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How does the repo market behave under stress? Evidence from the Covid-19 crisis

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Abstract

We examine how the repo market operates during liquidity stress by applying network analysis to novel transaction-level data of the overnight gilt repo market including the Covid-19 crisis. During this crisis, the repo network becomes more connected, with most institutions relying on existing trade relationships to transact. There are however significant changes in the repo volumes and spreads during the stress relative to normal times. We find a significant increase in volumes traded in the cleared segment of the market. This reflects a preference for dealers and banks to transact in the cleared rather than the bilateral segment. Funding decreases towards non-banks, only increasing for hedge funds. Further, spreads are higher when dealers and banks lend to rather than borrow from non-banks.

Key words: Repo market, liquidity risk, financial networks, market microstructure, Covid-19 crisis.

JEL classification: D85, G01, G21, G23.

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1 Introduction

The recent "dash for cash" during the COVID-19 pandemic has underlined the need to better understand the dynamics of liquidity stress in key funding markets. Sharp spikes in repo rates in March 2020 were evidence of a severe liquidity stress at the time. Although the repo market is key to the provision of short-term liquidity in the financial system, our current knowledge of this market is still very limited, not least due to scarce granular data (Gorton et al., 2020).

In this paper, we examine how the repo market operates during liquidity stress by applying network analysis to novel transaction-level data of the overnight gilt repo market[1] including the COVID-19 crisis. Studies of previous repo turmoils during the GFC and the European sovereign debt crisis highlight that different repo market segments and participants can behave very differently during times of stress (Gorton & Metrick, 2012; Copeland et al., 2014; Krishnamurthy et al., 2014; Mancini et al., 2016; Boissel et al., 2017),[2] pointing to the importance of empirically capturing the heterogeneity of the repo market structure. All of the above studies are however only based on an analysis of the cleared or tri-party segment of the market.[3] As Krishnamurthy et al. (2014) points out, they "lack data on the bilateral repo market, and thus the full picture on repo is yet to be assembled." We fill this gap by providing a joint empirical analysis of the bilateral and cleared segment of the repo market and offering a unique window into the current structure and functioning of the market, both in normal and stress times.

The repo market network has a core-periphery structure. Only banks and gilt dealers[4] trade among each other and therefore only they can in principle be part of the core. They are the key intermediaries and can transact amongst each other as well as with all the other sectors active in the market. Non-banking sectors are located in the periphery,[5] only trading with the core sectors. Central counterparties (CCPs) have a special role in the repo market. They do not actively provide liquidity, but clear trades between core sectors and invest cash margin with them via reverse repo.

For the repo market network at institutional level, we find that the network is sparse and that there is no daily roll-over of overnight repo, not even in the core. During the COVID-19 crisis, the repo network experiences an increase in activity and becomes more connected, with most institutions relying on existing trade relationships to transact. Overall, the evidence shows market participants' reliance on established trading relationships during stress.

To further analyse any significant change in repo volumes and spreads in the overnight gilt repo market during stress periods, we fit a linear model for the repo market network at sectoral level. The methodology represents a simple and innovative approach to statistically characterize changes in market activity between different sectors and to visualize the results in

[1]The gilt repo market is the secured sterling money market where the underlying security is a UK government bond, also referred to as a "gilt". We focus on the overnight gilt repo market as it is the largest maturity segment in terms of daily volumes traded, and of extreme importance for the supply of short-term liquidity in the system.

[2]Gorton & Metrick (2012), using the LIB-OIS spread as a proxy for the state of the repo market for lack of repo market data, provide evidence that repo haircuts on securitized bonds rose during the GFC in a segment of the US interbank bilateral repo market, which they interpret as a run. By contrast, Copeland et al. (2014) conclude that there was no system wide run on the tri-party repo market where margins changed very little. Krishnamurthy et al. (2014) corroborate these findings by reporting that the magnitude of the run on the US tri-party repo market was small in aggregate. Similarly, Mancini et al. (2016) show that the CCP-based euro interbank repo market was resilient during crisis periods. Boissel et al. (2017) however find that repo investors behaved as if the conditional probability of CCP default was substantial.

[3]There are only few studies on the bilateral repo market, based on US data: Gorton & Metrick (2012), who study the bilateral segment but using proxy data, and **?**, who adopts data from a pilot voluntary collection from nine banks.

[4]We characterise as gilt dealers the Gilt-Edged Market Makers (GEMMs), as classified by the UK Debt Management Office (DMO) here: `https://www.dmo.gov.uk/responsibilities/gilt-market/market-participants/`. These are: Barclays, Lloyds, UBS, JP Morgan, RBS, Goldman Sachs, Toronto Dominion Bank, Morgan Stanley, Deutsche Bank, Nomura, BAML, HSBC, Royal Bank of Canada, Citigroup, Banco Santander.

[5]The following sectors appear in the periphery of the network: fund, hedge fund, pension fund, insurer, MMF.

the form of a network. Our key finding is that overall volumes traded with the CCP sector increase significantly compared to normal times during the COVID-19 stress episode. This finding is due to several factors.

First, banks lend more cash through cleared markets during the COVID-19 episode, compared to normal times. At the same time banks lend less bilaterally to gilt dealers, and decrease borrowing from almost all sectors. Indeed, Giese & Haldane (2020) argue that banks were a shock-absorber during the COVID-19 crisis given banks' strong capital and liquidity positions before the crisis struck. A possible explanation for this striking preference of banks to lend via cleared markets rather than bilaterally during the COVID-19 episode is that the cleared segment is more attractive because it is less capital-intensive due to the ability to net trades. Transacting repos through a CCP creates opportunities for banks to net their repo transactions because doing so increases the proportion of trades on which banks face a single counterparty. As a result of these netting benefits, cleared trades reduce the impact of repo market intermediation on banks' balance sheet as reported for regulatory purposes. In line with our findings, Eren et al. (2020) also find evidence of dealers' marked preference for cleared markets in the US dollar funding markets during the COVID-19 crisis.

Second, the CCP sector increases reverse repo trades with gilt dealers, investing the additional cash margin they collected during this period of increased volatility.[6] We find that the average net lending by the CCP sector was double its sample average. Given that the CCP sector has a net zero position on its cleared transactions in the overnight gilt repo market, this large increase in net lending must reflect the very sharp increase in initial margin collected.[7] Thus, while on one hand CCPs margining practice have weighed on the liquidity of clearing members in several markets (Huang & Takáts, 2020), on the other hand CCPs increased their cash investment in the repo market. In particular, we show that the increase in cash lent via the CCP sector goes towards the gilt dealers sector rather than the banks. These results contribute to the literature on CCP-bank nexus, providing new evidence on the nexus during COVID-19.

In the bilateral segment of the overnight market we observe the following changes. Funding decreases towards non-banks in the periphery, only increasing for hedge funds. Since 2018, hedge funds have significantly increased their reliance on short-term funding via repo (Roberts-Sklar & Baines, 2020). During the COVID-19 stress period, their short-term funding needs increased. As described in Bank of England (2020), in mid-March 2020 some highly leveraged hedge funds were forced to unwind positions and faced margin calls, explaining their increased demand for short-term liquidity.

Next, we analyse changes in the spreads during the COVID-19 stress. Overall, they increase significantly during the COVID-19 stress period reflecting the severity of this liquidity stress episode. The highest level of spreads are all happening when the core sectors engage in reverse repo transactions, with a concentration of the higher increase in spreads observed in transactions between core sectors. Furthermore, we find that spreads tend to increase more when sectors in the core lend to non-banks compared to when they borrow from non-banks. As repo spreads for lending from the core to the periphery are on average higher also in normal times, we can conclude that when core sectors trade with non-banks in the periphery they lend at higher rates than borrowing rates. This finding is in line with the theory of He et al. (2020) that dealers during the COVID-19 stress period were pricing in the shadow cost of intermediation on their balance sheet due to regulatory constraints, in particular the leverage ratio[8]. While

[6]See Bank of England (2020) and Huang & Takáts (2020) for a detailed account on the increase in initial margin collected in March 2020.

[7]This finding is corroborated by analysis by the Bank of England (2020), which states that most of the additional cash margin collected during the March 2020 volatility was indeed reinvested in the repo market.

[8]Using a theoretical model, He et al. (2020) explain that post-crisis regulation, in particular the leverage ratio, may have constrained dealers' ability to expand their balance sheets via direct holdings or repo. As a result, dealers demand compensation for the shadow cost of balance sheet expansion via repo, in the form of higher rates, as well as requiring higher yields for direct holdings. They show that spreads between dealers' reverse repo

they provide evidence for this channel based on aggregate data that approximate repo rates at which dealers lend and borrow, we show that this channel holds when looking at more granular data on repo rates from transactions across sectors in the gilt repo market.

We compare these results to another liquidity stress episode: the US repo market turmoil in September 2019. During this stress episode, we saw spikes in the average daily transactions volumes in the overnight gilt repo market of a similar magnitude than during the COVID-19 crisis, pointing to some spillovers to this market. We find similar patterns for changes in sectoral volumes, with transactions in cleared market rising also during the US repo market turmoil stress episode. However, we do not find a similar rise in the spreads, highlighting the exceptionally severe nature of the COVID-19 stress.

Our paper provides useful lessons for policy makers on the functioning of repo markets during recent stress episodes. One of the key findings of our paper is that volumes traded with CCPs have proved resilient. As suggested in CGFS (2017), an important driver of this trend is netting benefits of central clearing, and "one further potential means of increasing netting is to widen participation in CCPs by end users of repos." If non-banks were members of the same CCP as their intermediating dealer, then that dealer would be able to net transactions for the purpose of regulation thus alleviating its balance sheet constraints.

More generally, our paper sheds light on the behaviour of non-banks under stress. This is an area of the financial system in need of further consideration as recommended by Giese & Haldane (2020). The COVID-19 crisis has re-emphasized the importance of non-banks and their potential to generate systemic risk. In a recent speech (Cunliffe, 2020) the Bank of England deputy governor for financial stability John Cunliffe asked: "do we need more resilience, particularly liquidity resilience, in the non-bank parts of the financial system?" While we cannot offer a complete answer, we document important patterns in non-bank behaviour during recent stress episodes in the overnight repo market. In particular, hedge funds increased their borrowing relative to normal times, signalling an increasing reliance on this market for short-term funding in stress. To reduce this demand for liquidity, and support market functioning, central banks could consider broadening liquidity facilities to non-bank participants in times of stress. For example, as noted by **?**, central banks could supply backstop government bond repo finance to a broad array of market participants including non-banks as long as they met certain requirements[9].

A broader implication of our results is that it is crucial to analyse the interplay of different financial sectors when thinking about financial stability. This is already done by several system wide stress testing frameworks, as for instance Aikman et al. (2019) and Farmer et al. (2020). Taking a more system wide perspective provides two different types of insights. First, as already widely understood, it allows for the identification of negative spill-over effects from other sectors and reinforcing feedback loops of losses amplified by actions of different sector. Second, it also allows for the detection of possible risk sharing mechanisms that can be achieved by the pure presence or adjustments in the underlying network structure. Our empirical analysis suggests that this second aspect also needs to be taken into consideration.

The rest of the paper is organized as follows. In Section 1.1 we discuss related literature. In Section 2 we give an overview of the gilt repo market and in particular the overnight segment. Furthermore, we provide background on the COVID-19 stress episode. Section 3 analyses the network structure of the institutional network of the repo market and changes under stress. Section 4 provides details on the different sectors trading in the repo market and their interconnections by introducing the sectoral network underlying the repo market. In Section 5 we

and repo rates, measured as the general collateral finance repo rates and the tri-party repo rates respectively, was highly positive during the COVID-19 crisis in the US repo market, which they use as empirical evidence for this channel.

[9]Further, as pointed out by **?**, such liquidity support measures to deal with financial instability caused by market dysfunction ex-post should be complemented by measures to reduce the scale of inherent vulnerabilities ex-ante, ensuring that non-banks active in financial markets are more resilient to future liquidity shocks.

conduct the main statistical analysis of the sectoral repo network. We analyse how repo market activity, in terms of volumes and spreads between sectors, changes during the COVID-19 crisis. We then compare these results to an earlier crisis in the US repo market in 2019. Section 6 concludes.

1.1 Related literature

Our results contribute to the existing literature in several ways. First, we contribute to the literature that empirically analyses repo markets during stress periods. Our uniquely granular dataset covers almost the entire universe of transactions in the gilt repo market, including different segments, market participants and their repo trades volumes, rates and haircuts. As a result, we are, to the best of our knowledge, the first to jointly analyse the bilateral and the cleared segment of the repo market and to quantify empirically inter-sectoral changes in repo market activity in these segments during times of stress. Indeed, previous empirical studies using detailed repo market data either focused on the US tri-party market (Copeland et al., 2014; Krishnamurthy et al., 2014) or on the CCP-based euro interbank repo market (Mancini et al., 2016; Boissel et al., 2017). We add to this literature by looking at the bilateral segment, as well as cleared, of the gilt repo market in stress, which is one of the world's core repo markets[10]. Furthermore, we are the first study to document the dynamics of the COVID-19 "dash for cash" in March 2020 in the repo market using granular transaction level data.

Second, we contribute to the literature that empirically analyses dealer intermediation in the repo market in the post-crisis regulatory framework. Bicu-Lieb et al. (2020) find that gilt repo liquidity worsened during the period when the UK leverage ratio policy was announced, and Kotidis & Van Horen (2018) show that it is indeed dealers subject to a more binding leverage ratio that have reduced liquidity supply after a tightening of reporting requirements in January 2017. Noss & Patel (2019) find that the gilt repo market is less able to accommodate an increase in demand for intermediation after the introduction of the UK leverage ratio. While these studies focus on the effects of a regulatory change on dealers' repo intermediation in normal times, we study dealers' intermediation during stress episode. We find that dealers intermediate less in the bilateral segment and trade even more in the cleared segment, compared to normal times. The appeal of the cleared segment stems from netting benefits and indicates that constraints to intermediation are even more binding in stress.

Finally, given the scarcity of data on repo markets (Gorton et al., 2020), we provide a unique insight for the theoretical debates on repo market structure (Martin et al., 2014), central clearing (Duffie & Zhu, 2011; Capponi et al., 2015; Duffie et al., 2015) and the modelling of its network dynamics (Luu et al., 2020; Ghamami et al., 2020+). Regarding the latter, while most of the existing approaches consider models of a dynamic contagion process on a static network[11], we provide empirical evidence that networks do change in times of stress. These results suggest that using static networks and assuming continuous roll over of repo contracts is perhaps not suited for models that aim to capture contagion risk in collateralized debt markets. This points to the importance of developing dynamic network models to assess financial stability.[12]

[10]The gilt repo market is the fourth largest repo market, in terms of amounts outstanding, following US, Europe and Japan (CGFS, 2017)

[11]See for example Gai et al. (2011), Hüser (2015), Glasserman & Young (2016) for overviews.

[12]Recently there have been extensions to multiple maturity and dynamic settings, see for instance Kusnetsov & Veraart (2019) and the references therein.

2 The overnight gilt repo market

2.1 Definitions and scope

Throughout this paper we focus on the overnight gilt repo market, i.e., the secured sterling money market where the underlying security is a UK government bond denominated in British pounds - a gilt. The party who is selling the gilt is effectively borrowing cash and the party who is buying the gilt is effectively lending cash. In this context one refers to the party selling the security and hence borrowing cash as doing the *repo*, whereas the other party who buys the gilt and therefore lends cash is doing the *reverse repo*. The *repo spreads* will refer to the difference between the interest rate of the trade, i.e., the *repo rate*, and the Bank of England's Bank Rate at the time of the trade in question.

A repurchase agreement (repo) is an agreement to sell an underlying security (called *collateral*) together with an agreement to buy the security back at a later date (the maturity) in the future for an agreed (typically higher) price. Suppose party 1 is doing the repo and borrows $V > 0$ in cash (in sterling) from party 2 by selling a gilt with market value $g > 0$. Typically, $V \leq g$. We will refer to V as the *volume* of the transaction. At the maturity date T, party 1 repays $V(1 + R)$, where $R \in \mathbb{R}$ and usually $R \in [0, \infty)$. Then, R is referred to as the *repo rate*.

A repo transaction at overnight maturity is subject to the following timeline. On the trade date t party 1 is doing the repo and borrows $V > 0$ in cash (in sterling) from party 2 by selling a gilt to party 1. This transaction will be settled on the same day, meaning cash will be exchanged on the same day t. At maturity date, which is the next day $T = t + 1$, party 1 repays $V(1 + R)$ to party 2.

2.2 The data

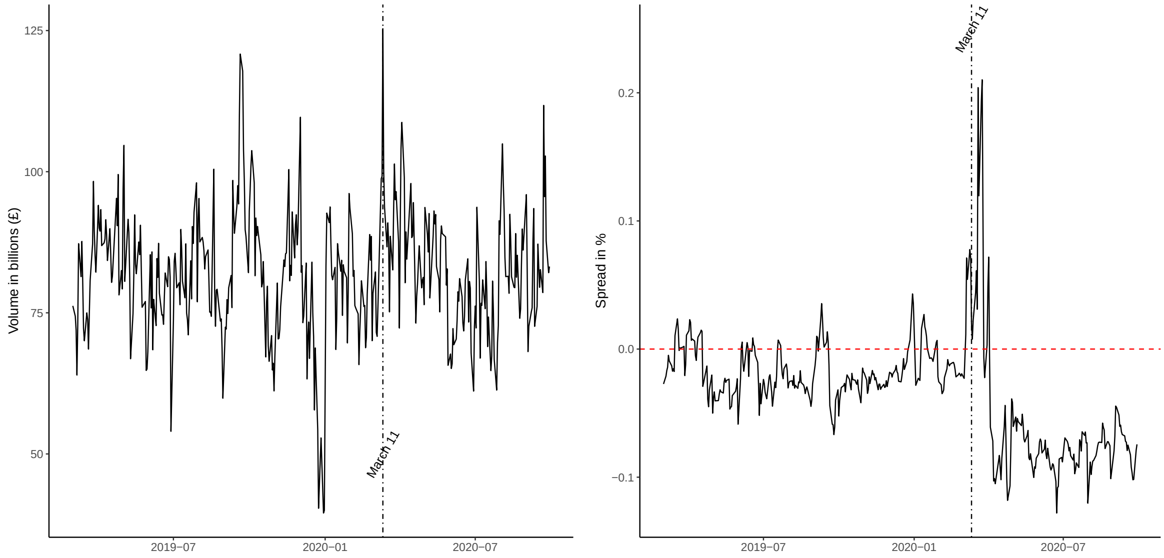
The Bank of England Sterling Money Market data represent a unique laboratory to explore the structure of the gilt repo market and analyse its key dynamics in normal times and stress episodes. The data captures repurchase and reverse repurchase agreements, where borrowing/lending of sterling cash is secured against UK government-issued securities. Our data sample spans from the 1 March 2019 until 31 October 2020.

Specifically the Bank requires institutions that have significant activity, measured using their annual turnover, in the gilt repo market to report their transactions. The reporting population is chosen to capture all institutions whose activity falls within the top 95% of activity at either overnight or up to one-year maturity. Some activity in the gilt repo market is not captured, specifically where neither party is a bank or major broker dealer.[13] However, according to Harris & Taylor (2018), this type of activity is currently not thought to be material.

Total transaction volumes in the aggregate gilt repo market are around £180 trillion on average in our data sample. Transaction volumes are highly concentrated at shorter maturities. Almost 50% of those are at overnight maturity and 35% at maturities greater than overnight but less than two weeks. The overnight segment is the most active, and of extreme importance for the supply of short-term liquidity in the system. Indeed, the overnight segment of the repo market can be considered special, because market participants get the cash on the same day they enter the trade, as opposed to all the other maturities, where settlement happens on the day after entering the trade at the earliest. During a severe liquidity stress, disruptions in the overnight market might mean not having cash available to meet payment deadlines or margins calls on the same day which can have serious financial stability implications. Both the

[13] We constructed the data set that we analysed by taking all the reported repo (i.e., borrowing) transactions. We then added all the reported reverse repo (lending) transactions where the counterparty is not a reporting institution. Transactions where neither party is a reporting institutions are not in the data set. However, we do capture more data than if one only takes the perspective of the reporting institutions. For this reason our amount outstanding are higher than what previously reported in Harris & Taylor (2018).

overnight market's size and its relevance in liquidity stress are reasons why we focus on this maturity segment in this paper.



(a) Average volume in overnight market (in £ billions).

(b) Average volume weighted repo spread in overnight market (in percent).

Figure 1: Times series of key variables: repo volumes and spreads.

Average daily transaction volumes in the overnight gilt repo market are £80 billion, with wide fluctuations around key reporting dates at quarter- and year-ends, as shown in Figure 1(a). Around these dates we see large variations in the number of daily transactions in the overnight market, which is on average close to 1600. These reporting dates are well-known period of window dressing for banks and dealers, as documented in Kotidis & Van Horen (2018) for the UK repo market.

The cost of repo transactions is typically measured in terms of the (volume-weighted) repo spread. In our analysis, the (volume-weighted) repo spread is the overnight (volume-weighted) repo rate minus the Bank Rate. The Bank Rate is set by the Monetary Policy Committee at the Bank of England and it is also sometimes referred to as the Bank of England's base rate. Figure 1(b) shows the evolution of the average volume weighted repo spreads in the overnight market. Overall, there is a wide fluctuation in repo spreads in the overnight gilt market. Spreads tend to show large negative spikes at year-end and quarter-end, in line with the movements observed in the volumes.

Trades in the repo market can be settled in three ways: bilaterally, tri-party and through a central counterparty (CCP). On average, 36% of daily overnight gilt repo volumes are settled through a central counterparty and only 2% is settled tri-party, implying the majority of volumes are settled bilaterally.[14]

2.3 The COVID-19 crisis

In order to study how the repo market behaves under stress we focus our analysis on the COVID-19 pandemic, and in particular on the period of March 2020 where volatility in financial markets and liquidity stress was particularly pronounced. Specifically, in the remainder of the paper we refer to the COVID-19 stress episode as the period between 3^{rd} and 23^{rd} of March 2020.

[14] By contrast, the euro interbank repo market is mainly CCP-based (Mancini et al., 2016). In the US around half of the dealer-client market is settled tri-party via a clearing bank. The other half is settled bilaterally (?).

The episode has been described as an extreme "dash for cash" by the Bank of England (2020). As in financial markets asset prices adjusted very sharply, margin calls on derivative exposures went up sharply as well. The need to post additional margin generated strong liquidity pressure, as noted by Cunliffe (2020), adding to the already large demand for liquidity in the system. As reported in Bank of England (2020), as demand for safer assets rose, yields on advanced-economy government bonds fell between February and mid-March 2020, as investors sought to de-risk, and expectations of lower short-term interest rates were priced in. However, as reported in Bank of England (2020), "in mid-March even safe, typically highly liquid assets, such as government bonds, came under forced selling pressure and saw little demand, as markets became characterised by exceptionally high demand for cash and near-cash short-dated assets." Overnight repo rates rose sharply, as shown in Figure 1(b), interpreted as a "particularly serious sign of dysfunction" (Hauser, 2020). As explained in the Bank of England (2020), "the cost of repo borrowing increased as demand increased, and dealers' ability and willingness to intermediate was constrained." Figure 1(a) also shows that repo volumes were increasing sharply up to March 11, as demand for liquidity built up.

Several policy actions helped to ease pressure on money market rates. On March 11, the Bank of England reduced the Bank Rate by 50 basis points to 0.25%. On March 19, the Bank of England decided to buy gilts in large size, coupled with similar policy actions by other central banks, which helped stabilise broader markets. On 24 March the Bank activated its Contingent Term Repo Facility (CTRF), committing to lend unlimited amounts of sterling at close to Bank Rate against a broad range of collateral. These operations, together with the passing of the March quarter end, contributed to bringing repo rates back to more normal levels.

3 Financial institutions trading in the repo market

3.1 Activity at institution level

The daily average number of institutions active is 58, but a total of 156 institutions traded at least once in the overnight repo market between March 2019 and October 2020. In the full sample, the average daily repo transaction volume by active institution is £0.6 billion, the average trade size £0.05 billion and the average number of daily repo transactions by institution is 13. During the COVID-19 stress episode 125 institutions were active, trading at least once. The market experienced an increase in activity: the average daily repo transaction volume by active institution rose to £2 billion, the average trade size to £0.06 billion and the average number of daily repo transactions by institution rose to 36.

3.2 The institutional network

In order to study the structure of the market, we will now look at the network created by the institutions trading in this market. A network approach will allow us to better visualise and analyse the trading relationships between each financial institution and how they change in times of stress.

We denote by $\mathcal{T} = \{t_0, t_1, \ldots, t_T\}$ the set of all discrete time points (i.e., days) considered in our analysis of the overnight repo market. We have $t_0 = 1$ March 2019, $t_T = 31$ October 2020 and $T + 1 = 400$.

Definition 3.1 (Institutional network of volumes)**.**

1. *The institutional network of volumes consists of a set of nodes denoted by* $\mathcal{N}^{(I)} = \{1, \ldots, N^{(I)}\}$*,* $N^{(I)} = 156$*, representing the institutions engaging in the overnight gilt repo market. For every day* $t \in \mathcal{T}$*, we denote by* $V_{ij}^{(I)}(t)$*,* $i, j \in \mathcal{N}^{(I)}$*, the total notional amount of cash that node* i *lends to node* j *in an overnight repo transaction at time* t*. If* $V_{ij}^{(I)}(t) > 0$*, we refer*

to the corresponding pair of nodes (i,j) as an edge *and to $V_{ij}^{(I)}(t)$ as the* weight *or the* volume*.*

2. *We denote by $V^{(I)}(t) = (V_{ij}^{(I)}(t))_{i,j\in\mathcal{N}^{(I)}} \in [0,\infty)^{N^{(I)}\times N^{(I)}}$ the matrix of total notional cash lent at time t in the institutional network.*
3. *We denote by $A^{(I)}(t) = (A_{ij}^{(I)}(t))_{i,j\in\mathcal{N}^{(I)}} \in \{0,1\}^{N^{(I)}\times N^{(I)}}$ the adjacency matrix at time t that corresponds to the network of cash lent in the institutional network, i.e.,*

$$A_{ij}^{(I)}(t) = \begin{cases} 1, & \text{if } V_{ij}^{(I)}(t) > 0, \\ 0, & \text{else.} \end{cases} \tag{1}$$

Hence, if a pair of nodes (i,j) engages in several overnight repo agreements on the same day but at different times during the day, $V_{ij}^{(I)}(t)$ represents the sum of the corresponding notional amounts of cash, i.e., the total amount of cash traded on day t. In the following, we will illustrate the main general features of the institutional network of volumes.

First, we consider the transaction volumes between each pair of institutions averaged over the whole sample period. These can be represented by the matrix $\bar{V}^{(I)} = (\bar{V}_{ij}^{(I)})_{i,j\in\mathcal{N}^{(I)}} \in [0,\infty)^{N^{(I)}\times N^{(I)}}$, where

$$\bar{V}_{ij}^{(I)} = \frac{\sum_{t\in\mathcal{T}} V_{ij}^{(I)}(t)}{T+1}. \tag{2}$$

Figure 2(a) shows the heatmap of $\bar{V}^{(I)}$, i.e., each coloured cell represents the average transaction volume between two institutions in the overnight gilt repo market over the whole sample. The rows show the average volumes lent in the overnight gilt repo market over the whole sample for each institution. The columns show the average volumes borrowed in the overnight gilt repo market over the whole sample for each institution. The institutions are ordered by the sum of average repo and reverse transactions, with the institution with the largest average volumes traded located in the lower left corner. The coloured scale represents the average transaction volume of each institution for the whole sample. The darker the red, the larger the average transaction volume of that institution.

We see that the overnight gilt repo market exhibits a core-periphery structure. Craig & Von Peter (2014) define this structure as: core institutions borrow from, and lend to, at least one institution in the periphery and they intermediate between institutions in the periphery. Periphery institutions, on the other hand, may only lend, or borrow from the core (or might not participate in the market when they have no deficits or risks to cover at that time). Periphery institutions do not lend to each other. The overnight repo market we analyse fits this definition.

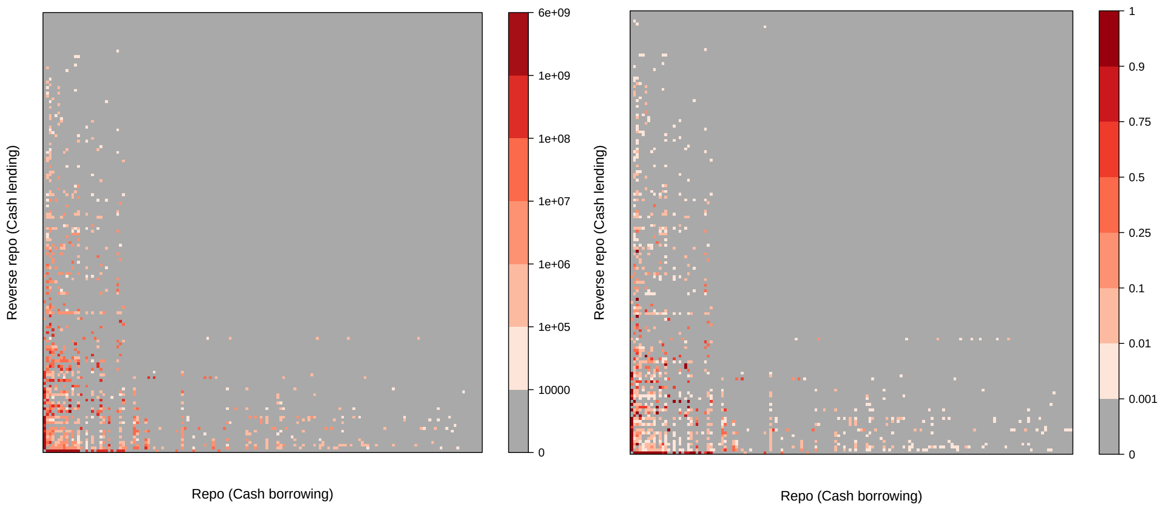
In the lower left corner of Figure 2(a) we can identify a cluster, as well as more scattered elements in the leftmost columns and the last few rows of the heatmap. The cluster in the lower left corner is the core of institutions which transact repo amongst themselves as well as with the periphery, which are the more scattered elements extending top and right of the cluster. It is interesting to note that the cluster in the lower left corner is darker, hence trading higher volumes, whereas the colours tend to fade to white as we move towards the top left and bottom right corners. Furthermore, in line with the definition of a periphery in a financial network, there is a large empty grey area in the middle/top right corner which indicates that there is no trading between periphery institutions. Repo is only intermediated through the core to the periphery. In the overnight gilt repo market, only banks and gilt dealers trade among each other and therefore only these types of institutions are in the core, while non-banks constitute the periphery. The central counterparty is a sector with a special role, and we therefore classify it as neither core nor periphery. We will provide more detail on the different sectors and the sectoral structure in Section 4.

Second, we investigate how likely it is in our sample that a given pair of institutions trade with each other. We define the matrix $\bar{A}^{(I)} = (\bar{A}^{(I)}_{ij})_{i,j\in\mathcal{N}^{(I)}} \in [0,1]^{\mathcal{N}^{(I)}\times\mathcal{N}^{(I)}}$, where

$$\bar{A}^{(I)}_{ij} = \frac{\sum_{t\in\mathcal{T}} A^{(I)}_{ij}(t)}{T+1}. \tag{3}$$

Hence, $\bar{A}^{(I)}_{ij}$ represents the empirical probability that institution i lends institution j cash in a repo transaction on average daily. Figure 2(b) shows a heatmap of $\bar{A}^{(I)}$. For ease of comparison, the institutions are ordered in the same way as in Figure 2(a). Each cell represents the probability that two institutions trade with each other on any given day in the whole sample. The darker the red of the cell, the higher is the likelihood that these two institutions trade on any given day. The darkest red ranges from 0.9 to 1 and means that two institutions trade between 90 and 100 percent of days in our sample, implying an almost continuous daily roll-over of trades.

Figure 2(b) shows that overall the empirical transaction probabilities corresponding to the lower left corner, i.e., the core, are still rather low for the majority of institution pairs. This implies, that there is no daily roll-over of overnight repo (not even in the core) for the majority of core institution pairs for the whole sample. This is consistent with earlier findings in Langfield et al. (2014) who find that in "repo markets, the big players are not strongly connected to each other". However, note that there are few dark red cells predominantly in the core, whereas there are none in the periphery. Thus, for some select pairs in the core, we do observe almost daily roll-over for the whole period.



(a) Average transaction volumes for each pair ($\bar{V}^{(I)}$). (b) Empirical probability for a transaction between each pair ($\bar{A}^{(I)}$).

Figure 2: Descriptive statistics of the linkages in the institutional network.

Figure 3 provides further evidence that there are indeed some highly connected nodes, but that the majority of nodes only has a small number of connections. In particular, it shows the empirical survival functions (i.e., $1 - F(d)$ where F is the empirical cumulative distribution function of the average in- and outdegree[15] and $d \in \{1, \ldots, N^{(I)} - 1\}$) on a log-scale. In the

[15] The degree of a node (representing individual institutions in this case) is the number of links (representing transactions in this case) the node has to other nodes. The in-degree is the number of incoming links (borrowing transactions) and the outdegree is the number of outgoing links (lending transactions). The average in- and

figure, the circles corresponds to the outdegrees and the triangles to the indegrees. The x-axis represents the possible in- or outdegrees, i.e., the number of incoming our outgoing connections that a node in the institutional network has on average (where the average is taken over the daily trading days). Since the institutional network has $N^{(I)} = 156$ nodes, it is clear that an upper bound on the possible in- or outdegree is $N^{(I)} - 1$. This is because an institution does not engage in repo transactions with itself. As described earlier, nodes in the core can in principle have repo or reverse repo agreements with all other nodes. But in this market, nodes in the periphery do not have repo or reverse repo agreements with other nodes in the periphery but only with banks or gilt dealers in the core. This substantially lowers the possible number of connections for peripheral nodes. For the y-axis we consider all values in $[0, 1]$ since we are interested in a probability, i.e., the empirical survival function. The empirical survival function (indicated by the label 1-CDF) represents the probability that a node in our sample has a strictly larger (in- or out-) degree than the number indicated on the $x-$axis. For example, when we consider the (in- or out-) degree of 5 on the x-axis, we see in Figure 3, that the probability that a node has an in- or outdegree larger than 5 is roughly 0.2, i.e., rather small. This means, that around 80% of nodes have less than 5 incoming edges and less than 5 outgoing edges. If we choose 50 on the x-axis, then the probability that a node has an (in- or out-) degree larger than 50 is 0. We find that the maximum number of incoming or outgoing edges is around 50. Overall, we see that the majority of nodes only has a small number of connections, but there is a small number of highly connected nodes.[16]

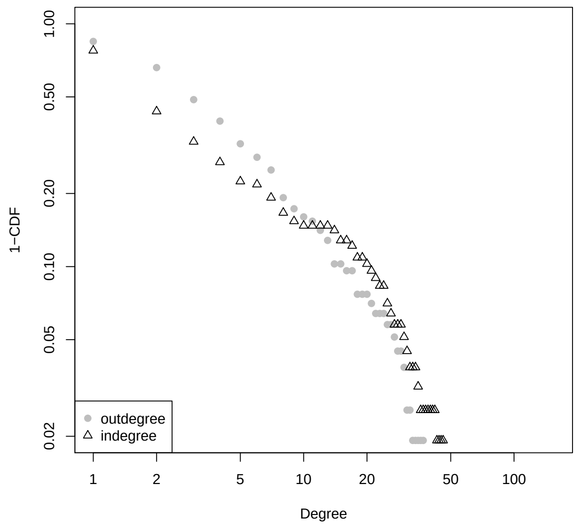


Figure 3: Empirical survival function of the average in- and outdegrees for the institutional network of volumes.

3.2.1 Changes under stress

We will now investigate whether the repo network becomes more connected during the COVID-19 stress and if so if more connections are caused by establishing trading relationships exclusively for this stress period or by relying on trading relationships that have been used prior to the COVID-19 crisis or afterwards.

outdegree is the average over the daily in- and outdegrees for all the institutions in our sample.

[16]Note that Figure 3 represents a log-log plot of the empirical survival function, and we see that particularly the tails of the distribution appear linear, indicating that one could successfully fit a power law distribution to the tails of the degree distribution.

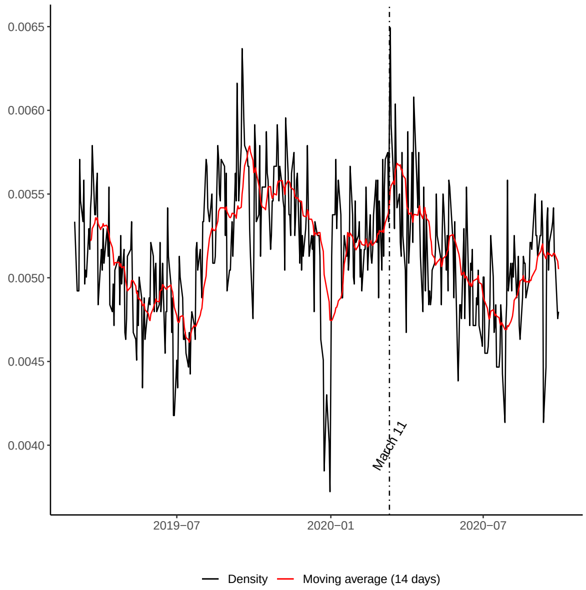


Figure 4: Time series of density of institutional network.

To do so, we consider the density of the network of all institutions over time in Figure 4. The density of a network is the ratio of existing links between nodes out of all the possible links that could exist between the nodes in the network. Mathematically, the time-t density at time t for the institutional network is defined as $\frac{1}{N^{(I)}(N^{(I)}-1)}\sum_{i=1}^{N^{(I)}}\sum_{j=1}^{N^{(I)}}A_{ij}^{(I)}$.

We highlight two key observations for the overall behaviour of the density over the sample period: First, the average density for the whole sample is very low: 0.005. This means that on average, 0.5% of the possible edges are present in the network, which confirms our findings from Figure 2 that the network is very sparse. Indeed, the average degree is around 1, meaning that, on average, institutions will only trade with one other institution on any given day in the sample.
Second, we see clear dips at year ends and some smaller dips at quarter ends which is in line with the window dressing effects at quarter ends discussed earlier.

We notice that there are two specific periods in which the density spikes, i.e., the network becomes more connected. The highest peak occurs at the height of the COVID-19 crisis in March 2020. The second highest spike can be observed in September 2019 which coincides with the turmoil in the US repo market.

Next we investigate how this higher level of connection is achieved during the COVID-19 crisis. In particular, we investigate whether this increase is due to new trading relationships exclusively formed for this crisis period. We find that there were 755 unique directed trade pairs in the overnight gilt repo market from the beginning of our sample up to the beginning of the COVID-19 crisis (March 1 2019 - March 8 2020) and 287 unique directed trade pairs during the COVID-19 stress. Of those, 9 were new bilateral trading relationships during the COVID-19 crisis relative to the 755 trading relationships that exist in our sample before COVID-19.[17] This clearly shows that the vast majority of market participants relied on existing trading relationships to secure liquidity in this market. Further, we compare the number of days a trade pair made at least one transaction during the stress to our full sample. While few trade relationships are active almost exclusively during this stress episode, many trading pairs that traded during the COVID-19 crisis did trade also before and/or after the COVID-19 crisis. Overall, the evidence shows market participants' reliance on established trading relationships

[17] Most of the 9 new trading pairs are between a core and periphery sector. Out of those 9, 4 trading pairs transact again at least once after the crisis, whereas 5 do not transact again.

during stress.

4 Financial sectors trading in the repo market

4.1 Sectoral activity in the overnight gilt repo market

Repo markets bring together two types of end users that interact through intermediaries (CGFS, 2017). The first type includes those sectors that provide collateral in return for cash, such as funds, pension funds, hedge funds and insurance companies. The second type of end users is those sectors lending cash while receiving collateral, such as money market funds (MMFs), hedge funds[18] or corporate treasurers. Figure 5 illustrates the structure of the sectoral overnight gilt repo network, breaking it down into 10 sectors.[19] High-level observations are that gilt dealers and banks are the only sectors that have trade relationships with all the other sectors, they are the intermediaries connecting all the sectors in the repo market. These are the only nodes in the sectoral network that have self-loops - meaning that gilt dealers have repo/reverse repo agreements with gilt dealers and banks have repo/reverse repo agreements with banks. Gilt dealers and banks are the only two sectors that are clearing members and hence are the only ones interacting with the CCP sector. The non-banks only trade bilaterally with the gilt dealers and the banks, but not amongst each other as shown in the network visualization. We will describe the role of each of these sectors in more detail below, starting with the intermediaries.

[18] Hedge funds are active on both sides of the market.

[19] For our sectoral descriptive statistics, we do not display the non-financial sector and the government sector (e.g. central banks and treasury departments) as these are well below £1 billion of daily average repo and reverse repo volumes.

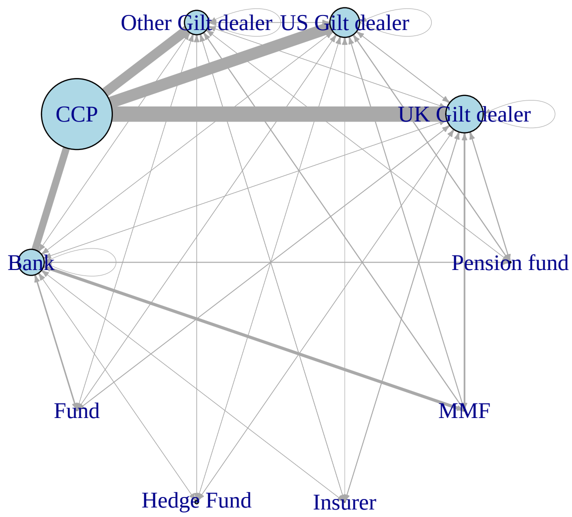


Figure 5: Sectoral network.

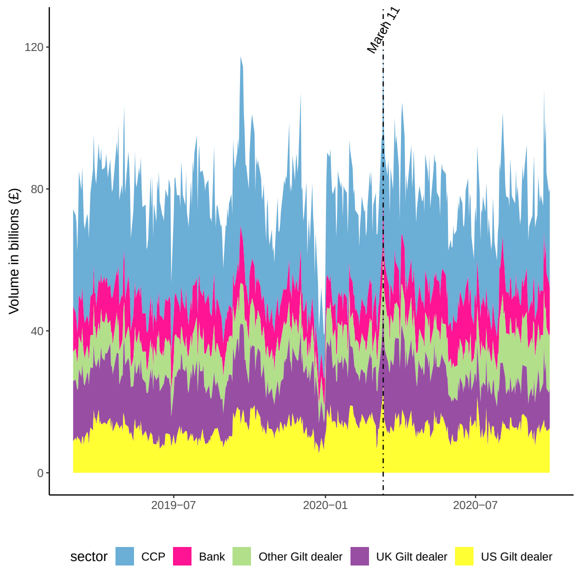
Note: The directed edges represent the average amount of cash borrowed by one sector from another sector over the whole sample range, meaning that the size of the link is proportional to that amount. The arrow head identifies the sector that is borrowing the cash (doing the repo). The node sizes are proportional to the average amount that was borrowed by that sector over the whole sample range.

	Full sample				COVID-19 crisis			
Sector	#	Av. lend	Av. borrow	Av. net lend	#	Av. lend	Av. borrow	Av. net lend
Bank	26	3.16	11.02	-7.87	15	6.77	9.95	-3.18
CCP	6	34.30	29.56	4.74	4	40.26	32.62	7.64
Fund	18	2.40	0.04	2.36	12	2.73	0.01	2.72
Hedge Fund	28	1.23	1.39	-0.15	14	1.32	2.59	-1.28
Insurer	4	1.81	0.10	1.71	4	2.33	0.08	2.25
MMF	9	5.58	0.16	5.42	5	4.39	0.00	4.39
Pension fund	15	2.57	0.58	1.99	8	3.39	0.35	3.04
UK Gilt dealer	6	13.97	15.87	-1.91	5	15.94	19.68	-3.74
US Gilt dealer	5	8.67	12.52	-3.85	5	8.62	14.85	-6.23
Other Gilt dealer	7	7.59	10.33	-2.74	7	6.96	12.96	-6.00

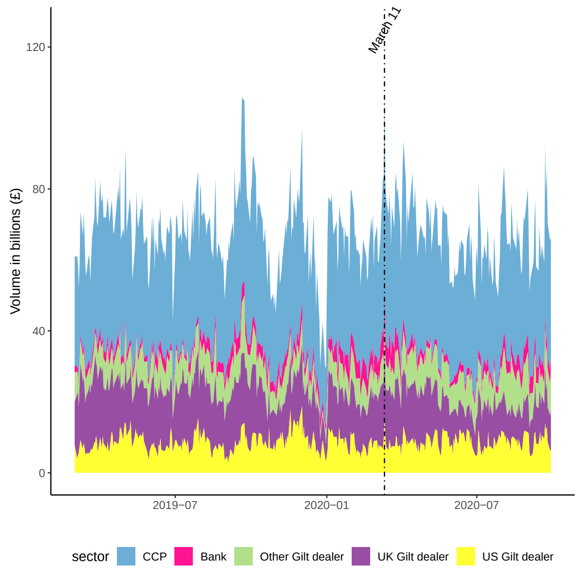
Table 1: Overview of daily average volumes for the sectors trading in the overnight gilt repo market for the full sample and the COVID-19 crisis, volumes are expressed in £billion.

4.1.1 Gilt dealers and banks

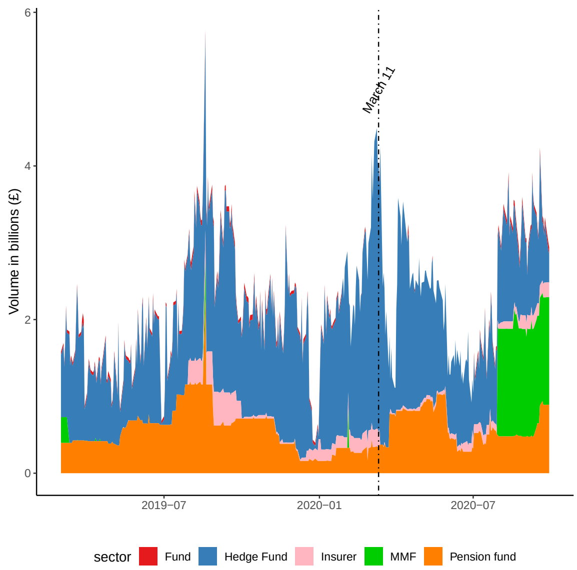
Gilt dealers are the banks that are Gilt-Edged Market Makers (GEMMs) as classified by the UK Debt Management Office (DMO), which means they are the primary dealers in the UK sterling government bond market. We divide the gilt dealers by the location of their headquarters into



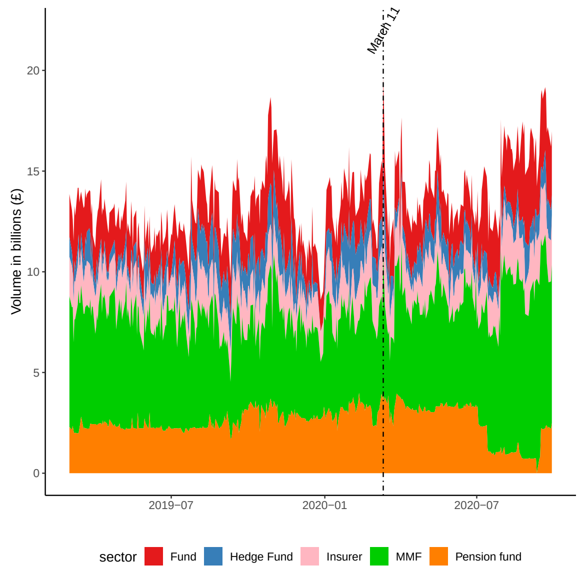
(a) Total volumes borrowed by core sectors and CCP (in £ billions).



(b) Total volumes lent by sectors and CCP (in £ billions).



(c) Total volumes borrowed by periphery sectors (in £ billions).



(d) Total volumes lent by periphery sectors (in £ billions).

Figure 6: Total volume borrowed (repo) and lent (reverse repo) by different sectors.

	Full sample		COVID-19 crisis	
Sector	Repo spread	Reverse repo spread	Repo spread	Reverse repo spread
Bank	-0.04	-0.01	0.02	0.14
CCP	-0.04	-0.03	0.08	0.08
Fund	-0.02	-0.03	0.13	0.04
Hedge Fund	0.01	-0.08	0.13	0.03
Insurer	0.00	-0.02	0.06	0.07
MMF	-0.07	-0.03	-	0.03
Pension fund	0.13	-0.04	0.32	0.04
UK Gilt dealer	-0.04	-0.03	0.07	0.08
US Gilt dealer	-0.02	-0.06	0.07	0.08
Other Gilt dealer	-0.02	-0.05	0.11	0.06

Table 2: Overview of the average volume weighted spread by sectors trading in the overnight gilt repo market for the whole sample and during the COVID-19 crisis, expressed in percent. The sector is a borrower for the repo spread and a lender for the reverse repo spread.

three groups: the UK gilt dealers, the US gilt dealers and other gilt dealers, where the latter are neither headquartered in the UK nor the US.

For dealers, repo lending to clients is a core part of their business and a large part of their repo borrowing is to finance that lending (the so-called 'matched book') CGFS (2017). Most of the rest of their repo borrowing is to finance inventories for market-making and to source short-term funding. The introduction of the leverage requirement has affected dealers' behaviour in the repo market and has incentivised a more pro-active management of their balance sheets, including by limiting repo activity[20] or increasing its price.[21]

Table 1 illustrates that all the gilt dealer sectors are net borrowers, with the UK gilt dealers being the closest to a matched book whereas the US and other gilt dealers tend to be larger net borrowers on average. While all three gilt dealer sectors increased their net borrowing during the COVID-19 crisis, the ranking in terms of size of net borrowing position remains the same as in the full sample. The UK gilt dealer sector has the lower net borrowing position, followed by the other gilt dealers and then the US gilt dealers. Their lending and borrowing positions are also quite stable over time throughout the sample, see Figures 6(a) and 6(b), aside from a large drop at year-end.

Table 2 provides an overview of the average volume weighted spread by sectors. On average in the full sample, the spread for both repo and reverse repo transactions faced by the gilt dealers is negative. However, during the COVID-19 crisis, the gilt dealers all faced positive spreads on both their repo and reverse repo transactions.

Banks use the repo market to earn a return on their liquid assets and to source short-term funding. We group into the banking sector all the banks that are not GEMMs. Overall, banks are the largest net borrowers on average in the overnight gilt repo market (see Table 1). However, during the COVID-19 crisis their net borrowing decreases, as banks more than double their average lending and decrease their borrowing. As highlighted by Giese & Haldane (2020), banks went into the COVID-19 crisis with sizeable buffers and contrary to the Great Financial Crisis were not at the centre of the financial turmoil.

4.1.2 Central counterparties

The CCP sector has a special role in the repo market. In particular, the CCPs do not actively provide liquidity. They do two things. First, they clear trades between their members, which

[20] For evidence on this trend we refer to Kotidis & Van Horen (2018), Noss & Patel (2019) and Ranaldo et al. (2019).

[21] He et al. (2020) provides evidence that in the US Treasury repo market dealers price in the balance sheet cost of the leverage ratio constraint during COVID-19 crisis.

in this market are the gilt dealers and the banks. Second, they lend cash collected from margin payments as reverse repo to gilt dealers and banks. These are indeed the only sectors trading with them in the overnight gilt repo market (see Figure 5). We cannot distinguish in the data whether a *reverse* repo by a CCP is traded as part of their clearing business or their cash management. In those cases we will refer to these as trades with *the CCP sector*. A repo transaction however should only be performed as part of their clearing business and we will refer to these as trades via *cleared markets*. As shown in Ranaldo et al. (2019), CCPs' incentives to invest cash in the repo market have been strengthened by EMIR which requires CCPs to continually acquire safe assets, thus expanding the supply of cash in repo markets. As Table 1 shows, the CCP sector is one of the largest net lenders. Since the CCP sector should have a net zero position on their clearing business, the net lending is likely to reflect the average daily investment of cash margin into the overnight gilt repo market. Their net lending position increases substantially during the COVID-19 crisis, partially reflecting an increase in cash margin investment as we will discuss in more details in Section 5.2.2.

The average repo spreads reported in Table 2 for the CCP sector reflects repo rates decided by their clearing members, i.e. banks and gilt dealers. For the reverse repo transactions, the spreads reflect a combination of price setting by the clearing members and the CCP itself investing margin. Similarly to the other sectors, repo spreads for transactions with the CCP sector are negative on average in the full sample, but become positive during COVID-19. However, these spreads remain among the lowest (see Table 2).

4.1.3 Non-banks

We will now describe how non-banking sectors at the periphery of the market use its bilateral segment to trade with banks and gilt dealers. MMFs, insurers, pension funds and funds[22] are net lenders in the overnight gilt repo market.[23] These sectors are indeed cash rich and use the overnight repo market to place cash safely short-term. MMFs are used by a wide variety of investors[24] as part of their cash management strategies as alternatives or complements to bank deposits. MMFs invest in short-term money market instruments and are key providers of short-term funding to financial institutions (particularly banks), corporates and governments. In the overnight gilt repo market they are the largest net lenders, with significant lending volumes which are quite stable over time throughout the sample[25] as reported in Figure 6(d).

Hedge funds are instead net borrowers on average, as reported in Table 1, although only marginally as their repo borrowing is largely matched by cash lending in aggregate. Hedge funds can be active on both sides of the repo market. They use the repo market both to borrow cash, by placing securities as collateral with dealers, and to borrow securities from dealers, offering cash in return. Hedge funds can also use repo to increase their leverage,[26] which magnifies both their potential gains and their potential losses. During COVID-19 we observe an increase in borrowing from hedge funds[27], significantly more than lending. Furthermore, while they borrow at positive spreads throughout the sample, repo spreads they face increase significantly during this stress episode.

[22]Funds are the residual category for non-banks in this paper and are all the asset managers that are not MMFs, insurers, hedge funds or pension funds.

[23]However, pension funds are net borrowers in the longer maturity segments - borrowing large amounts between 1 month and 1 year maturity - to buy more gilts as part of their liability driven investment (LDI) strategies as reported in Bank of England (2018).

[24]Investors in MMFs include non-financial corporations, public authorities, insurers, pension funds, investment funds and households.

[25]Lending volumes only increase towards the end of the sample in the second half of 2020. At the same time their borrowing, which is almost zero for most of the sample, also increases significantly.

[26]They borrow cash, secured against gilts, in order to buy other assets and thereby obtain leverage.

[27]Similar evidence has been provided for hedge funds use of the US repo market by Schrimpf et al. (2020).

4.2 The sectoral repo network

Similarly to Section 3.2 we now use a network approach to further analyze repo transactions across sectors. We define the sectoral network of volumes in the overnight repo market.

Definition 4.1 (Sectoral network of volumes)**.**

1. *The* sectoral network of volumes *consists of a set of nodes denoted by* $\mathcal{N}^{(S)} = \{1, \dots, N^{(S)}\}$, $N^{(S)} = 10$, *representing the sectors engaging in the overnight gilt repo market. For every day* $t \in \mathcal{T}$, *we denote by* $V_{ij}^{(S)}(t)$, $i, j \in \mathcal{N}^{(S)}$, *the total notional amount of cash that node* i *lends to node* j *in an overnight repo transaction at time* t. *If* $V_{ij}^{(S)}(t) > 0$, *we refer to the corresponding pair of nodes* (i, j) *as an* edge *and to* $V_{ij}^{(S)}(t)$ *as the* weight.

2. *We denote by* $V^{(S)}(t) = (V_{ij}^{(S)}(t))_{i,j \in \mathcal{N}^{(S)}} \in [0, \infty)^{N^{(S)} \times N^{(S)}}$ *the matrix of total notional cash lent at time* t *in the sectoral network.*

3. *We denote by* $A^{(S)}(t) = (A_{ij}^{(S)}(t))_{i,j \in \mathcal{N}^{(S)}} \in \{0, 1\}^{N^{(S)} \times N^{(S)}}$ *the adjacency matrix at time* t *that corresponds to the sectoral network of cash lent, i.e.,*

$$A_{ij}^{(S)}(t) = \begin{cases} 1, & \text{if } V_{ij}^{(S)}(t) > 0, \\ 0, & \text{else.} \end{cases} \tag{4}$$

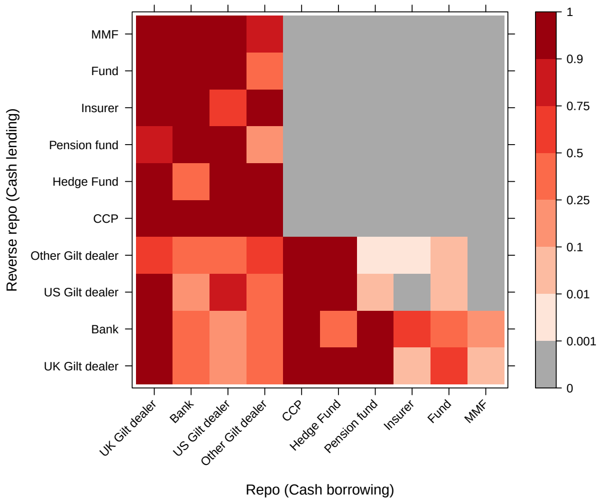


Figure 7: Transaction likelihood in the sectoral network.

Next, we will investigate how regularly the sectors trade with each other. We define the matrix $\bar{A}^{(S)} = (\bar{A}_{ij}^{(S)})_{i,j \in \mathcal{N}^{(S)}} \in [0, 1]^{N^{(S)} \times N^{(S)}}$, where

$$\bar{A}_{ij}^{(S)} = \frac{\sum_{t \in \mathcal{T}} A_{ij}^{(S)}(t)}{T + 1}. \tag{5}$$

Here $\bar{A}_{ij}^{(S)}$ represents the empirically observed probability that sector i lends sector j cash in a repo transaction on a given day. Figure 7[28] shows a heatmap of this matrix $\bar{A}^{(S)}$. Each

[28]This is the sector-level version of Figure 2(b).

cell represents the probability that two sectors trade with each other on any given day in the whole sample. The darker the red of the cell, the higher is the likelihood that these two sectors trade on any given day. The darkest red ranges from 0.9 to 1 and means that two sectors trade between 90 and 100 percent of days in our sample, implying an almost continuous daily roll-over of trades.

Not surprisingly, the CCP sector is active on both sides (repo and reverse repo) with all their possible trading partners (all types of gilt dealers and banks) essentially daily. Interestingly, we see that within the core only UK gilt dealer borrow on a daily basis from US and UK gilt dealers and banks. All other core sectors display no daily roll over of transactions within the core.

Lending from the periphery sectors (MMF, fund, insurer, pension fund and hedge fund) to the core sectors, UK and US gilt dealers and banks, also occurs with high probabilities, almost daily. Periphery sectors lend slightly less frequently to other gilt dealers. Hedge funds and pension funds are the sectors in the periphery who borrow most often. In terms of periphery sectors borrowing from the core, we observe that hedge funds borrow (almost) daily from all types of gilt dealers and slightly less frequently from banks. Pension funds mainly borrow daily from UK gilt dealers and banks. The other periphery sectors (insurer, fund and MMF) borrow much less frequently.

Finally, note the grey square in the top right which, as already observed in Figure 5, reflects the fact that the CCP sector and the non-banks and non-gilt dealers do not trade with each other or amongst each other in our data set.

5 How do volumes and spreads change under stress?

We now statistically analyse changes in repo market activity between sectors during the COVID-19 stress episode. We compare the results with the market behaviour in normal times, and with another liquidity stress episode: the US repo market turmoil in September 2019. In both stress periods, we saw spikes in the average daily transactions volumes in the overnight gilt repo market of a similar magnitude, see Figure 1(a). The spreads, however, only spiked very sharply during the COVID-19 stress, see Figure 1(b).

Definition 5.1 (Time windows for stress episodes). *We will denote by $\mathcal{T}^{CS\ COVID\text{-}19} \subset \mathcal{T}$ the dates associated with the COVID-19 "dash-for-cash", i.e., 03 March 2020 - 23 March 2020; and by $\mathcal{T}^{CS\ US} \subset \mathcal{T}$ the dates associated with the US repo market turmoil, i.e., 03 September 2019 - 17 September 2019.*

5.1 Model

We fit a linear model to analyse any significant change in repo volumes and spreads in the overnight gilt repo market between different sectors during stress periods. The methodology developed, described below in more details, represents a simple and innovative approach to statistically characterize changes in market activity between different sectors and to visualize the results in the form of a network.

First, we consider the sectoral network of volumes introduced in Definition 4.1. Hence, we adopt as daily observations the notional amount of cash lent from a sector i to sector j at time t in an overnight repo agreement, denoted by $Y_{ijt} := V_{ij}^{(S)}(t)$, where $i, j \in \{1, \ldots, N^{(S)}\}$ and $t \in \tilde{\mathcal{T}}$. Here $\tilde{\mathcal{T}}$ denotes the set of time points $\mathcal{T}$ in which the quarter ends were removed from the time series.[29] In our data we have $N^{(S)} = 10$ and $\tilde{T} = |\tilde{\mathcal{T}}| = 381$. Hence, we have

[29] We removed the quarter ends from the time series by removing the two first days and the two last days in each quarter, as quarter ends exhibit high fluctuations in volumes driven by regulatory accounting which are not related to the stress episodes we are interested in. This has been done in other empirical research using repo market data, see e.g. Mancini et al. (2016).

$10^2 \cdot 381 = 38100$ observations to fit the model.[30] We then consider the following linear model with only categorical explanatory variables

$$\begin{aligned} Y_{ijt} = & \beta_{ij}^{(\text{Normal, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \\ & + \beta_{ij}^{(\text{CS2, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{CS US}}\}} \\ & + \beta_{ij}^{(\text{CS3, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{CS COVID-19}}\}} + \epsilon_{ijt}, \end{aligned} \tag{6}$$

where $\mathbb{I}_{\{.\}}$ denotes the indicator and it is 1 if the condition in $\{\}$ is satisfied and 0 otherwise. Furthermore, the ϵ_{ijt} are the error terms. Hence, this model consists of $3(N^{(S)})^2 = 300$ model parameters that can be represented as three $(N^{(S)} \times N^{(S)})$-dimensional matrices:

- $\beta^{(\text{Normal, Vol})} = (\beta_{ij}^{(\text{Normal, Vol})})_{i,j \in \{1,\ldots,N^{(S)}\}} \in \mathbb{R}^{N^{(S)} \times N^{(S)}}$ represent the average daily volume that is being traded between the sector pairs outside the two stress periods, i.e., $\beta_{ij}^{(\text{Normal, Vol})}$ is the average daily volume lent from sector i to sector j for $t \in \tilde{\mathcal{T}} \setminus (\mathcal{T}^{\text{CS US}} \cup \mathcal{T}^{\text{CS COVID-19}})$.

- $\beta^{(\text{CS3, Vol})} = (\beta_{ij}^{(\text{CS3, Vol})})_{i,j \in \{1,\ldots,N^{(S)}\}} \in \mathbb{R}^{N^{(S)} \times N^{(S)}}$ represents the change in the average daily volume between the sector pairs during the time period of the COVID-19 stress. More specifically, $\beta_{ij}^{(\text{CS3, Vol})}$ is the change in average daily volume lent from sector i to sector j during the period of 3-23 of March 2020. Hence, the average daily volume lent from sector i to sector j at a time $t \in \mathcal{T}^{\text{CS COVID-19}}$ would be given by the model as $\beta_{ij}^{(\text{Normal, Vol})} + \beta_{ij}^{(\text{CS3, Vol})}$.

- $\beta^{(\text{CS2, Vol})}$ can be defined and interpreted along the lines of the definitions and interpretations of $\beta^{(\text{CS3, Vol})}$ but represent the US stress episode.

Second, we consider the sectoral network of repo spreads. The linear model for the repo spreads is the same as (6), with the only difference that the observations are no longer the volumes, but the repo spreads. More specifically, the observations Y_{ijt} are the volume weighted repo spreads associated with the repo transaction with non-zero volume $V_{ij}^{(S)}(t)$. We will denote the corresponding three matrices of parameters that we estimate by $\beta^{(\text{Normal, Spread})}$, $\beta^{(\text{CS2, Spread})}$ and $\beta^{(\text{CS3, Spread})}$.

Before we discuss the results we describe how we estimate the significance of our model parameters. We use a bootstrapping approach to determine whether the different effects that we observed during the two stress episodes are significant. Our time series consists of $\tilde{T}$ data points representing days. We consider a simple block bootstrap for time series. We split these $\tilde{T}$ days into blocks of length $b = 10$. Hence, we have $N_B = \lfloor \tilde{T}/b \rfloor$ blocks of length b and one block of length $\tilde{T} - N_B b$. Then we sample a new time series as follows. We draw with replacement N_B blocks of length b and one block of length $\tilde{T} - N_B b$ and piece those blocks together as a new time series. We then fit our linear model (6) to the new time series. We repeat this process $R = 1000$ times and therefore obtain R estimates of our model parameter. The heatmaps in Figures 8 and 9 all have numbers in the coloured fields taking values between 0 and 100. These represent the percentile of the parameter estimate corresponding to the observed time series relative to the empirical cumulative distribution generated by the bootstrap. If these numbers are very high (i.e., 99 or 100) this indicates that these parameter estimates are in the right tail of the bootstrap distribution and therefore highly significant. Similarly, very low numbers such as 0 or 1 indicate that these parameter estimates are in the left tail of the bootstrap distribution and also highly significant.

[30] If we do not observe a repo/reverse repo transaction between a pair of sectors on a given day, we set the corresponding observation for volumes to be equal to zero. For repo spreads, the number of observations is slightly lower, since they only exists for actual trades, and not for the trades that we create with a volume of zero.

5.2 Results

We present the parameter estimates of the model in normal times and during the COVID-19 stress for volumes (i.e., $\beta^{(\text{Normal, Vol})}$, $\beta^{(\text{CS3, Vol})}$) and for spreads (i.e., $\beta^{(\text{Normal, Spread})}$, $\beta^{(\text{CS3, Spread})}$) in Figure 8. The results for the US stress episode are reported in Figure 9. The colour legend of the heatmaps represents the value of those estimates in pound sterling for volumes and in percentage for spreads.

5.2.1 Normal times

Figure 8(a) reports the model estimates for the average volume for the whole sample excluding the two stress periods. First, we observe that in normal times the largest volumes are traded between the CCP sector and gilt dealers and banks. In particular, UK gilt dealers are borrowing and lending large volumes in the centrally cleared segment of the market. In addition to clearing trades, CCPs can also do reverse repo as proprietary trading for cash margin management. This supply of cash from CCPs can then go to gilt dealers and banks.

Within the core, banks are net borrowers (see Table 1) and they borrow the largest quantities from the CCP sector, funds and MMFs. Gilt dealers are also net borrowers. They borrow the largest amounts from the CCP sector. UK gilt dealers additionally borrow large amounts from MMFs.

In the periphery, hedge funds are the only net borrowers, albeit only by a small margin. They borrow and lend rather similar volumes to and from all gilt dealers and banks. As explained in Section 4.2 hedge funds are active in both sides of the market. All other institutions in the periphery are net lenders.

Figure 8(c) shows that repo spreads in normal times are small and very close to zero (see also the times series of spreads in Figure 1(b)). Overall, there is very little variation in normal times across sectors. However, spreads on reverse repos from the core to the periphery sectors tend to be positive and higher on average, relative to the rest.

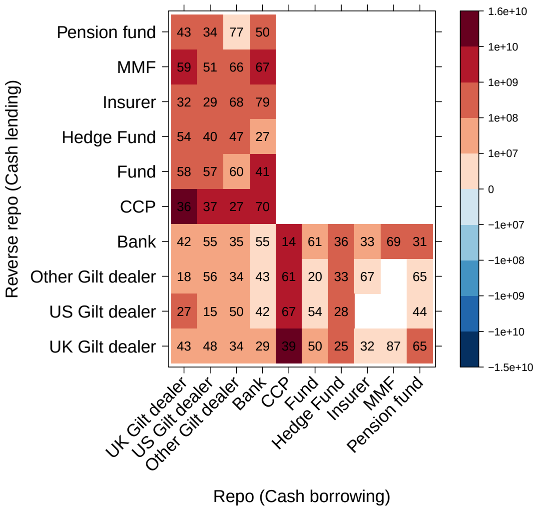
5.2.2 COVID-19 stress period - repo volumes

Our key finding is that overall volumes traded with the CCP sector increase significantly compared to normal times during the COVID-19 stress episode. This finding, which can be seen in Figure 8(b), is due to several factors.

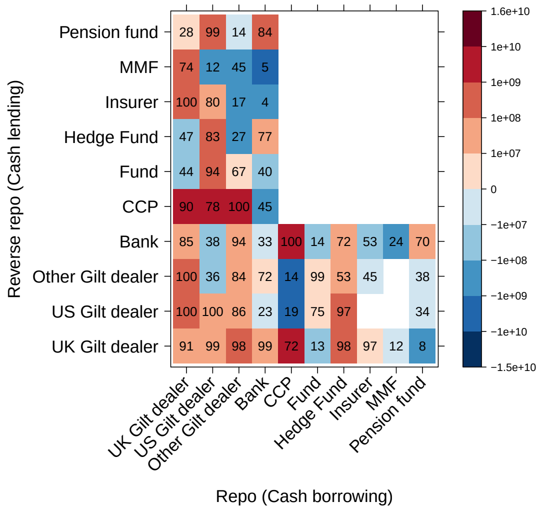
First, banks lend more cash through cleared markets during the COVID-19 episode, compared to normal times. At the same time banks lend less bilaterally to gilt dealers, and decrease borrowing from almost all sectors.[31] While banks are still net borrowers (see Table 1), their net borrowing positions decrease markedly relative to normal times and some of their lending positions are in the highest percentiles of the distribution in Figure 8(b). Indeed, Giese & Haldane (2020) argue that banks were a shock-absorber during the COVID-19 crisis given banks' strong capital and liquidity positions before the crisis struck. The additional liquidity provided by banks via cleared markets ends up with sectors that are clearing members. We can narrow this down even further given that gilt dealers borrow higher volumes from the CCP sector, whereas banks do not. Hence the increased repo lending of banks into cleared markets goes to gilt dealers.

A possible explanation for this striking preference of banks to lend via cleared markets rather than bilaterally during the COVID-19 episode is that the cleared segment is more attractive because it is less capital-intensive due to the ability to net trades. Transacting repos through a CCP creates opportunities for banks to net their repo transactions because doing so increases the proportion of trades on which banks face a single counterparty. As a result of these netting benefits, cleared trades reduce the impact of repo market intermediation on bank's balance

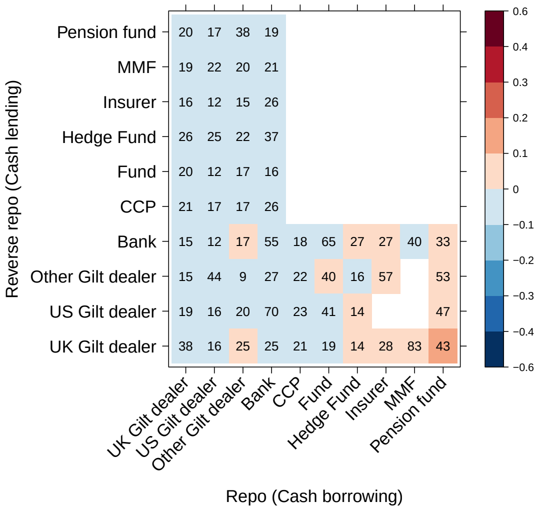
[31] The only exceptions are hedge funds and pension funds.



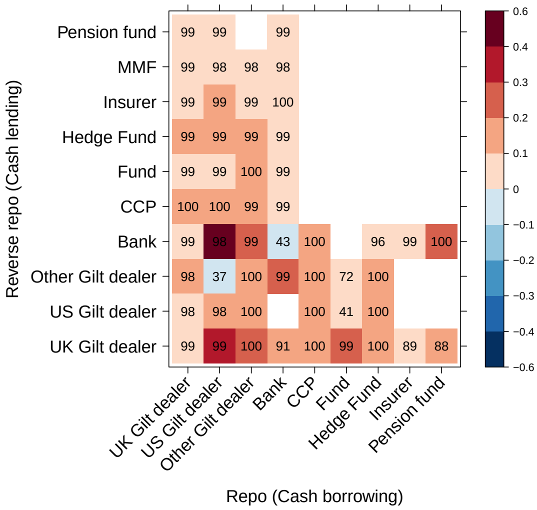
(a) Normal times: Estimate of $\beta^{(\text{Normal, Vol})}$.



(b) COVID: Estimate of $\beta^{(\text{CS3, Vol})}$.



(c) Normal times: Estimate of $\beta^{(\text{Normal, Spread})}$.



(d) COVID: Estimate of $\beta^{(\text{CS3, Spread})}$.

Figure 8: Linear model for volumes (first row) and for spreads (second row): Parameter estimates (represented by colours) and their percentiles in the distribution generated by bootstrap (represented by numbers). The heatmaps in the first row represent the average volume in normal times in Figure 8(a), and the changes in the average volume during the COVID-19 stress period in Figure 8(b). The heatmaps in the second row represent the average repo spreads in normal times in Figure 8(c) and the changes in the average repo spreads during the COVID-19 stress period in Figure 8(d). All estimates for the spreads are given in percent.

sheet as reported for regulatory purposes.[32] Balance sheet netting has been identified as an important driver of repo market intermediation by CGFS (2017). In line with our findings, Eren et al. (2020) also find evidence of dealers' marked preference for cleared markets in the US dollar funding markets during the COVID-19 crisis.[33] Another possible reason to prefer trading with CCPs during the "dash for cash" are that the settlement of trades might have been perceived as easier and less risky than trading bilaterally.

Second, the CCP sector increases reverse repo trades with gilt dealers. Besides banks lending more into cleared markets, another source of this increase in cash supply are the CCPs investing the additional cash margin they collected during this period of increased volatility.[34] As explained in Section 4.2, we cannot separate reverse repo transactions that are part of the clearing business from reinvesting cash margin. However, we do know that most of the additional cash margin collected during the March 2020 volatility was indeed reinvested in the repo market (Bank of England, 2020).[35] We also know that the average net lending by the CCP sector during COVID-19 was almost double the sample average and the largest compared to the other sectors during that stress (see Table 1). Given that the CCP sector should have a net zero position on its clearing in the overnight gilt repo market, this large increase in net lending must reflect the very sharp increase in initial margin collected[36]. It is impossible to say whether the additional cash from initial margin would have ended up in the repo market in any case, since the main intermediaries in this market were among those firms strongly hit by the increase in margin calls (Bank of England, 2020; Huang & Takáts, 2020). Nonetheless, our analysis shows how the shift in liquid assets from dealers to CCPs, due to large margin calls, affects volumes traded between sectors in the overnight gilt repo market.

Third, UK gilt dealers also lend higher volumes via cleared markets. By contrast, US and other gilt dealers decrease their lending through cleared markets and seem to use the gilt repo market more to acquire sterling cash via cleared markets. Overall, both lending and borrowing via cleared markets increases significantly during the COVID-19 stress period.

In the bilateral segment of the overnight market we observe the following changes. First, in terms of lending from the core to the periphery we find that the core lends more to hedge funds. Since 2018, hedge funds have significantly increased their reliance on short-term funding via repo (Roberts-Sklar & Baines, 2020). During the COVID-19 stress period, their short-term funding needs increased, as is visible in Figure 8(b). As described in Bank of England (2020), in mid-March 2020 some highly leveraged hedge funds were forced to unwind positions and faced margin calls, explaining their increased demand for short-term liquidity.

Second, regarding bilateral lending from the periphery to the core, selected non-banks (e.g. pension funds, hedge funds, and insurers) invest more cash into the overnight segment of the repo market than in normal times, mainly lending more to gilt dealers.

Finally, we consider the response of MMFs to the COVID-19 crisis. As discussed before MMFs are generally net-lenders of cash in the repo market. As can be seen from Figure 8(a)

[32] This is important as dealer banks have recently been reaching limits to further balance sheet expansion, as reported in Schrimpf et al. (2020), not least due to large amounts of securities they had been taking into their inventories.

[33] For a discussion on recent regulatory-driven incentives to trade via a CCP to increase nettable transactions to avoid certain capital charges in the UK we refer to Noss & Patel (2019).

[34] See Bank of England (2020) and Huang & Takáts (2020) for a detailed account on the increase in initial margin collected in March 2020.

[35] Bank of England (2020) finds that relative to the average level over January and February, UK CCPs' initial margin requirements had grown by around £58 billion in March — a 31% increase — with a daily peak increase of around £10 billion. Around half of the additional initial margin was provided in cash, most of which the CCPs reinvested in the repo market.

[36] Note that under the EMIR legislation and Commission Delegated Regulation (EU) No 153/2013, European Commission (2013), CCPs are incentivised to place their cash from margins in the overnight repo market. In particular article 47 states that "Where cash is maintained overnight [...] then not less than 95% of such cash, calculated over an average period of one calendar month, shall be deposited through arrangements that ensure the collateralization of the cash with highly liquid financial instruments."

their lending is particularly large to UK gilt dealers and banks in normal times. During the "dash for cash" in mid-March 2020 MMFs experience liquidity issues, due to large outflows as reported in Hauser (2020). Indeed, MMFs had to pay cash out to redeeming investors, and hence had less cash available overall to lend. Nonetheless, we find that MMFs remain net lenders in the overnight gilt repo market during the COVID-19 stress episode but with a slightly lower net lending position. In particular, they do not borrow at all while they are still lending to sectors in the core. They increase lending to UK gilt dealers, while decreasing lending towards the other sectors in the core. [37]

Given the overall liquidity problems faced by MMFs, we analyse MMF lending behaviour in the gilt repo market at longer maturities and find that lending in the overnight segment reflects a shortening of maturities.[38] That is, during the "dash for cash" period we observe a preference of MMFs for the overnight segment. A possible reason for this is that cash placed overnight is still available in time to meet redemption requests the next day.[39] Eren et al. (2020) found a similar dynamic for US prime MMFs during the COVID-19 stress. In order to preserve the liquidity of their portfolios, US prime MMFs shed longer-maturity assets and rolled them over into shorter maturities, which improved the liquidity and decreased the average maturity of their holdings.

5.2.3 COVID-19 stress period - repo spreads

Next, we analyse changes in the spreads during the COVID-19 stress. Overall, they increase significantly during the COVID-19 stress period reflecting the severity of this liquidity stress episode (see also Figure 1(b) for the time series of the spreads and Table 2 for the sectoral averages.).

The highest level of spreads are all happening when the core sectors engage in reverse repo transactions, with a concentration of the higher spreads observed in transactions between core sectors. UK gilt dealers' spreads on reverse repo are consistently between the 98 or 100 percentiles and between 10 and 30 basis points higher than in normal times. The highest average increase is when banks are lending to US gilt dealers, which are associated with a decrease in volumes relative to normal times (located at the 38th percentile of the distribution, as reported in Figure 8(b)) which can be taken as a sign of strains in the market.

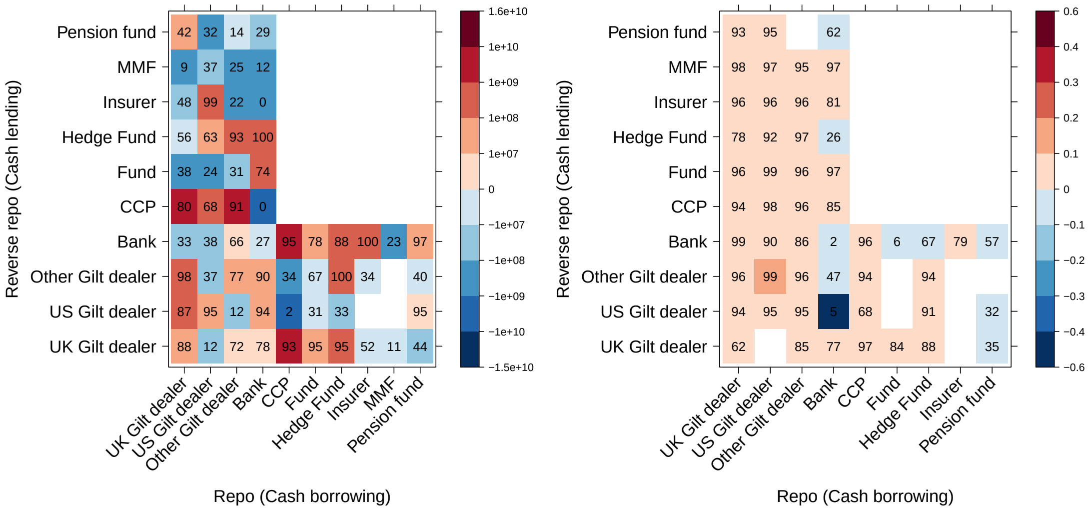
Furthermore, we find that spreads increase more when sectors in the core lend to non-banks compared to when they borrow from non-banks, with the exceptions of hedge funds. As repo spreads for lending from the core to the periphery are on average higher also in normal times, we can conclude that when core sectors trade with non-banks in the periphery they lend at higher rates than borrowing rates. This finding is in line with the theory of He et al. (2020) that dealers during the COVID-19 stress period were pricing in the shadow cost of intermediation on their balance sheet due to regulatory constraints, in particular the leverage ratio, when lending to leveraged investors, such as hedge funds, and borrowing from cash-rich investors, such as MMFs. While they provide evidence for this channel based on aggregate data that approximate repo rates at which dealers lend and borrow, we show that this channel holds when looking at more granular data on repo rates from transactions across sectors in the gilt repo market.

[37] Note that since MMFs do not do repo transactions (but only reverse repo transactions) during the COVID-19 stress episode they do not occur on the x-axis in Figure 8(d) which reports the change in spreads during this time. They do, however, occur on the x-axis for Figure 8(b) which reports the changes in volumes, since no trading during this time corresponds to zero volumes and hence a negative volume change for this stress episode.

[38] In particular, MMF lending to UK gilt dealers at maturities longer than overnight completely stopped during the COVID-19 episode. For the US and other gilt dealers, MMF lending at maturities of one month and more stopped too. In addition, in the case of other gilt dealers, MMF lending at short maturities (2 days to less than 2 weeks) also completely stopped. For US gilt dealers, MMF lending at short maturities drastically declined.

[39] Similar observations have been made in Bank of England (2020), stating that "outflows from MMFs have since reversed but concerns about the potential for further redemptions at short notice remain, so MMFs have sought to keep investments short-dated or backed by government securities".

5.3 Comparison to the stress in the US repo market in 2019



(a) US turmoil: Estimate of $\beta^{(\text{CS2, Vol})}$.

(b) US turmoil: Estimate of $\beta^{(\text{CS2, Spread})}$.

Figure 9: Parameter estimates (represented by colours) and their percentiles in the distribution generated by bootstrap (represented by numbers) for the US repo stress period: change in the average volume (Figure 9(a)) and change in the average spread (Figure 9(b)). The estimates for the spreads are given in percent.

We now analyse changes in trading activities during another liquidity stress period: the period of stress in the US repo market in 2019. On 17th September 2019, the secured overnight funding rate (SOFR) - the new repo market-based US dollar overnight reference rate[40] - more than doubled[41] reaching 3.15% above the interest paid on reserves (IOR)[42]. The short term causes of the market turmoil have been attributed to very high temporary liquidity demand to satisfy a due date for US corporate taxes and a large settlement of US Treasury securities (Bank of England, 2019). Several structural changes in financial markets have potentially compounded the strains caused by the temporary factors. [43]

While this stress episode did not originate in the UK, we are interested in understanding the potential spillovers to the gilt repo market. Figure 1(a) shows that aggregate gilt repo volumes in the overnight market spiked on September 17, indicating a large temporary increase in borrowing volumes. Indeed, US gilt dealers more than doubled their borrowing in the gilt repo market during that time compared to normal times. The Federal Reserve launched a number of operations, aimed at returning the market to conditions consistent with its target monetary policy range. These policy measures "stabilised the market [...] and helped to limit spillovers to broader market conditions", as reported in Bank of England (2019).

[40] For more details see `https://apps.newyorkfed.org/markets/autorates/SOFR`

[41] Repo rates typically fluctuate in an intra-day range of 10 basis points, or at most 20 basis points as reported by Avalos et al. (2019). On the 17th September SOFR intra-day range jumped to about 700 basis points, as reported in (Avalos et al., 2019).

[42] For more details on the IOR, see `https://www.federalreserve.gov/monetarypolicy/reqresbalances.htm`.

[43] The first change is that the Fed has been reducing the size of its balance sheet, which implies a reduction of cash reserves banks hold at the Fed. Ultimately this implies that banks have less cash directly available to cover short-term funding stress. A second change is the increased demand for funding from leveraged financial institutions such as hedge funds via Treasury repos (Avalos et al., 2019). A third change is due to liquidity and leverage regulations which might constrain banks' ability to lend out large amounts of cash for example in the repo market. In line with this explanation, Kotidis & Van Horen (2018) have shown that dealers subject to a more binding leverage ratio have reduced liquidity supply in the UK repo market after a tightening of reporting requirements in January 2017.

Now, we compare the changes observed during the COVID-19 stress to the US repo stress period in 2019. Figure 9 shows the parameter estimates for the changes to the average volume $\beta^{(\text{CS2, Vol})}$ and the changes in the spreads $\beta^{(\text{CS2, Spread})}$ during the US repo stress.

Comparing Figures 9(a) and 8(b) we observe that there are common patterns between the US repo stress and the COVID-19 stress when considering changes in volumes. In both stress episodes, we find a significant increase in volumes traded in the cleared segment of the market. As discussed before, this reflects a preference for dealers and banks to transact in the cleared rather than the bilateral segment of the market.

Figure 9(a) illustrates that overall US gilt dealers significantly increased borrowing and decreased lending, more than doubling their net borrowing position compared to normal times. A significant increase in liquidity comes via the CCP sector to the US gilt dealers. In the core of the market, UK gilt dealers and banks significantly increased their lending through cleared markets, which can then be lent out to US gilt dealers via the CCP. Focusing on periphery to core lending, US gilt dealers' additional liquidity needs were met by increased lending from insurers and hedge funds.

When looking at the changes in the spread during stress periods, however, in Figures 9(b) and Figures 8(d), we see that there is a distinct difference between the US repo stress period and the COVID-19 stress period. While spreads increased in both stress periods, the increase during the COVID-19 stress was significantly higher.[44] Comparing Figures 9(b) and 8(d), we can see that the COVID-19 episode displays the highest increase in the level of spreads relative to the other case studies and that most percentiles are at 100. As a result, repo spreads reached elevated levels up to 60 basis points. This was indeed the most stressful period for the gilt repo market, but also for the financial system more generally. The US repo turmoil also features high percentiles (most are between 90 and 99), suggesting that rates increased too, although without reaching more than 20 basis points.

It is important to notice that US gilt dealers did not face extreme increases in the cost of borrowing additional liquidity in the repo market. When their borrowing from non-banks and the CCP increases, repo spreads increase but only up to 0.1 percentage points more than in normal times. Only when US gilt dealers borrow more from other gilt dealers they face a significant increase in spreads between 0.1 and 0.2 percentage points. When US gilt dealers lend to banks they do so at a substantially lower spread than in normal times which is significant at the 5 percentile.

In conclusion, during the US repo crisis in September 2019 we see that the spillover effects to the gilt repo market were visible but limited, as also explained in (Bank of England, 2019, p. 65). The COVID-19 crisis, however, exposed substantial strains on liquidity in the repo market as evidenced by the significant increase in spreads during this time.

6 Conclusions

The repo market has shown signs of strain in recent stress episodes. In particular, overnight repo rates in the gilt repo market spiked in the "dash-for-cash" episode during the COVID-19 crisis. Similar large increase in repo rates have been observed in the US repo market during the turmoil in mid-September 2019, although with limited spillovers in the gilt repo market. Given the critical importance of the repo market as a source of financing for the financial system, its behaviour in recent stress episodes deserves proper investigation. To this end we have applied network analysis to a unique granular data set on transactions in the overnight gilt repo market, including both the cleared and bilateral segments.

Having data on the bilateral segment enabled us to shed light on the non-banking sectors behaviour in the repo market under stress, which is a key contribution of our paper. The non-

[44] Missing cells compared to normal times (white squares or no row/column for the sector) mean that there was no trading during that specific stress episode.

banking sectors are an increasingly important part of the financial system and their behaviour a crucial driver of its performance under stress. Our analysis reveals that funding to non-banks decreased during the COVID-19 stress episode, with the exception of hedge funds. Hedge funds are net borrowers throughout our sample, but particularly during the COVID-19 stress episode, they satisfy short-term funding needs by increasing their use of the overnight gilt repo market. Furthermore, we show that when banks and gilt dealers lend to non-banks they do so at higher rates than when they borrow from these sectors. This result holds both in stress and normal times.

Another key result of the paper is that volumes traded by the CCP sector increase during stress episodes relative to normal times. This result reflects a preference of the core sectors, i.e. gilt dealers and the banking sector, to intermediate volumes through the cleared segment of the market due to netting benefits. Further, the CCP sector increased their investment of cash margins collected during times of stress in the repo market via reverse repos. The increased importance of the CCP sector in the repo market, a trend already highlighted by CGFS (2017), deserves close monitoring and raises some important questions for policy makers. As we show, CCPs can increase funding during stress. Hence, policymakers could consider further broadening access to CCPs beyond banks and dealers to repo end users, such as non-bank financial institutions. However, increasing concentration on CCPs has its own risks[45] which could create unintended consequences for the financial system. Understanding the full implications of the role of CCPs in the repo market, and its impact on financial stability, is an important question for future research.

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[45]For example, CCP liquidity needs are inherently procyclical. Further, CCPs are only allowed to access central banks' liquidity support under limited restrictions.

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