \\ q_{i\mathcal{C}} &= \frac{q_{\mathcal{B}i} - q_{\mathcal{B}j}}{2}. \end{aligned}$$

Examine now how the equilibrium changes without a $\mathcal{C}$ market. The equilibrium quantities in the decentralized market satisfy the following optimality conditions

$$
\begin{aligned}
q_{11} &= \frac{\beta}{2\gamma+\beta}q_{\mathcal{B}1} - \frac{1}{2\gamma+\beta}c - \frac{\beta}{2\gamma+\beta}q_{12} \\
q_{12} &= \frac{\beta}{2\gamma+\beta}q_{\mathcal{B}1} - \frac{1}{2\gamma+\beta}c - \frac{\beta}{2\gamma+\beta}q_{11} - \frac{\gamma}{2\gamma+\beta}q_{22} \\
q_{22} &= \frac{\beta}{2\gamma+\beta}q_{\mathcal{B}2} - \frac{1}{2\gamma+\beta}c - \frac{\beta}{2\gamma+\beta}q_{23} - \frac{\gamma}{2\gamma+\beta}q_{12} \\
q_{23} &= \frac{\beta}{2\gamma+\beta}q_{\mathcal{B}2} - \frac{1}{2\gamma+\beta}c - \frac{\beta}{2\gamma+\beta}q_{22}.
\end{aligned} \tag{B.1}
$$

To solve the system of equations, we first plug in q_{11} and q_{23} into the second and third equations, respectively. This leaves us with a system of two equations in two unknowns that define the best response functions of the two dealers when borrowing from their common lender l_2

$$
\begin{aligned}
q_{12} &= \frac{\beta}{2(\gamma+\beta)}q_{\mathcal{B}1} - \frac{1}{2(\gamma+\beta)}c - \frac{2\gamma+\beta}{4(\gamma+\beta)}q_{22} \\
q_{22} &= \frac{\beta}{2(\gamma+\beta)}q_{\mathcal{B}2} - \frac{1}{2(\gamma+\beta)}c - \frac{2\gamma+\beta}{4(\gamma+\beta)}q_{12}.
\end{aligned} \tag{B.2}
$$

Note that it is easy to show that the best-response function has a slope less than one-half $\frac{2\gamma+\beta}{4(\gamma+\beta)} < \frac{1}{2}$ for all positive values of the underlying coefficients. The strategic substitutability of the dealers' borrowing from their common lender are dampened when there is no $\mathcal{C}$ market. The resulting equilibrium quantities are the following functions of the underlying parameters

$$
\begin{aligned}
q^*_{11} &= \frac{7\beta^2+6\gamma\beta}{A(\beta,\gamma)}q_{\mathcal{B}1} + \frac{2\beta^2}{A(\beta,\gamma)}q_{\mathcal{B}2} - \frac{9\beta+6\beta\gamma}{A(\beta,\gamma)}c \\
q^*_{12} &= \frac{8\beta(\beta+\gamma)}{A(\beta,\gamma)}q_{\mathcal{B}1} - \frac{2\beta(\beta+2\gamma)}{A(\beta,\gamma)}q_{\mathcal{B}2} - \frac{6\beta+4\gamma}{A(\beta,\gamma)}c \\
q^*_{22} &= \frac{8\beta(\beta+\gamma)}{A(\beta,\gamma)}q_{\mathcal{B}2} - \frac{2\beta(\beta+2\gamma)}{A(\beta,\gamma)}q_{\mathcal{B}1} - \frac{6\beta+4\gamma}{A(\beta,\gamma)}c \\
q^*_{23} &= \frac{7\beta^2+6\gamma\beta}{A(\beta,\gamma)}q_{\mathcal{B}2} + \frac{2\beta^2}{A(\beta,\gamma)}q_{\mathcal{B}1} - \frac{9\beta+6\beta\gamma}{A(\beta,\gamma)}c
\end{aligned} \tag{B.3}
$$

The term $A(\beta,\gamma) = 15\beta^2 + 28\gamma\beta + 12\gamma^2$ is a polynomial function of the two cost parameters. There are two properties of the equilibrium quantities that can be easily inferred. First, increases in the lender marginal costs c reduce equilibrium quantities for all trading relationships. Second, increases in demand to a competing dealer result in a reduction of borrowing from the common lender ℓ_2 consistent with strategic substitutability of actions. In contrast, an increase in the demand of a competitor increases the borrowing from the exclusive lenders ℓ_1 and ℓ_3 for dealers 1 and 2, respectively, which indicates strategic complementarity of dealer actions. The simple example illustrates that in a networked market with Cournot competition actions of agents could be strategic substitutes or complements depending on the nature of the connectedness of the market.

B.2 Fully connected $\mathcal{T}$ market

Finally, we examine how the equilibrium changes, if all dealers can borrow from all lenders or the $\mathcal{T}$ is fully connected. In particular, we are interested in comparing the equilibrium of a fully-connected $\mathcal{T}$ and the role of the centrally cleared $\mathcal{C}$ market. When the $\mathcal{T}$ market is not fully connected, the $\mathcal{C}$ market allows for the equalization of the marginal cost of funds across all lenders.

We can solve the system of equation formed by the first-order conditions as a function of the underlying parameters and the equilibrium rate $\rho^*_{\mathcal{C}}$ as follows

$$\begin{aligned} q_{ik} =& \frac{\rho^*_{\mathcal{C}} - c}{3\gamma}, \ \forall ik \in E \\ q_{i\mathcal{C}} =& q_{\mathcal{B},i} + \frac{1}{\gamma}c - \frac{\beta+\gamma}{\beta\gamma}\rho^*_{\mathcal{C}}, \text{ for } i = \{1,2\} \end{aligned} \tag{B.4}$$

The market clearing condition $q_{1\mathcal{C}} + q_{2\mathcal{C}} = 0$ can be easily solved to obtain the equilibrium rate $\rho^*_{\mathcal{C}}$

$$\rho^*_{\mathcal{C}} = \frac{\beta\gamma}{2(\beta+\gamma)}\bar{q}_{\mathcal{B}} + \frac{\beta}{\beta+\gamma}c,$$

The equilibrium quantities borrowed from lenders in the decentralized market are

$$\begin{aligned} q^*_{ik} =& \frac{\beta}{6(\beta+\gamma)}\bar{q}_{\mathcal{B}} - \frac{1}{3(\beta+\gamma)}c, \ \forall ik \in E \\ q^*_{\mathcal{T}} =& \frac{\beta}{\beta+\gamma}\bar{q}_{\mathcal{B}} - \frac{2}{\beta+\gamma}c \end{aligned}$$

The quantities transacted between the two dealers in the $\mathcal{C}$ market are

$$q_{1\mathcal{C}} = \frac{q_{1\mathcal{B}} - q_{2\mathcal{B}}}{2}$$
$$q_{2\mathcal{C}} = \frac{q_{2\mathcal{B}} - q_{1\mathcal{B}}}{2}.$$

The same trades as the case with symmetric but incomplete $\mathcal{T}$-market. The quantities traded along any dealer-lender relationship depend on the total dealer demand rather than the individual dealer demand conditions. Moving to the case of a fully connected $\mathcal{T}$ market without an interdealer $\mathcal{C}$ market, the equilibrium quantities are

$$q^*_{ik} = \frac{\beta(2\gamma+3\beta)}{3(\gamma+\beta)(\gamma+3\beta)} q_{\mathcal{B}i} - \frac{\beta\gamma}{3(\gamma+\beta)(\gamma+3\beta)} q_{\mathcal{B}j} - \frac{1}{3(\gamma+\beta)} c, \; \textit{where } i,j \in \{d_1, d_2\}.$$

The symmetric wiring introduces also symmetry in the sensitivity of quantities to demand and supply shocks across all trading relationships. The total quantity traded in the $\mathcal{T}$ market is

$$q^*_{\mathcal{T}} = \frac{\beta}{\beta+\gamma}\bar{q}_{\mathcal{B}} - \frac{2}{\beta+\gamma}c, \tag{B.5}$$

The total amount borrowed is the same as in the equilibrium with a centrally cleared market. The difference is that with a centrally cleared market, the dealer with low demand borrows extra and lends the extra cash to the dealer with high demand through the centrally cleared market.[30]

B.3 Asymmetric wiring of the $\mathcal{T}$ market

Examine a wiring in which dealer d_1 borrows from all lenders, whereas dealer d_2 only borrows from l_2 and l_3. In this case, dealers share l_2 and l_3, and dealer d_1 has an exclusive lender l_1 as illustrated in Panel B of Figure 4.

Beginning with an asymmetric wiring that involves a $\mathcal{C}$ market and following the same steps as before we can easily solve for the equilibrium quantities as follows. First, the optimal quantities borrowed across the three lenders are $q_{11} = \frac{1}{2\gamma}(\rho^*_{\mathcal{C}} - c)$

[30]Note that condition (18) becomes $\bar{q}_{\mathcal{B}} > \frac{2}{\beta}c$ and is required to guarantee that equilibrium quantities are positive.

and $q_{12} = q_{22} = q_{13} = q_{23} = \dfrac{1}{3\gamma}(\rho^*_{\mathcal{C}} - c)$ and the total quantities borrowed by each dealer are

$$q^*_{1\mathcal{T}}(\rho^*_{\mathcal{C}}) = \frac{7}{6\gamma}(\rho^*_{\mathcal{C}} - c)$$
$$q^*_{2\mathcal{T}}(\rho^*_{\mathcal{C}}) = \frac{2}{3\gamma}(\rho^*_{\mathcal{C}} - c).$$

For any spread between the lender marginal cost c and the centrally cleared rate, dealer d_1 has a higher borrowing than the less connected dealer d_2. The market clearing condition

$$\rho^*_{\mathcal{C}} = \frac{6\beta\gamma}{12\gamma + 11\beta}\bar{q}_{\mathcal{B}} + \frac{11\beta}{12\gamma + 11\beta}c,$$

gives us a solution for the centrally cleared market rate. The quantities borrowed in the decentralized market are

$$q^*_{1\mathcal{T}} = \frac{7\beta}{12\gamma + 11\beta}\bar{q}_{\mathcal{B}} - \frac{14}{12\gamma + 11\beta}c$$
$$q^*_{2\mathcal{T}} = \frac{4\beta}{12\gamma + 11\beta}\bar{q}_{\mathcal{B}} - \frac{8}{12\gamma + 11\beta}c$$
$$q^*_{\mathcal{T}} = \frac{11\beta}{12\gamma + 11\beta}\bar{q}_{\mathcal{B}} - \frac{22}{12\gamma + 11\beta}c.$$

The quantities for the $\mathcal{C}$ market are

$$q_{1\mathcal{C}} = q_{\mathcal{B}1} - \frac{7\beta + 6\gamma}{12\gamma + 11\beta}\bar{q}_{\mathcal{B}} + \frac{3}{12\gamma + 11\beta}c$$
$$q_{2\mathcal{C}} = q_{\mathcal{B}2} - \frac{4\beta + 6\gamma}{12\gamma + 11\beta}\bar{q}_{\mathcal{B}} - \frac{3}{12\gamma + 11\beta}c.$$

Note that unlike the symmetric cases, the asymmetric case introduces dependence of the quantities transacted in the interdealer market on the lenders' the marginal cost parameter c. Furthermore, the net borrowing of dealer d_1 in the interdealer market increases with higher c, whereas the net borrowing of dealer d_2 decreases. If there is no centrally cleared market and following the steps from before, the equilibrium quantities borrowed in the decentralized market can be solved as follows

$$
\begin{aligned}
q_{11}^* =& \frac{4\beta^2 + 3\beta\gamma}{A(\gamma,\beta)} q_{B1} + \frac{2\beta^2}{A(\gamma,\beta)} q_{B2} - \frac{6\beta + 3\gamma}{A(\gamma,\beta)} c \\
q_{12}^* =& q_{13}^* = \frac{4\beta^2 + 4\beta\gamma}{A(\gamma,\beta)} q_{B1} - \frac{\beta^2 + 2\beta\gamma}{A(\gamma,\beta)} q_{B2} - \frac{3\beta + 2\gamma}{A(\gamma,\beta)} c \\
q_{22}^* =& q_{23}^* = \frac{6\beta^2 + 4\beta\gamma}{A(\gamma,\beta)} q_{B2} - \frac{2\beta\gamma}{A(\gamma,\beta)} q_{B1} - \frac{6\beta + 2\gamma}{A(\gamma,\beta)} c,
\end{aligned}
\tag{B.6}
$$

where $A(\gamma, \beta) = 12\beta^2 + 19\beta\gamma + 6\gamma^2$. Similar to the symmetric case, the effects of dealer changes in demand result in strategic substitutability of actions across shared lenders and strategic complementarity of actions at exclusive lenders.

C Data and institutional details

C.1 Data construction

We use confidential tri-party OTC repo data collected by the Federal Reserve Bank of New York from the two clearing banks—Bank of New York Mellon (BNYM) and JP-Morgan Chase (JPM). The data contain information on the borrower, lender, amount borrowed, maturity, interest rate and collateral. We focus on government collateral which includes U.S. Treasury securities, agency debt, and agency MBS. Note that we do not observe haircuts in this dataset. However, as discussed below, we add information on haircuts from the money market mutual funds (MMFs) data collected with the SEC's N-MFP reporting form.

We first identify all counterparties in the data and assign unique identifiers. We then identify subsidiaries of large conglomerates and create a unique identifier to track the parent company over time and across different datasets. We then aggregate all trades of subsidiaries under the same parent holding company. For example, all the trades of individual mutual funds under the same fund complex are aggregated under the parent fund complex or under the parent holding company. Similarly, trades of dealers and commercial banks affiliated with a financial holding company are consolidated under the top-holder parent holding company.

We also identify internal transactions as trades that involve a borrower and a lender belonging to the same financial conglomerate.[31] In most cases, the data do not

[31] A large share of lending in the decentralized market is done by asset management funds affiliated with bank holding companies. Those funds do not lend to affiliated dealers. This absence is expected and reflects SEC restrictions on dealings between the affiliated funds and their parents.

allow us to identify the subsidiaries that execute internal transactions. However, in a few cases we are able to identify the type of subsidiaries. For example, we observe trades between two affiliated broker-dealers, one domestic and the other located in a foreign country, or between a commercial bank and a broker-dealer. Because internal transactions are netted for the purposes of the supplementary leverage requirement, those transactions are likely used by financial conglomerates to optimize their regulatory requirements, while taking advantage of regulatory arbitrage opportunities.[32] We exclude all internal transactions from our analysis.

Once we construct consistent entities identifiers across the different datasets, we merge the information on centrally-cleared general collateral repurchase agreements provided by the Fixed-Income Clearing Corporate (FICC). Those data include both the general collateral anonymous GCF segment and the centrally-cleared delivery versus payment (DvP) segment. We follow the same process to normalize the counterparty names to their parent holding company, assign a unique identifier to match the dealers to the tri-party OTC repo dataset.

We supplement the repo data with information on the dealers' and lenders' balance sheets. On the dealer side, we use Moody's KMV data to obtain information on dealers' credit risk, market valuations, and balance sheet information. On the lender side, we classify lenders into two categories—money market mutual funds (MMFs) and other lenders. We focus on money fund complexes, as detailed balance sheet information is usually only available at this level. We use two data sources for MMF data. For information on money fund liabilities, we use iMoneyNet, which contains comprehensive information on expense ratios, minimum investment, investor flows by share class, and investor types. We supplement information from iMoneyNet with the monthly N-MFP form SEC filings. These data contain detailed CUSIP-level information on the composition of securities holdings of money market funds including repurchase agreements and the corresponding counterparties. For repurchase agreements, we are able to verify the counterparties, collateral type, haircuts, and the interest rates for individual repo transactions with the tri-party repo data.

[32] Correa, Du, and Liao [2020] use confidential supervisory data and provide evidence for internal repo transactions that allow large conglomerates to take advantage of arbitrage opportunities in foreign exchange markets and minimize impact on their leverage ratios.

C.2 Tri-party repo and other repo markets

The tri-party repo market is a large, systemically-important funding market with close to $4 trillion of cash and collateral exchanged daily. The tri-party repo market provides cash to dealers for their repo trades with clients in the bilateral repo market. As such, the tri-party repo market is the first leg of an intermediation chain that funnels cash from cash lenders such as money funds to dealer counterparties in bilateral markets, such as as hedge funds and REITs.[33]

The tri-party market involves repurchase agreements or repo contracts between dealers as cash borrowers and money funds and others as cash lenders. A repo is a secured loan that combines a temporary sale of securities with an agreement to repurchase those securities at a later date.[34] A repo agreement specifies the loan amount, the collateral type, the maturity date, the interest rate and the haircut.

The institutional details of how repo contracts are executed differ across the tri-party and the bilateral repo markets. The first difference is that the tri-party market uses the clearing, collateral allocation, and settlement services of a custodian or clearing bank, which is the third party in the repo contract and the reason this market is called "tri-party".[35] The services of the custodian bank are also used for the anonymous FICC interdealer market as well as the Federal Reserve's ON RRP facility. In contrast, in the bilateral segment, cash and collateral are directly exchanged between the lender and the borrower in delivery versus payment (DvP) settlement.

The second difference is the nature of collateral pledged. Tri-party repo are governed by a master repo agreement, which specifies a broad class of generic securities such as Treasury securities, agency debt, and agency MBS, private label collateralized mortgage obligations (CMOs), corporate bonds, equities, asset backed securities, municipal bonds, and other. In contrast, the bilateral repo contracts involve pledging of specific securities and the settlement is done by the counterparties themselves

[33] See Banegas and Monin [2023] for a review of recent developments in bilateral repo markets, including a discussion of hedge funds that engage in Treasury futures basis trading.

[34] The repo contract receives different treatment under bankruptcy laws than other types of lending. In the event of bankruptcy, repo lenders can sell the collateral, rather than be subject to an automatic stay, as would be the norm for other collateralized loans. Refer to Acharya, Anshuman, and Viswanathan [2024] for a discussion.

[35] At the beginning of our sample, clearing in the tri-party segment was facilitated by one of two custodian banks—Bank of New York Mellon and JPMorgan Chase. In 2016, JPMorgan Chase exited the market leaving Bank of New York Mellon as the single clearing bank. The role of the clearing bank is to provide settlement of trades, book keeping, collateral management, and also ensures that the collateral is available to lenders in case of dealer default.

through a delivery versus payment (DvP). Both features of the tri-party repo market, the settlement via a clearing bank and the pledging of general collateral, makes it easier for money market funds and other cash lenders to participate in the market without the need to establish their own collateral management systems and instead rely on the infrastructure provided by the clearing bank.[36]

[36]See Copeland, Martin, and Walker [2010], Ennis [2011], Copeland, Martin, and Walker [2014], and Copeland, Davis, and Martin [2014], and for a more detailed exposition of the institutional details of the tri-party repo market and how those institutional features have evolved since the Global Financial Crisis.