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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. We find that during this crisis the repo network becomes more connected, with most institutions relying on previously used counterparties. There are however important changes in the repo volumes and spreads during the stress relative to normal times. There is a significant increase in volumes traded with the central counterparties (CCPs) sector. At the same time non-banks, except hedge funds, decrease borrowing and face higher spreads in the bilateral segment. Overall, this evidence reflects a preference for dealers and banks to transact in the centrally cleared rather than the bilateral segment. Our results can inform the policy debate around the behaviour of banks and non-banks in recent liquidity stress and on widening participation in CCPs by non-banks.

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 and Metrick, 2012; Copeland et al., 2014; Krishnamurthy et al., 2014; Mancini et al., 2016; Boissel et al., 2017),[2] pointing to the

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[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 and 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.

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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 centrally 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 centrally cleared segment of the repo market, capturing a broad set of banks and non-bank institutions.[4] We offer a unique window into the current structure and functioning of the market, both in normal and stress times.

The overnight gilt repo market network has a core–periphery structure. Only banks and gilt dealers[5] trade among each other and therefore only they can in principle be part of the core. They are the key intermediaries and can transact among each other as well as with all the other sectors active in the market. Non-banking sectors are located in the periphery,[6] 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.

First, we investigate the repo market network at institutional level. We find that the network is sparse. Furthermore, there is no daily roll-over of overnight repo – not even in the core – and most trading relationships are not persistent over time. However, during the COVID-19 crisis, the repo network experiences an increase in activity and becomes more connected, with most institutions relying on previously used – even though not frequently – counterparties.

We then investigate the repo market network aggregating institutions at sectoral level. We are interested in analysing any significant change in repo volumes and spreads in the overnight gilt repo market during stress periods in the bilateral and centrally cleared segments. To this end 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 the form of a network.

We document significant changes of the sectoral repo network, in terms of volumes and spreads, during the COVID-19 stress relative to normal times. First, overall volumes traded with the CCP sector increase significantly. This is because banks and UK gilt dealers increase their lending via the centrally cleared segment and the CCP sector increases reverse repo trades with gilt dealers, reflecting investments of the additional cash margin they collected during this period of increased volatility. Second, in the periphery, all non-banks decrease their borrowing and increase their lending with two notable exceptions: hedge funds, that significantly increase their borrowing, and MMFs that reduce lending. Third, repo spreads increase the most in the bilateral segment of the market, where banks and gilt dealers lend at significantly higher rates than borrowing from non-banks. This is not the case for trades with the CCP sector. Overall, these results point to a preference of gilt dealers and the banking sector to intermediate volumes through the centrally cleared segment of the market.

In the following, we will discuss these key findings in more detail. Our first key result 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. Banks and UK gilt dealers lend more cash through the centrally cleared segment during the COVID-19 episode, compared to normal times. At the same time banks lend less bilaterally to gilt dealers, and decrease borrowing from most sectors markedly decreasing their aggregate net borrowing positions. Indeed, Giese and 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.

Further, the CCP sector increases reverse repo trades with gilt dealers, investing the additional cash margin they collected during this period of increased volatility.[7] 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.[8] Thus, while on one hand CCPs margining practice have weighed on the liquidity of clearing members in several markets (Huang and 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.

Our second key result is concerned with the non-banks in the periphery of the market. Hedge funds stand out as the only non-bank sector which increases borrowing during the COVID-19 stress relative to normal times. Since 2018, hedge funds have significantly increased their reliance on short-term funding via repo (Roberts-Sklar and Baines, 2020) and the COVID-19 stress period led to a further rise in their short-term funding needs. 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. Furthermore, we find that all non-bank sectors except MMFs increase their lending and this lending goes mainly to gilt dealers. During the COVID-19 stress episode MMFs experienced liquidity issues due to large outflows as reported in Hauser (2020). Despite this, MMFs kept lending in the overnight repo market, reflecting a shortening of maturities.

Finally, we document that spreads in the bilateral market are more sensitive to liquidity stress than spreads in the centrally cleared segment. Further, the difference between core sectors to non-banks reverse repo and repo rates is positive during normal times and increases during the COVID-19 stress episode. By contrast the difference between core sectors to CCP reverse repo and repo rates is negative during normal times and close to zero during the COVID-19 stress episode. This finding is in line with the theory of He et al. (2022) 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.[9] This not the case for trades with the CCP sector,

[3] There are only few studies on the bilateral repo market, based on US data: Gorton and Metrick (2012), who study the bilateral segment but using proxy data, and Baklanova et al. (2019), who adopts data from a pilot voluntary collection from nine banks.

[4] One of the key benefits of looking at the bilateral segment is the broader set of institutions active in this segment, as non-banks cannot trade directly in the centrally cleared segment of the gilt repo market.

[5] We characterize 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.

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

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

[8] 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.

[9] Using a theoretical model, He et al. (2022) 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 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.

as the shadow cost on their balance sheet due to regulatory constraints is lower due to netting benefits. 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.

Overall, we take these findings to indicate banks and gilt dealers preference to trade via the centrally cleared segment rather than bilaterally during the COVID-19 episode. As discussed above, a possible explanation for this is that the centrally cleared segment is more attractive because it is less capital-intensive due to the ability to net trades. Central clearing can also reduce settlement fails and counterparty risk. However, trading in the centrally cleared segment can also be more expensive due to risk management requirements. In line with our findings, Eren et al. (2020) also find evidence of dealers' marked preference for the centrally cleared segment in the US dollar funding markets during the COVID-19 crisis.

We compare our 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' volumes with the CCP sector 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. Baranova et al. (2023) analyse this channel and show that greater central clearing could have a material positive impact on dealers' intermediation capacity in the gilt repo market.

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 and 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 Hall (2021), 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.[10]

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 overnight gilt repo market. In particular, Section 3.1 analyses the network structure of the institutional network of the repo market and changes under stress. Section 3.2 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 4 we 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 5 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 and rates. As a result, we are, to the best of our knowledge, the first to jointly analyse the bilateral and the centrally 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 centrally cleared, of the gilt repo market in stress, which is one of the world's core repo markets.[11] 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 and 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 and 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 evidence of gilt dealers preference to intermediate via the centrally cleared segment rather than bilaterally during the COVID-19 episode. The appeal of the centrally cleared segment stems from netting benefits and indicates that constraints to intermediation can be 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

[10] Further, as pointed out by Hauser (2021) 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.

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

market structure (Martin et al., 2014), central clearing (Duffie and Zhu, 2011; Capponi et al., 2015; Duffie et al., 2015) and the modelling of its network dynamics (Luu et al., 2020; Ghamami et al., 2022). Regarding the latter, we apply recently developed methodologies (Mazzarisi et al., 2020) to study network dynamics in the institutional repo network, and develop a novel approach to statistically characterize changes in market activity between different sectors and to visualize the results in the form of a network. While most of the existing approaches consider models of a dynamic contagion process on a static network,[12] 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.[13]

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*. In the rest of the paper, we will refer to the party doing the repo as the *cash borrower* (or simply borrower) and the party doing the reverse repo as the *cash lender* (or simply lender). 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. Institutional framework

In this section we describe the institutional framework of the gilt repo market – namely trade execution, settlement and clearance – and define the different market segments. We refer to Section 3.2 for a description of the sectors trading in the different segments of the market.

The gilt repo market currently operates through direct, voice broker transactions or screen trading. Similarly to the US (Baklanova et al., 2015; Hempel et al., 2022; Paddrik et al., 2021) and the Euro repo market (Mancini et al., 2016), we can differentiate different segments of the gilt repo market depending on the type of settlement and clearance. Although the precise structure of the repo market can vary across countries, generally speaking repo transactions can be settled on the books of a third party or bilaterally, usually on a delivery-versus-payment (DVP) basis. Further, repo transactions can be centrally cleared or non-centrally cleared.[14]

Following Mancini et al. (2016) we define three segments for the gilt repo market: bilateral, triparty and centrally cleared. In bilateral repos the two parties select the collateral, initiate the transfer of cash and securities, conduct collateral valuation and negotiate margins. Bilateral repos are settled on a delivery-versus-payment (DVP) basis and are non-centrally cleared. DVP is a mechanism whereby cash and securities are exchanged in electronic book-entry form. For gilts and other UK securities the securities settlement system CREST is used to settle DVP transactions.[15]

In the triparty segment a third party (clearing bank or central securities depository) acts as an intermediary and organizes the settlement and collateral management. However, the counterparty risk remains with the repo traders. For gilts, Euroclear offers triparty repo services and operates CREST since 2002.[16]

In the centrally cleared segment trades are settled on the books of a third party, and the CCP becomes the counterparty assuming counterparty risk of every trade. In the gilt repo market LCH RepoClear LTD is the main CCP clearing trades (Benos et al., 2023). LCH allows its members to register their trades on a novation basis, thereby facilitating trade anonymity. LCH accepts trades from a variety of sources, including electronic platforms, direct and broker trades.[17] LCH provides netting services: balance sheet netting, allowing to net trades (with the same counterparty, currency, maturity date and settlement location) and reducing notional outstanding, and settlement netting also called payment netting (for trades with the same counterparty, security, settlement date and location) allowing to net down the number of daily settlements. LCH requires its members to post margins (initial, variation and delivery margins)[18] which are updated during the day and can be deposited in the form of eligible cash or securities.[19]

On average, 36% of daily overnight gilt repo volumes are centrally cleared and only 2% is triparty, implying the majority of volumes are in the bilateral segment. In the US the bilateral segment is a key part of the repo market as well, however only recently data on this segment has started to be collected. Based on recently collected data from the Federal Reserve Bank of New York, the bilateral segment is the largest segment of the repo market in gross exposure by primary dealers (Hempel et al., 2022). By contrast, the Euro interbank repo market is mainly centrally cleared (Mancini et al., 2016).

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

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

[14] We refer to CPSS (2010) for a description and comparison of settlement and clearance of repo markets in different jurisdictions.

[15] For more information see https://www.bankofengland.co.uk/payment-and-settlement/ and https://www.icmagroup.org/assets/documents/Legal/GMRA-2011/GMRA-2011-Gilts-Annex-FINAL-091215.pdf.

[16] See https://www.euroclear.com/en.html for more information.

[17] Trades are currently accepted from: BrokerTec, ETCMS, MTS, tpREPO, Tradeweb.

[18] Variation margin represents the change in net present value of the contract over a one day period based on the mark to market calculation. Delivery margin is designed to protect the CCP against possible losses caused by the different timings of the payments of variation margin and the settlement of positions in the event of a clearing member failing to deliver bonds or defaulting.

[19] See https://www.lch.com/services/repoclear/repoclear-ltd/resources and https://www.lch.com/sites/default/files/media/files/211124_Procedures%20Section%202B_Deleting%20requirements_CLEAN.pdf for more information.

2.3. 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.[20]

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.[21] However, according to Harris and 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 overnight market's size and its relevance in liquidity stress are reasons why we focus on this maturity segment in this paper.

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 Fig. 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 have been identified as periods of window dressing for banks and dealers by Kotidis and Van Horen (2018) for the UK repo market and Munyan (2017), Anbil and Senyuz (2018) for the US repo market.[22]

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. Fig. 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.

2.4. 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 9th and 23rd of March 2020.

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 characterized by exceptionally high demand for cash and near-cash short-dated assets". Overnight repo rates rose sharply, as shown in Fig. 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". Fig. 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 stabilize 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. The network structure of the overnight gilt repo market

We will now analyse the network structure of the overnight repo market. First, we consider trading activities at the institutional level. We then focus on activities at the sectoral level in Section 3.2.

3.1. Institutional activity in the overnight gilt repo market

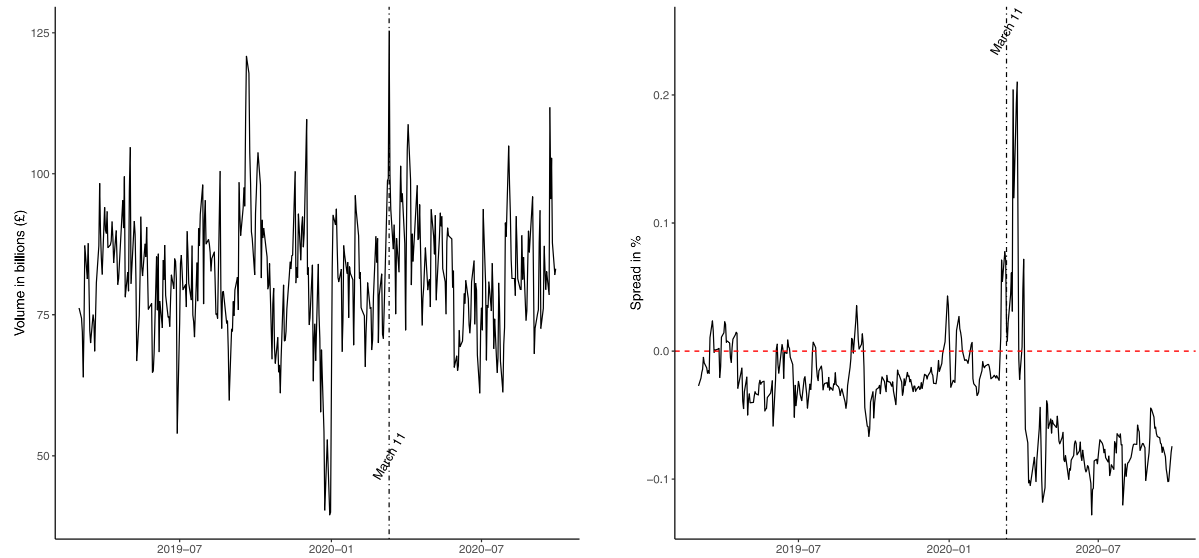
The daily average number of institutions active in the overnight gilt repo market is 58, but a total of 156 institutions traded at least once in the overnight repo market between March 2019 and October 2020. In the full sample, the average daily repo transaction volume by active institution is £0.6 billion, 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.

In this section we first define the institutional repo network and its key characteristics throughout the sample. We then investigate the increase in activity during the COVID-19 pandemic.

[20] The Bank of England Sterling Money Market data is available since June 2016. However, given the focus of the paper on recent stress episodes, we have excluded the first part of the sample. We refer to Hüser et al. (2021) for a previous version of the paper including the longer dataset from June 2016. We note that the gilt repo market exhibited different dynamics when the data started to be collected, for instance repo spreads were more negatively skewed and volatile in 2016–2018.

[21] 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 and Taylor (2018).

[22] Other factors could also drive fluctuations in repo market activity, as documented for the repo markets in the US and Europe, such as non-banks behaviour (Anbil and Senyuz, 2018) and monetary policy (Dunne et al., 2013; Mancini et al., 2016). Future research could investigate these channels for the UK repo market.



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

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

Fig. 1. Times series of key variables: Repo volumes and spreads.

3.1.1. The institutional repo network

We define the institutional networks of volumes as follows. We denote by $\mathcal{T} = \{t_0, t_1, \dots, t_T\}$ 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 $\mathcal{N}^{(I)} = \{1, \dots, N^{(I)}\}$, $N^{(I)} = 156$, 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 analyse how trade relationships between pairs of institutions change over time and in particular during times of stress. First, we investigate how likely it is in our sample that a given pair of institutions trade with each other. We define the matrix $\bar{A}^{(I)} = (\bar{A}_{ij}^{(I)})_{i,j \in \mathcal{N}^{(I)}} \in [0, 1]^{\mathcal{N}^{(I)} \times \mathcal{N}^{(I)}}$, where

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

Hence, $\bar{A}_{ij}^{(I)}$ represents the empirical probability that institution i lends institution j cash in a repo transaction on a given day.

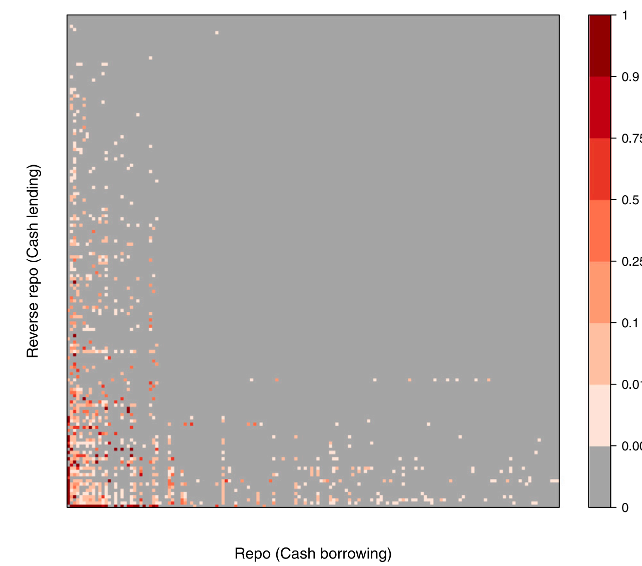


Fig. 2. Empirical probability for a transaction between each pair on a given day ($\bar{A}^{(I)}$).

Fig. 2 shows a heatmap of $\bar{A}^{(I)}$. Each cell represents the probability that two institutions trade with each other on any given day in the whole sample. Institutions have been ordered in the same way along the two axes based on their gross position (volume) in the repo market over 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.

We observe a cluster in the lower left corner and more scattered elements in the leftmost columns and the last few rows of the heatmap in Fig. 2. This cluster can be interpreted as the core of institutions which transact repo among themselves as well as with the periphery, which are the more scattered elements extending top and right of the cluster. Overall, the overnight gilt repo market exhibits a core–periphery structure in the sense of Craig and Von Peter (2014). Craig and Von Peter

(2014) define a perfectly tiered (core–periphery) network as a network in which all institutions can be divided into two sets of nodes (core and periphery) such that each node in the core borrows from and lends to all nodes in the core, each node in the core borrows from at least one node in the periphery and lends to at least one node in the periphery. Furthermore, nodes in the periphery are nodes that may borrow from or lend to nodes in the core, but they do not borrow from or lend to other nodes in the periphery. In empirical data, this definition is usually not strictly satisfied, but we see that Fig. 2 is very close to such a structure. We provide additional details on this in Appendix A. 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. Central counterparties have a special role, and we therefore classify them as neither core nor periphery. We have provided more detail on the different sectors and their role in the repo market in Section 3.2.

Furthermore, the Figure shows that the network is very sparse with many grey areas in the heatmap indicating that no trading took place between the corresponding pairs. Fig. 2 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.

For robustness, we have also conducted a more detailed statistical analysis on edge persistence in the institutional network supporting these findings.[23] In particular, we have investigated the stability of trade relationships over time in the institutional network at daily but also weekly, biweekly and four-weekly frequency (i.e., institutions trade at least once during a one, two or four weeks period).[24] The analysis confirms that most trade relationships are not persistent over time, meaning that the existence of a repo transaction between two institutions on a given day (week, two weeks, four weeks period) does not have a strong influence on the two institutions trading with each other the next day (week, two weeks, four weeks period). There are however a small number of institutions with highly persistent trading relationships. We refer to Appendix A.3 for more details. This finding differs from those of similar analyses on the US triparty repo which find stable relationships (Han et al., 2022; Paddrik et al., 2021).[25]

Second, we investigate whether there are important changes in the institutional network characteristics during the COVID-19 stress episode. In particular, given the observed increase in activity, we are interested in understanding whether the repo network becomes more connected during the COVID-19 stress and if so how. To this end, we consider the density of the network of all institutions over time in Fig. 3(a). The density of a network is the ratio of existing edges between nodes out of all the possible edges that could exist between the nodes in the network. Mathematically, the time-t density for the institutional network is defined as $\frac{1}{N^{(I)}(N^{(I)}-1)}\sum_{i=1}^{N^{(I)}}\sum_{j=1}^{N^{(I)}} A_{ij}^{(I)}(t)$.

The network density displays large variations over time.[26] 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. Fig. 3(b) reports the density of the following subnetworks: (i) core to core, defined as the institutional network of volumes considering only cash lent from institutions in the core to institutions in the core, (ii) core to periphery, defined as the institutional network of volumes considering only cash lent by institutions in the core to the institutions in the periphery, (iii) periphery to core, defined as the institutional network of volumes considering only cash lent by institutions in the periphery to the institutions in the core. The figure shows that the increase in the institutional network density during the COVID-19 stress episode was driven by both institutions in the core and the periphery. However, while the density of the subnetworks involving the periphery reaches its highest peak during this episode close to March 11 and then declines, the density of the core to core subnetwork peaks later after the Bank of England interventions.[27]

How is this higher level of connection achieved during the COVID-19 stress episode? In particular, we ask whether this increase is due to trading pairs exclusively formed for this crisis period, and if not how often trading pairs traded before. We define a trading pair as two institutions that have traded at least once in a given period of time. There are 755 unique trading pairs in the overnight gilt repo market from the beginning of our sample up to the beginning of the COVID-19 stress episode (March 1 2019–March 9 2020) and 287 unique trading pairs during the COVID-19 stress. Of those, 9 were new trading pairs formed during the COVID-19 crisis relative to the 755 trading pairs that exist in our sample before COVID-19.[28] This shows that the vast majority of market participants relied on previously used counterparties to secure liquidity in this market.

However, most of these trading pairs did not trade regularly before the COVID-19 crisis. Table 1 shows how often trading pairs trade in a given period (before and during the COVID-19 stress episode): daily, weekly, biweekly, four-weekly. First, we note that before COVID-19, only 14.04% of trading pairs trade at least every four weeks and only 4.37% daily. This is in line with the institutional network being sparse, as discussed above. Second, we note that almost all the trading pairs that traded at least every four weeks before the COVID-19 stress episode kept trading with each other during the stress episode. However, these represent only 35.89% or all trading pairs during COVID-19. The remaining trading pairs during COVID-19 were trading less frequently before.

Overall, our analysis of the institutional network shows that despite the low daily average roll-over and low persistence of most trading relationships, during times of stress market participants rely on previously

[23] Edge persistence describes the tendency of institutions to trade with institutions they have interacted with in the past.

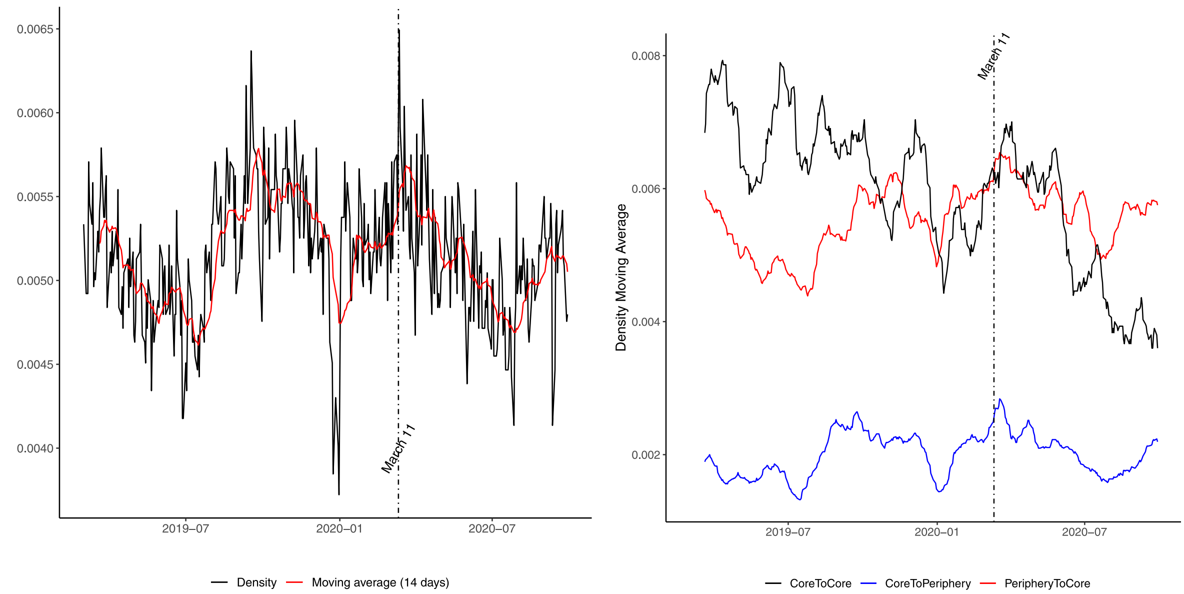
[24] Specifically, we have estimated the *Discrete AutoRegressive Graphs model (DAR(1))* by Mazzarisi et al. (2020).

[25] We note that Han et al. (2022) focus only on MMFs and top dealers relationships. By contrast our data set includes a rich set of institutions from many additional sectors. Our findings can be explained by the fact that in the overnight gilt repo market, where transactions are secured by high-quality collateral and are intermediated by sophisticated financial institutions, informational asymmetries and search frictions tend to be low and persistent relationships occur only within a small group of institutions. Future research could further investigate the drivers of this dissimilarity.

[26] We also note 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 Fig. 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.

[27] It is also interesting to observe that the density of this subnetwork displays a declining trend over time looking at the entire sample. That is, the core to core subnetwork is becoming less connected. The volume traded within the core, however, does not decline over time and the fraction of the volume that is centrally cleared does not increase over time, see Fig. 12.

[28] 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.



(a) Time series of the density of the institutional network.

(b) Time series of the density moving average (14 days) of the institutional subnetworks.

Fig. 3. Time series of the density of the institutional network and subnetworks.

Table 1
Overview of number and share of trading pairs before and during the COVID-19 stress episode, by trade frequency: daily, weekly (i.e., at least once a week), biweekly (i.e., at least every two weeks), four-weekly (at least every four weeks).

Frequency of trading	Daily	Weekly	Biweekly	Four-weekly
Number of pre-COVID-19 trading pairs	33	58	76	106
Share out of all pre-COVID-19 trade pairs (755), in %	4.37	7.68	10.07	14.04
Number of pre-COVID-19 trading pairs that traded during COVID-19	33	58	76	103
Share out of all COVID-19 trading pairs (287), in %	11.50	20.21	26.48	35.89

used (even though not always frequently) counterparties. These results contribute to the literature on the importance of trading relationships in repo markets, see Paddrik et al. (2021), Anbil et al. (2021), Julliard et al. (2022), Anderson and Kandrac (2018), Macchiavelli and Zhou (2022).

3.2. Sectoral activity in the overnight gilt repo market

In order to shed light on sectoral activity in the overnight gilt repo market, we now move to the analysis of the repo market network at sectoral level. Overall we consider 10 different sectors for the sectoral overnight gilt repo network, which we can broadly divide in *banks and gilt dealers*, *non-banks* and *CCPs*.[29]

3.2.1. Sectors in the overnight gilt repo market

The gilt repo market can be used both to source cash and to source securities. We now describe how different sectors trade in the market.

Gilt dealers and banks. We refer to banks that are classified as Gilt-Edged Market Makers (GEMMs) by the UK Debt Management Office (DMO) as *gilt dealers* and we refer to all other banks that are not GEMMs as *banks*. The gilt dealers are the primary market makers in the UK sterling government bond market.[30] We divide the gilt dealers by the location of their headquarters into 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 gilt 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. Table 2 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.[31]

Banks use the repo market to earn a return on their liquid assets and to source short-term funding. Overall, banks are the largest net borrowers on average in the overnight gilt repo market (see Table 2).

Gilt dealers and banks are the only sectors that have trade relationships with all the other sectors. They can trade both in the bilateral segment, with other gilt dealers and banks and non-banks, and in the centrally cleared segment. Gilt dealers and banks are the only two sectors that are clearing members and hence trade with the CCP sector.

Central counterparties. The CCP sector has a special role in the repo market. In particular, the CCPs do not actively provide liquidity. They

[29] For the sectoral analysis we do not include 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.

[30] The gilt dealers have privileges and obligations that come with being a GEMM (and banks that are non-GEMMs do not have those). For example, GEMMs play a leading role in the primary issuance of gilts. Only GEMMs can make direct bids to the DMO in the DMO's gilt auctions and they are expected to purchase a certain amount of gilt issuance (U.K. DMO, 2021). Therefore they have a gilt inventory that they need to finance.

[31] Their lending and borrowing positions are also quite stable over time throughout the sample, see Figs. 11(a) and 11(b), aside from a large drop at year-end.

do two things. First, they clear trades between their members, which 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.[32] As Table 2 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 likely reflects the average daily investment of cash margin into the overnight gilt repo market.[33] 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 the *centrally cleared segment*.

Non-banks. Non-banking sectors at the periphery of the market can only trade in the bilateral segment with banks and gilt dealers. MMFs, insurers, pension funds and funds are net lenders in the overnight gilt repo market, see Table 2.[34] 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 as part of their cash management strategies as alternatives or complements to bank deposits.[35] 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 as reported in Fig. 11(d).[36] Pension funds and insurers are also net lenders in the overnight repo market. However, we note that 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) and Czech et al. (2021).

Hedge funds are instead net borrowers on average, as reported in Table 2, 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 and since 2018 they have been increasing their reliance on the repo market for short-term funding (Roberts-Sklar and Baines, 2020). Hedge funds can use repo to borrow cash to fund long positions and increase their leverage.[37] They also use it to borrow securities that they sell short.

3.2.2. The sectoral repo network

In order to study the structure of the market, we will now look at the network created by the different sectors trading in this market rather than the network created by the individual institutions. A network approach will allow us to better visualize and analyse the trading relationships between the different sectors and how they change in times of stress. We consider the same trading days as before, i.e., the set of discrete timepoints (i.e., days) is $\mathcal{T} = \{t_0, t_1, \dots, t_T\}$, with $t_0 =$ 1 March 2019, $t_T =$ 31 October 2020 and $T + 1 = 400$. We define the sectoral network of volumes in the overnight repo market.

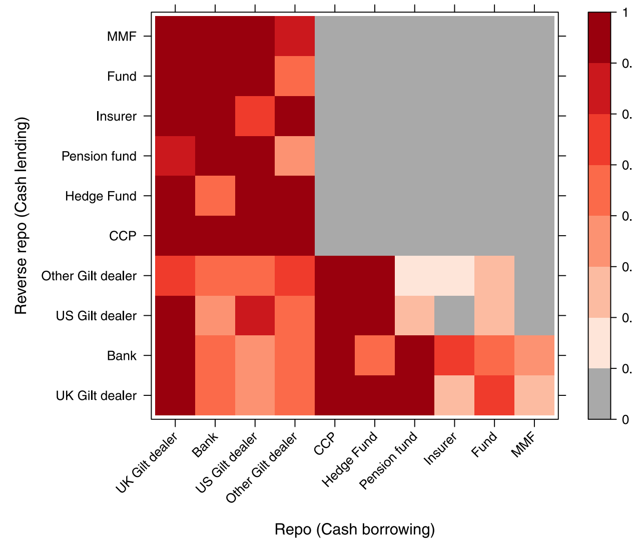


Fig. 4. Transaction likelihood in the sectoral network.

Definition 3.2 (*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.,

$$A_{ij}^{(S)}(t) = \begin{cases} 1, & \text{if } V_{ij}^{(S)}(t) > 0, \\ 0, & \text{else.} \end{cases} \tag{3}$$

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

$$\bar{A}_{ij}^{(S)} = \frac{\sum_{t\in\mathcal{T}} A_{ij}^{(S)}(t)}{T + 1}. \tag{4}$$

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. Fig. 4 shows a heatmap of this matrix $\bar{A}^{(S)}$. 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.

[32] 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.

[33] 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 4.2.

[34] 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.

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

[36] 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.

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

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, reflects the fact that the CCP sector and the non-banks and non-gilt dealers do not trade with each other or among each other in our data set.

4. 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.[38] In both stress periods, we saw spikes in the average daily transactions volumes in the overnight gilt repo market of a similar magnitude, see Fig. 1(a). The spreads, however, only spiked very sharply during the COVID-19 stress, see Fig. 1(b).

Definition 4.1 (*Time Windows for Stress Episodes*)**.** We will denote by $\mathcal{T}^{\text{COVID-19}} \subset \mathcal{T}$ the dates associated with the COVID-19 "dash-for-cash", i.e., 09 March 2020–23 March 2020; and by $\mathcal{T}^{\text{US}} \subset \mathcal{T}$ the dates associated with the US repo market turmoil, i.e., 03 September 2019–17 September 2019.

4.1. 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 3.2. 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 $i, j \in \{1, \dots, N^{(S)}\}$ 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.[39] In our data we have $N^{(S)} = 10$ and $\tilde{T} = |\tilde{\mathcal{T}}| = 381$. Hence, we have $10^2 \cdot 381 = 38100$ observations to fit the model.[40] We then consider the following linear model with only categorical explanatory variables

$$\begin{aligned} Y_{ijt} = {} & \beta_{ij}^{(\text{Normal, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \\ & + \beta_{ij}^{(\text{US, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{US}}\}} \\ & + \beta_{ij}^{(\text{COVID-19, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{COVID-19}}\}} \\ & + \epsilon_{ijt}, \end{aligned} \tag{5}$$

where $\mathbb{I}_{\{\cdot\}}$ 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:

- $\beta^{(\text{Normal, Vol})} = (\beta_{ij}^{(\text{Normal, Vol})})_{i,j \in \{1,\dots,N^{(S)}\}} \in \mathbb{R}^{N^{(S)} \times N^{(S)}}$ 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 $t \in \tilde{\mathcal{T}} \setminus (\mathcal{T}^{\text{US}} \cup \mathcal{T}^{\text{COVID-19}})$.
- $\beta^{(\text{COVID-19, Vol})} = (\beta_{ij}^{(\text{COVID-19, Vol})})_{i,j \in \{1,\dots,N^{(S)}\}} \in \mathbb{R}^{N^{(S)} \times N^{(S)}}$ represents the change in the average daily volume between the sector pairs during the time period of the COVID-19 stress. More specifically, $\beta_{ij}^{(\text{COVID-19, Vol})}$ is the change in average daily volume lent from sector i to sector j during the period of 9–23 of March 2020. Hence, the average daily volume lent from sector i to sector j at a time $t \in \mathcal{T}^{\text{COVID-19}}$ would be given by the model as $\beta_{ij}^{(\text{Normal, Vol})} + \beta_{ij}^{(\text{COVID-19, Vol})}$.
- $\beta^{(\text{US, Vol})}$ can be defined and interpreted along the lines of the definitions and interpretations of $\beta^{(\text{COVID-19, Vol})}$ 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 (5), 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 $\beta^{(\text{Normal, Spread})}$, $\beta^{(\text{US, Spread})}$ and $\beta^{(\text{COVID-19, Spread})}$.

We use a bootstrap approach to determine statistical significance of our model parameter. We present it together with the results in Appendix E.

4.2. Results

In order to fix the focus on the key aggregate dynamics at sectoral level we first present results on volumes aggregated by sector. Second, in Section 4.2.2 we show the results for the sectoral network. We can then analyse which pairs of sectors drive the aggregate results. The network results also allow us to compare results across different segments of the market.

4.2.1. Aggregate volumes by sector

Fig. 5 shows the daily average volume that is traded in repo or reverse repo transactions for each sector during the different time periods (Normal, US, COVID-19 periods).[41] Overall, changes in volumes were generally larger during the COVID-19 stress period compared to the US stress period. However, we see several common patterns of how repo and reverse repo volumes changed during the two stress episodes.

First, we note that volumes transacted by the CCP sector – both repo and reverse repo – increased in both stress periods. The increase in volumes is larger during the COVID-19 stress period for reverse repo.

Second, looking at sectors in the core we observe that banks are the only sector that decreases repo volumes during the stress periods compared to normal times. At the same time they increase reverse repo volumes, essentially doubling their average daily cash lending during the COVID-19 period compared to the normal time period. By contrast, all gilt dealer sectors increase repo volumes during both crisis periods.

Third, among sectors in the periphery the hedge fund sectors stands out as the only sector that substantially increases their repo volume

[38] We define normal times as the entire sample under consideration excluding the two stress periods.

[39] 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).

[40] 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.

[41] Reverse repo average daily volumes for sector i during normal times is given by $\sum_{j=1}^{N^S}[\beta_{ij}^{(\text{Normal, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}}]$. Reverse repo average daily volumes for sector i during COVID-19 are given by $\sum_{j=1}^{N^S}[\beta_{ij}^{(\text{Normal, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} + \beta_{ij}^{(\text{COVID-19, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{COVID-19}}\}}]$. Similarly, reverse repo average daily volumes for sector i during the US stress episode are given by $\sum_{j=1}^{N^S}[\beta_{ij}^{(\text{Normal, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} + \beta_{ij}^{(\text{US, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{US}}\}}]$. Analogous definitions apply to repo volumes, and repo and reverse repo spreads reported in Appendix D.

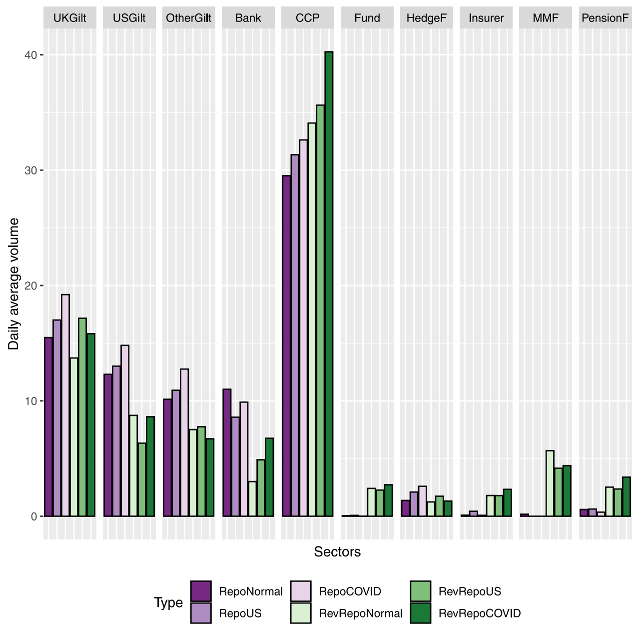


Fig. 5. Daily average volume traded in repo or reverse repo transactions for each sector during the different time periods (Normal, US, COVID-19 periods).

during both crisis periods and particularly during the COVID-19 crisis. Funds, insurers and pension funds increase their reverse repo volumes during the COVID-19 crisis while at the same time decreasing their repo volumes. The MMF sector decreases both repo and reverse repo volumes in the two stress episodes relative to normal times.

In the following, we will discuss these results in more detail. In particular, we will consider which trading pairs contribute the most to these changes using our network model.

4.2.2. Network results

We now present in Fig. 6 the parameter estimates of the model in normal times and during the COVID-19 stress for volumes (i.e., $\beta_{ij}^{(\text{Normal, Vol})}$, $\beta_{ij}^{(\text{COVID-19, Vol})}$) and for spreads (i.e., $\beta_{ij}^{(\text{Normal, Spread})}$, $\beta_{ij}^{(\text{COVID-19, Spread})}$) for each sector pair i, j. The results for the US stress episode are reported in Fig. 7. The colour legend of the heatmaps represents the value of those estimates in pound sterling for volumes and in percentage for spreads.

Normal times. Fig. 6(a) reports the model estimates for the average volume for the whole sample excluding the two stress periods.

We first look at the core and 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 Fig. 5 and Table 2) 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.

Despite by lower volumes compared to the centrally cleared segment, banks and gilt dealers also trade bilaterally with each other. There are benefits and costs of trading in the centrally cleared segment relative to the bilateral segment. Trading in the centrally cleared segment provides benefits in terms of risk management and netting efficiency. 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, centrally cleared trades reduce the impact of repo market intermediation on bank's balance sheet as reported for regulatory purposes.[42] Balance sheet netting has been identified as an important driver of repo market intermediation by CGFS (2017). Further, as discussed in CPSS (2010), a CCP might also be better equipped to administer the liquidation of large portfolios in case of a default. Centrally clearing reduce settlement fails, reduce counterparty credit risk and provides anonymity. However, trading in the centrally cleared segment can also be more costly than trading bilaterally due to margin requirements. Baranova et al. (2023) note that in normal times contacts often report centrally cleared repo can be more expensive due to the risk management requirements.[43] Further, the bilateral segment has the benefit of allowing for rehypothecation of collateral. That is banks and dealers can re-use the securities obtained as collateral in their repo lending to borrow from another client. This has been shown to be an important source of dealers' financing and profits in the gilt repo market (Kotidis and Van Horen, 2019).[44] Other benefits of trading bilaterally can come from forming trading relationships. For the UK repo market, Julliard et al. (2022) shows that repo haircuts are lower for parties with stable bilateral relationships.

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. All other institutions in the periphery are net lenders. These sectors lend rather similar amounts to all sectors in the core, while they borrow larger volumes from bank and UK gilt dealers relative to US and other gilt dealers.

Fig. 6(c) shows that repo spreads in normal times are small and very close to zero (see also the times series of spreads in Fig. 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.

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 Figs. 5 and 6(b), is due to several factors.

First, banks and UK gilt dealers lend more cash through the centrally cleared segment during the COVID-19 episode, compared to normal times.[45] At the same time banks lend less bilaterally to US gilt dealers, other banks and some non-banks, and decrease borrowing from most sectors. While banks are still net borrowers (see Fig. 5 and Table 2), 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 Fig. 14(b). By contrast, all gilt dealers net borrowing positions increase relative to normal times.[46] Giese and

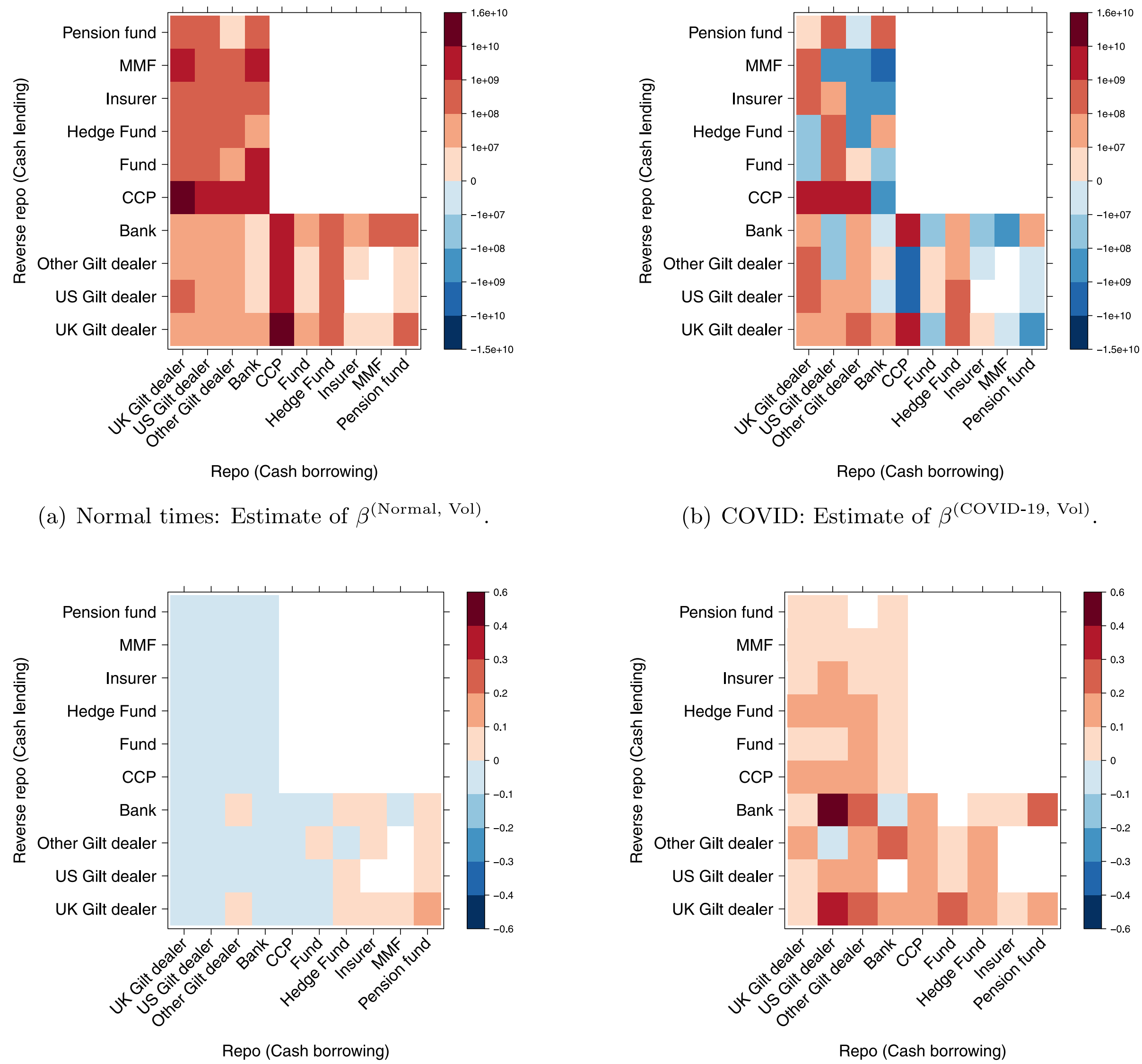
[42] This is important as dealer banks have recently been reaching limits to further balance sheet expansion, as reported in Schrimpf et al. (2020), not least due to large amounts of securities they had been taking into their inventories.

[43] The paper discusses benefits and risks of broader central clearing for the UK gilt and gilt repo markets.

[44] The paper shows that dealers affected by the tightening of the leverage ratio in the UK neutralize the cost of regulation through rehypothecation. See the updated version of the paper for more information https://neeltjevanhoren.com/wp-content/uploads/2020/01/Leverage-ratio-and-repo-_Dec2019.pdf.

[45] By contrast, US and other gilt dealers decrease lending to the CCP while increasing lending bilaterally to some other sectors, both in the core and the periphery.

[46] The different behaviour between sectors in the core could be driven by how tight regulatory constrains were for different participants. While analysing this driver is out of the scope of this paper, we note that recent papers have found significant effects of regulatory constraints on banks and dealers repo market activity during recent time periods including the COVID-19 stress episodes. In particular, Gerba and Katsoulis (2021) show that during the COVID-19 stress period banks and dealers that entered the stress jointly constrained by the leverage ratio and the liquidity coverage ratio reduced their gilt repo borrowing and reverse repo lending activity to a greater extent than



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

(b) COVID: Estimate of $\beta^{(\text{COVID-19, Vol})}$.

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

(d) COVID: Estimate of $\beta^{(\text{COVID-19, Spread})}$.

Fig. 6. Linear model for volumes (first row) and for spreads (second row): Parameter estimates (represented by colours). The heatmaps in the first row represent the average volume in normal times in Fig. 6(a), and the changes in the average volume during the COVID-19 stress period in Fig. 6(b). The heatmaps in the second row represent the average volume weighted repo spreads in normal times in Fig. 6(c) and the changes in the average volume weighted repo spreads during the COVID-19 stress period in Fig. 6(d). All estimates for the spreads are given in percent.

Haldane (2020) argue that indeed 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 the centrally cleared segment 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 the centrally cleared segment goes to gilt dealers.

A possible explanation for this striking preference of banks to lend via the centrally cleared segment rather than bilaterally during the COVID-19 episode is that the centrally cleared segment is more attractive because it is less capital-intensive due to the ability to net trades as discussed above. In line with our findings, Eren et al. (2020) also find evidence of dealers' marked preference for the centrally cleared segment in the US dollar funding markets during the COVID-19 crisis.[47] Another possible reason to prefer trading with CCPs during the COVID-19 stress episode 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 (but not with banks). Besides banks lending more into the centrally cleared segment, another source of this increase in cash supply are the CCPs investing the additional cash margin they collected during

banks that are either constrained by one ratio or unconstrained. Duncan et al. (2022) provide evidence that for US banks smaller supplementary leverage ratio buffers are linked to more repo book netting. The results are consistent with the observation that repo book netting peaked at the beginning of 2020, when SLR buffers were relatively smaller. Both papers' results are driven by the fact that the leverage ratio incentivizes institutions to net transactions in order to mitigate the associated capital charge.

[47] 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 and Patel (2019).

this period of increased volatility.[48] As explained in Section 3.2, 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).[49] 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 2). 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.[50] 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 and 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.

We now turn to the sectors in the periphery. These sectors can only trade bilaterally with banks and gilt dealers in the core. Hedge funds are the only sector significantly increasing their aggregate borrowing relative to normal times (Fig. 5). Hedge funds increase borrowing from all sectors in the core, but most significantly from US and UK gilt dealers (Fig. 6(b)). Since 2018, hedge funds have significantly increased their reliance on short-term funding via repo (Roberts-Sklar and Baines, 2020). Further, 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 cash borrowing in the overnight repo market.

In terms of periphery sectors lending to core sectors, we observe that funds, pension funds and insurers increase their net lending (Fig. 5 and Table 2) during the COVID-19 stress episode relative to normal times. 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. In particular, they increase lending to UK gilt dealers, while decreasing lending towards the other sectors in the core.[51] This is interesting as during the "dash for cash" in mid-March 2020 MMFs experienced 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. This result reflects a preference of MMFs for the overnight segment relative to longer maturities during a liquidity stress.

Given the overall liquidity problems faced by MMFs (Bank of England, 2020), 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.[52] 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. 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. 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". For US prime MMFs (Eren et al., 2020) found a similar dynamic 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.

COVID-19 stress period — repo spreads. Next, we analyse changes in the repo spreads during the COVID-19 stress (Fig. 6). Overall spreads increase significantly during the COVID-19 stress period reflecting the severity of this liquidity stress episode (see also Fig. 1(b) for the time series of the spreads and Table 3 and Fig. 13 for the sectoral averages.).

We note though that there are important differences between spreads in the bilateral and centrally cleared segment. Repo spreads in the centrally cleared segment (i.e., CCP repo trades), despite increasing during COVID-19, remain among the lowest. It is important to note that these rates reflect the rates at which banks and dealers are willing to lend in the centrally cleared market, as the rates are set by banks and dealers. By contrast, in the bilateral segment we observe the highest level of spreads increase, all happening when the core sectors engage in reverse repo transactions, with a concentration of the higher spreads rise observed in transactions between core sectors. For example, UK gilt dealers' spreads on reverse repo are between 10 and 40 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 which can be taken as a sign of strains in the market.

Furthermore, we observe that the difference between core sectors to non-banks reverse repo and repo rates is positive during normal times and increases during the COVID-19 stress episode. That is when core sectors trade with non-banks in the periphery they lend at higher rates than borrowing rates. By contrast the difference between core sectors to CCP reverse repo and repo rates is negative during normal times and close to zero during the COVID-19 stress episode (see Table 3 and Fig. 13).

This finding is in line with the theory of He et al. (2022) that dealers, and banks in our case, 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 for example lending to leveraged investors, such as hedge funds, and borrowing from cash-rich investors, such as MMFs. By contrast the shadow cost on their balance sheet due to regulatory constraints is lower when trading with the CCP, as reflected in the associated spreads. He et al. (2022) provide evidence for this channel, documenting a positive spread between dealers' reverse repo and repo rates (the so-called Treasury inconvenience yield) based on aggregate data that approximate repo rates at which dealers lend and borrow in the US

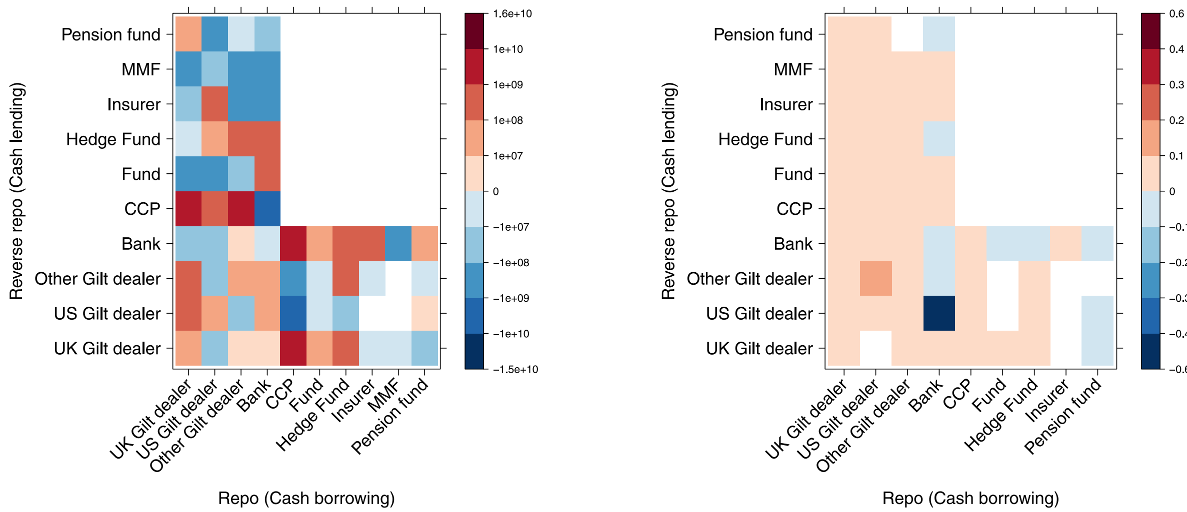
48 See Bank of England (2020) and Huang and Takáts (2020) for a detailed account on the increase in initial margin collected in March 2020.

49 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.

50 Note that under the EMIR legislation and Commission Delegated Regulation (EU) No 153/2013, European Commission (2013), CCPs are incentivized 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".

51 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 Fig. 6(d) which reports the change in spreads during this time. They do, however, occur on the x-axis for Fig. 6(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.

52 A similar analysis for other sectors is left for future research.



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

Fig. 7. Parameter estimates (represented by colours) for the US repo stress period: change in the average volume (Fig. 7(a)) and change in the average spread (Fig. 7(b)). The estimates for the spreads are given in percent.

repo market. 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 note that this result is not an obvious one. As we focus on the gilt repo market, hence a market with high quality liquid collateral, during times of stress flight-to-safety could have produced the opposite result. That is, if dealers and banks were in search for high quality liquid assets such as UK government bonds, they would have been willing to lend cash at a lower rates than the rates at which they borrow cash, in order to obtain the collateral. This was indeed observed in the US repo market during the financial crisis in mid-2008, as documented by He et al. (2022). By contrast, during the COVID-19 stress episode even government securities experienced selling pressures and saw little demand, as described in Section 2.4.

Comparison to the stress in the US repo market in 2019. 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[53] — more than doubled[54] reaching 3.15% above the interest paid on reserves (IOR).[55] 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.[56]

While this stress episode did not originate in the UK, we are interested in understanding the potential spillovers to the gilt repo market. Fig. 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 "stabilized the market [...] and helped to limit spillovers to broader market conditions", as reported in Bank of England (2019).

Now, we compare the changes observed during the COVID-19 stress to the US repo stress period in 2019. Fig. 7 shows the parameter estimates for the changes to the average volume $\beta^{(\text{US, Vol})}$ and the changes in the spreads $\beta^{(\text{US, Spread})}$ during the US repo stress.

Fig. 5 and a comparison of Figs. 7(a) and 6(b) show that there are common patterns between the US repo stress and the COVID-19 stress when considering changes in volumes. In particular, in both stress episodes, we find a significant increase in volumes traded in the centrally cleared segment of the market. As discussed before, this reflects a preference for dealers and banks to transact in the centrally cleared rather than the bilateral segment of the market.

When looking at the changes in the spread during stress periods, however, in Figs. 7(b) and 6(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.[57] Comparing Figs. 7(b) and 6(d), we can see that the COVID-19 episode displays the highest increase in the level of spreads compared to the US stress episode. 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 rate increases, although without reaching more than 20

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

[54] 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).

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

[56] 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 and 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.

[57] 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.

basis points. Fig. 7(a) illustrates that overall US gilt dealers significantly increased borrowing and decreased lending, more than doubling their net borrowing position compared to normal times (Tables 2 and 4 in the Appendix). 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 increased their lending through the centrally cleared segment, 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. 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.

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). Similarly to the COVID-19 stress episode, we find a significant increase in volumes traded in the centrally cleared segment of the market.

5. 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 centrally cleared and bilateral segments.

We document important differences between these two segments. First, we find that volumes traded with the CCP sector increase during stress episodes relative to normal times. This reflect both an increase in lending of banks via the centrally cleared segment and an increase in lending of the CCP to gilt dealers. Second, we document that while banks and gilt dealers lend to non-banks in the periphery at higher rates than when borrowing from them, and this difference increases in stress, this is not the case for trades with the CCP. We take this as evidence of the increase in importance of the CCP sector in this market, and as a preference of gilt dealers and the banking sector to intermediate volumes through the centrally cleared segment of the market, possibly due to netting benefits.

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. Further, the increase in funding comes at a lower cost than funding in the bilateral segment. At the same time, we find that volumes (and spreads) decrease (increase) for most non-banks which do not have access to CCPs. Overall, these results highlight the potential benefits of 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[58] 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.

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

Appendix A. Additional results on the institutional repo network

A.1. The institutional network of volumes

We will now look further into the institutional network of the repo market introduced in Section 3.1. In particular, we will illustrate the main general features of the institutional network of volumes.

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

$$\bar{V}_{ij}^{(I)} = \frac{\sum_{t \in \mathcal{T}} V_{ij}^{(I)}(t)}{T+1}. \tag{6}$$

Fig. 8 shows the heatmap of $\bar{V}^{(I)}$, i.e., each coloured cell represents the average transaction volume between two institutions in the

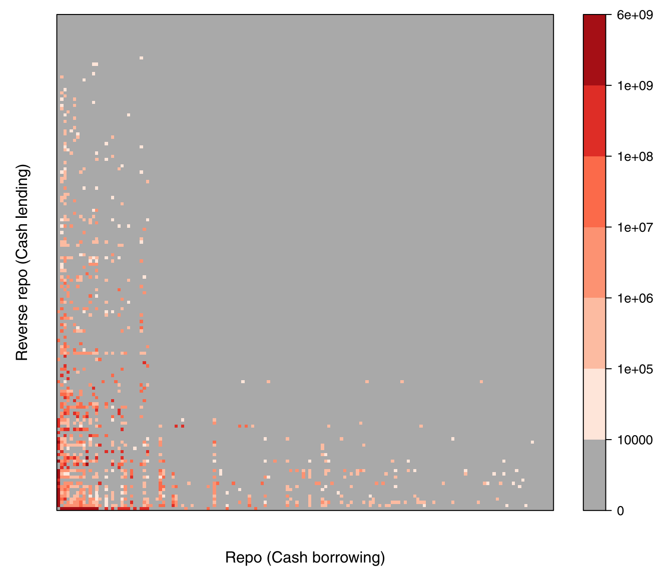


Fig. 8. Average transaction volumes for each pair ($\bar{V}^{(I)}$).

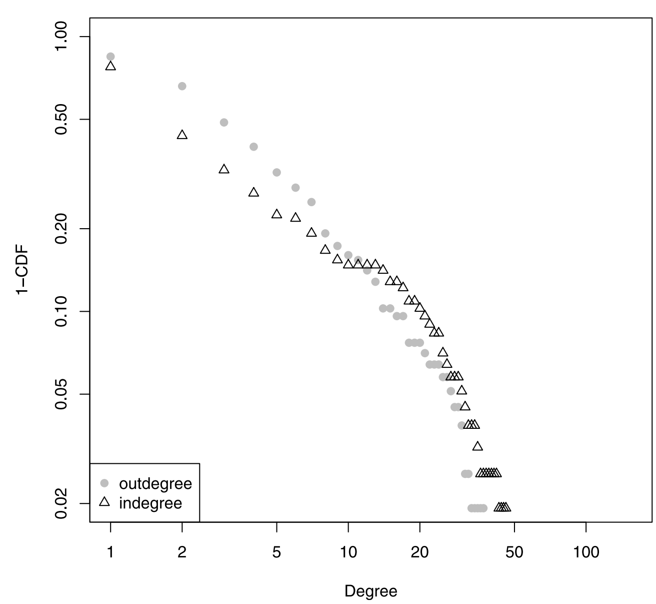
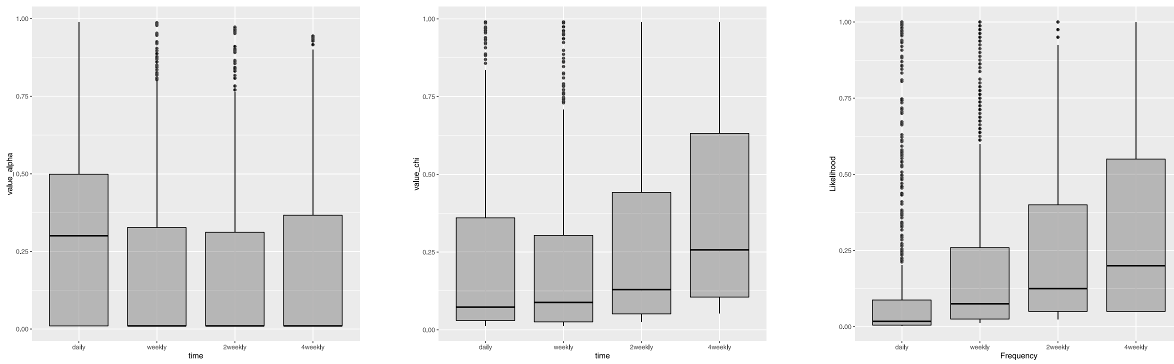


Fig. 9. Empirical survival function of the average in- and outdegrees for the institutional network of volumes.



(a) Estimates of $(\alpha_{ij}))_{i,j\in\mathcal{N}^{(I)}}$ (shows only results where $\alpha_{ij} < 0.99$).

(b) Estimates of $(\chi_{ij})_{i,j\in\mathcal{N}^{(I)}}$ (shows only results where $\chi > 0.01$).

(c) Empirical probability for a transaction between each pair.

Fig. 10. Boxplots of the estimates of the entries of the model parameter matrices α (left) and χ (middle) in the DAR(1) model for different observation periods (daily, weekly, biweekly and four-weekly). The third boxplot (right) shows the empirical probabilities for a transaction between each pair for different observation periods.

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. Institutions have been ordered in the same way along the two axes based on their gross position (volume) in the repo market over the whole sample, as in Fig. 2. 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.

As in Fig. 2, we also find in Fig. 8 in the lower left corner of 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 among 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.

A.2. Degree distribution in the institutional network

Fig. 9 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[59] and $d \in \{1,\dots,N^{(I)}-1\}$) on a log-scale. In the 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 Fig. 9, 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.[60]

A.3. Edge persistence in the institutional network

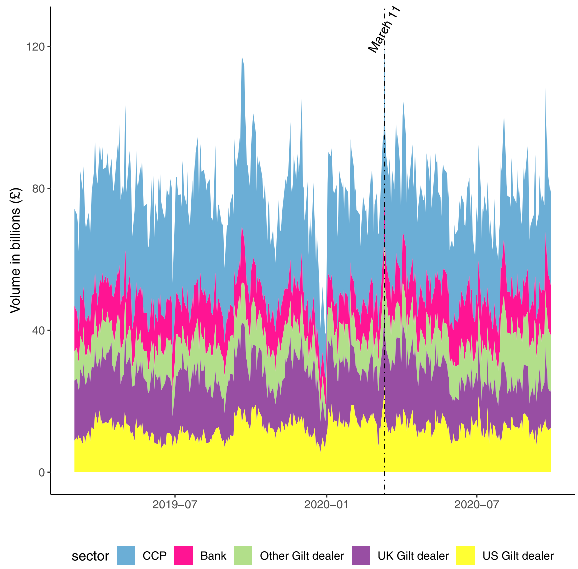
Next, we investigate how stable the trade relationships in the institutional network are. We consider the *Discrete AutoRegressive Graphs model (DAR(1))* by Mazzarisi et al. (2020). They model the time series of adjacency matrices of networks as a Markov Chain. In our case, we consider the time series of the institutional networks $(A^{(I)}(t)_{t\in\mathcal{T}})$ defined in Definition 3.1. According to the DAR(1) model, the adjacency matrix $A^{(I)}(t_v)$ at time t_v depends on the adjacency matrix $A^{(I)}(t_{v-1})$ at time t_{v-1} as follows:

$$A^{(I)}_{ij}(t_v) = F_{ij}(t_v)A^{(I)}_{ij}(t_{v-1}) + (1-F_{ij}(t_v))Y_{ij}(t_v), \quad \forall i,j \in \mathcal{N}, \forall v \in \{1,\dots,T\},$$

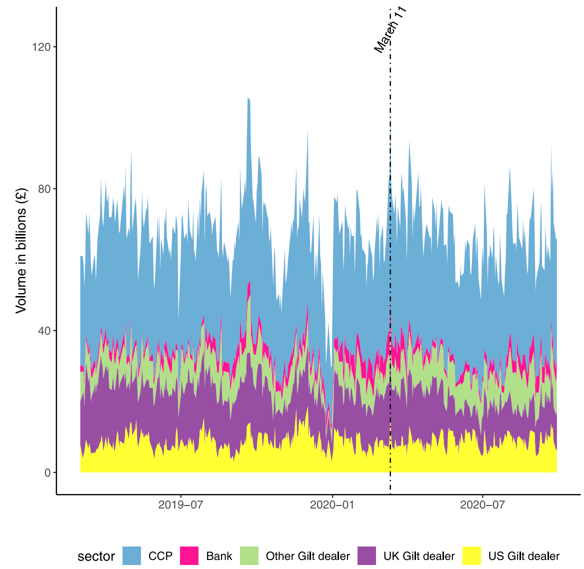
where $F_{ij}(t_v) \sim \text{Bernoulli}(\alpha_{ij})$ with $\alpha_{ij} \in [0,1]$ and $Y_{ij}(t_v) \sim \text{Bernoulli}(\chi_{i,j})$ with $\chi_{ij} \in [0,1]$ are mutually independent random variables. Here, Bernoulli(p) denotes the Bernoulli distribution with success probability p. In particular, $\mathbb{P}(F_{ij}(t_v) = 1) = \alpha_{ij}$ and $\mathbb{P}(F_{ij}(t_v) = 0) = 1 - \alpha_{ij}$ and $\mathbb{P}(Y_{ij}(t_v) = 1) = \chi_{ij}$ and $\mathbb{P}(Y_{ij}(t_v) = 0) = 1 - \chi_{ij}$ $\forall i,j \in \mathcal{N}, \forall v \in \{1,\dots,T\}$.

[59] The degree of a node (representing individual institutions in this case) is the number of edges (representing transactions in this case) the node has to other nodes. The in-degree is the number of incoming edges (borrowing transactions) and the outdegree is the number of outgoing edges (lending transactions). The average in- and outdegree is the average over the daily in- and outdegrees for all the institutions in our sample.

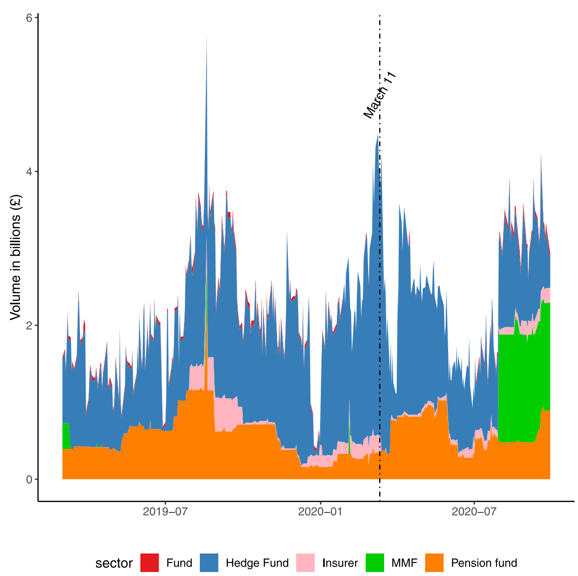
[60] Note that Fig. 9 represents a log–log plot of the empirical survival function, and we see that particularly the tails of the distribution appear linear, indicating that one could successfully fit a power law distribution to the tails of the degree distribution.



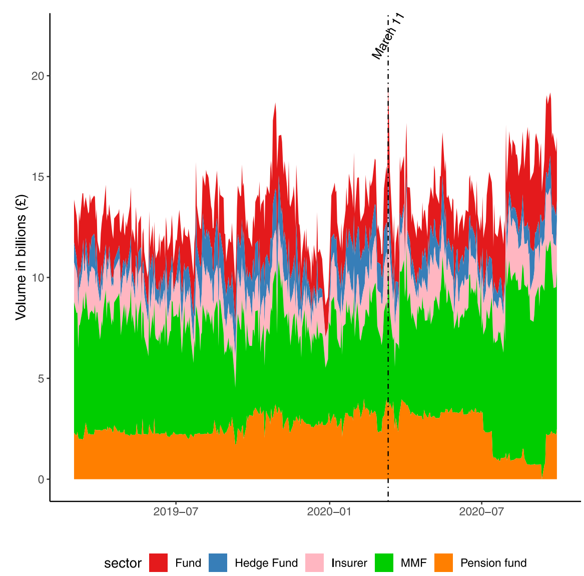
(a) Total volumes borrowed by core sectors and CCP (in £ billions).



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



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



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

Fig. 11. Total volume borrowed (repo) and lent (reverse repo) by different sectors.

As discussed in Mazzarisi et al. (2020), this autoregressive structure can be interpreted as follows. Let $i, j \in \mathcal{N}$, $v \in \{1, \ldots, T\}$, then, with probability α_{ij}, the value of the adjacency matrix at the next time step does not change, i.e., $A_{ij}^{(I)}(t_v) = A_{ij}^{(I)}(t_{v-1})$. With probability $1 - \alpha_{ij}$, the next value of the adjacency matrix is given by $Y_{ij}(t_v) \in \{0, 1\}$, which can be interpreted as the outcome of tossing another coin with marginal distribution Bernoulli($\chi_{i,j}$). This implies that values of α_{ij} that are close to 1 represent stable existence or non-existence of trade relationships over time, whereas values of α_{ij} close to 0 indicate that the current existence or non-existence of an edge does not have a large influence on the existence or non-existence of a directed edge at the next point in time.

As shown in Mazzarisi et al. (2020), the time series of adjacency matrices $(A^{(I)}(t))_{t\in\{t_0,\ldots,t_T\}}$ is a discrete Markov Chain on the state space $\{0,1\}^{N\times N}$ where the transition probabilities are given by

$$\mathbb{P}(A^{(I)}(t_v) \mid A^{(I)}(t_{v-1}), \alpha, \chi) = \Pi_{i=1}^{N} \Pi_{j=1}^{N} \mathbb{P}(A_{ij}^{(I)}(t_v) \mid A_{ij}^{(I)}(t_{v-1}), \alpha_{ij}, \chi_{ij})$$

$$= \Pi_{i=1}^{N} \Pi_{j=1}^{N} \left(\alpha_{ij} \mathbb{I}_{\{A_{ij}^{(I)}(t_v) = A_{ij}^{(I)}(t_{v-1})\}} + (1-\alpha_{ij}) \chi_{ij}^{A_{ij}^{(I)}(t_v)} (1-\chi_{ij})^{1-A_{ij}^{(I)}(t_v)} \right),$$

where $x^0 = 1$ for all x and $\mathbb{I}_{\{x=y\}} = 1$ if $x = y$ and 0 otherwise.

Hence, this model consists of two matrices $\alpha, \chi \in [0,1]^{N\times N}$ which are the model parameters that need to be estimated. Since in the institutional network nodes to not have trading relationships with themselves the entries on the diagonal of the adjacency matrix are all equal to zero. We therefore do not need to estimate the diagonal entries of α and γ, but can just set them to $\alpha_{ii} = 1$, $\chi_{ii} = 0$ for all $i \in \mathcal{N}^{(I)}$.

We estimate the remaining model parameters using Maximum Likelihood Estimation (MLE), see Mazzarisi et al. (2020) for the details.

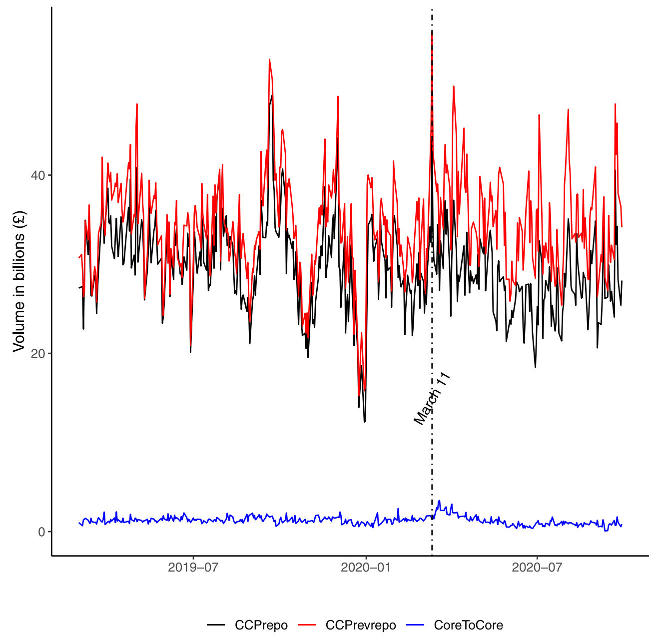


Fig. 12. Time series of the volumes traded core-to-core (blue) and between the core and the CCP sector (black indicates that the CCP sector does the repo, red indicates that the CCP sector does reverse repo with the core.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

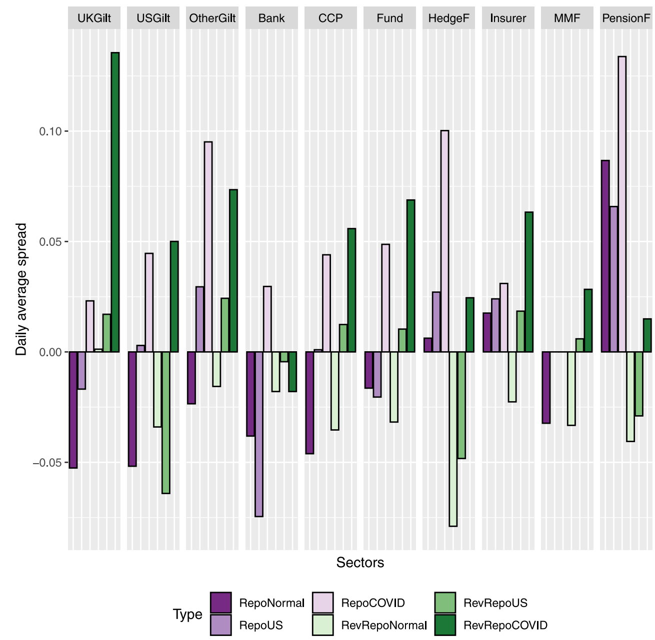


Fig. 13. Daily average spreads of repo or reverse repo transactions for each sector during the different time periods (Normal, US, COVID-19 periods).

Fig. 10 shows the results. It shows boxplots of the estimates of the entries of the model parameter matrices α and χ in the DAR(1) model for different observation periods (daily, weekly, biweekly and four-weekly). The different time periods specify which observation periods were used when estimating the model. The daily estimates are based on the daily adjacency matrices $(A^{(I)}(t))_{t\in\mathcal{T}}$. For all longer time periods, data were aggregated in blocks of one, two or four weeks and the DAR(1) model was estimated on time series with one-,two-,four-weekly observations. An entry in the adjacency matrix is one, if the corresponding pair traded at least once during one, two or four weeks, otherwise it is 0. The third boxplot (right) shows the empirical probabilities for a transaction between each pair. I.e., for the daily observation period it shows a boxplot of the elements of $\bar{A}^{(I)}$ given in (2) and for the longer time period it shows the elements of the observed average adjacency matrices computed from the observation blocks described before. Note, that the boxplots do not contain estimates of node pairs for which we know that they never trade with each other, i.e., pairs where both institutions are in the periphery or the estimates corresponding to the entries on the diagonal.

We find that the majority of estimates for α are generally small. They are largest for the daily observations with a mean of around 0.3, and close to 0 for weekly, biweekly, and four-weekly time periods. These small estimates for α indicate that trade relationships are not persistent over time. There is a small number of exceptions, where the corresponding value of α_{ij} is (almost) 1, indicating that for a small number of nodes the previous existence or non-existence of a trading relationship matters. When comparing the estimates for χ (Fig. 10(b)) to the empirically observed trading probabilities (Fig. 10(c)) we find that they are very similar for the weekly, biweekly, and four-weekly observation periods. These results indicate, that the autoregressive component in the model is rather small for the majority of nodes and the existence or non-existence of current directed edges does not have a strong influence on the next time step for these nodes.

Appendix B. Sectors' volumes over time

See Figs. 11 and 12.

Appendix C. Summary statistics of sectors' volumes and spreads

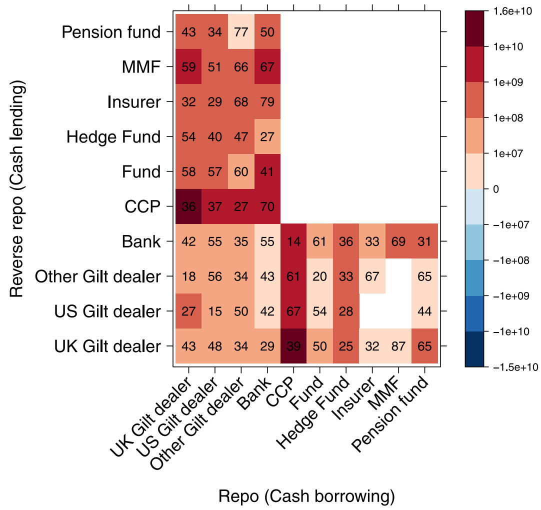
See Tables 2–4.

Appendix D. Aggregate spreads by sector

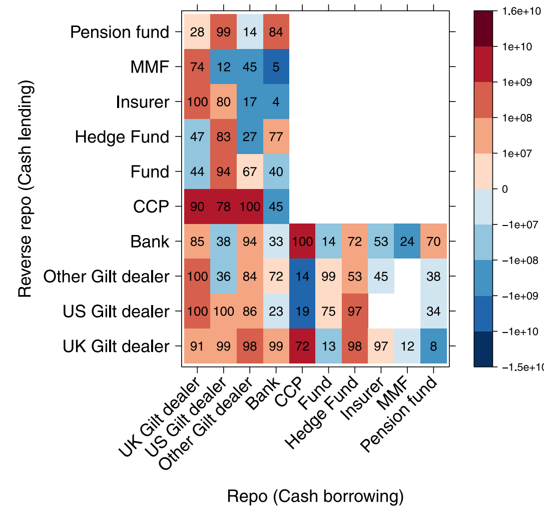
Fig. 13 shows the daily average spreads for repo or reverse repo transactions for each sector during the different time periods (Normal,

Table 2
Overview of daily average volumes (expressed in £billion) by sector in terms of reverse repo (average daily volumes lent), repo (average daily volumes borrowed) and net volumes (average net daily volumes lent). Daily average volumes are displayed for the full sample and the COVID-19 crisis. Sectors are ordered according to their net volumes over the full sample.

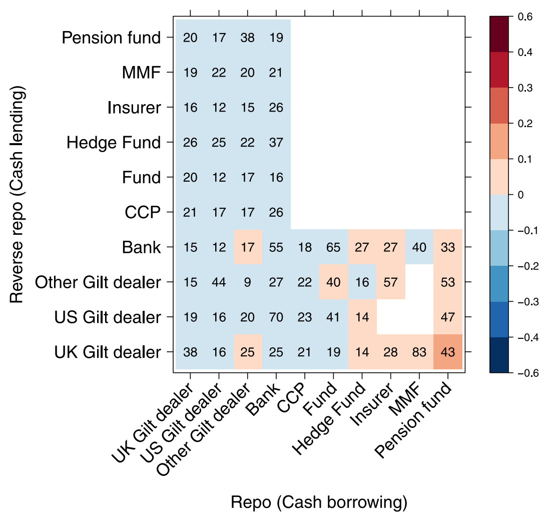
	Full sample				COVID-19 crisis			
Sector	N. of inst.	Rev. Repo volumes	Repo volumes	Net volumes	#	Rev. Repo volumes	Repo volumes	Net volumes
MMF	9	5.58	0.16	5.42	5	4.39	0.00	4.39
CCP	6	34.30	29.56	4.74	4	40.26	32.62	7.64
Fund	18	2.40	0.04	2.36	12	2.73	0.01	2.72
Pension fund	15	2.57	0.58	1.99	8	3.39	0.35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



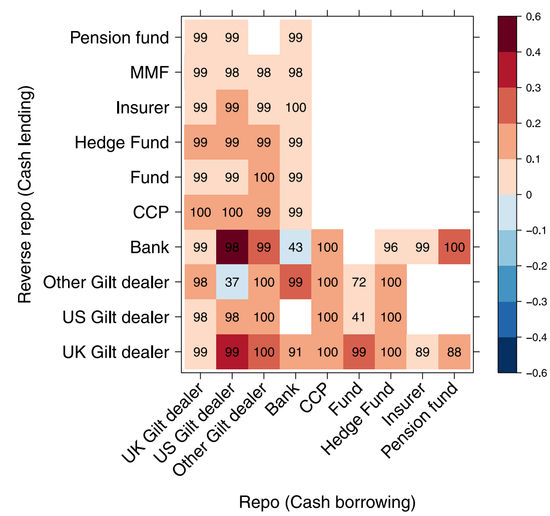
(a) Normal times: Estimate of $\beta^{(\text{Normal, Vol})}$.



(b) COVID: Estimate of $\beta^{(\text{COVID-19, Vol})}$.



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

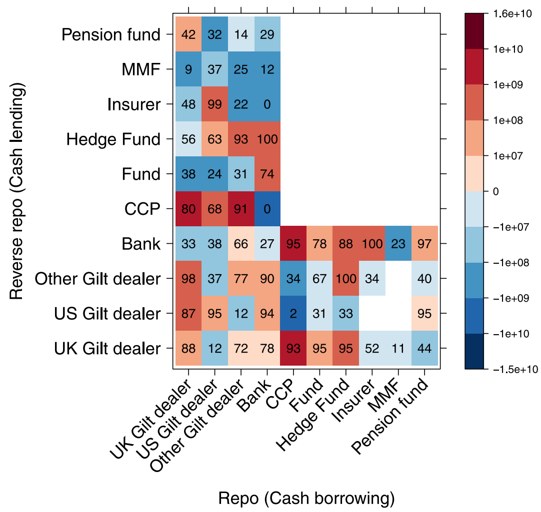


(d) COVID: Estimate of $\beta^{(\text{COVID-19, Spread})}$.

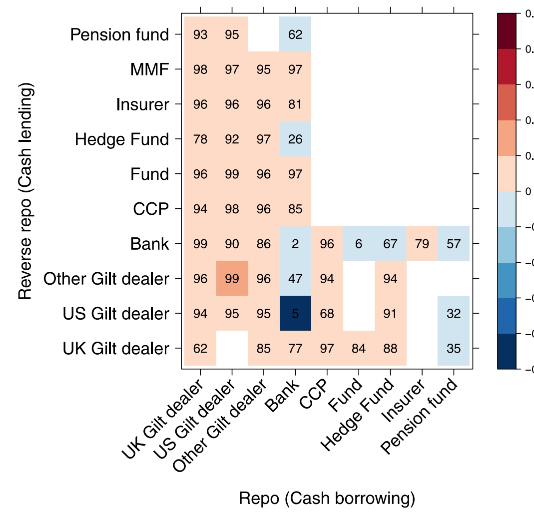
Fig. 14. Parameter estimates (represented by colours) as in Fig. 6 and their percentiles in the distribution generated by bootstrap (represented by numbers). If these numbers are very high (i.e., 99 or 100) or very low (i.e., 0 or 1) the parameter estimates are in the right or left tail of the bootstrap distribution respectively and hence highly significant.

Table 3
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.

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



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



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

Fig. 15. Parameter estimates (represented by colours) as in Fig. 7 and their percentiles in the distribution generated by bootstrap (represented by numbers). If these numbers are very high (i.e., 99 or 100) or very low (i.e., 0 or 1) the parameter estimates are in the right or left tail of the bootstrap distribution respectively and hence highly significant.

Table 4
Overview of the average daily volumes (expressed in £ billion) and volume weighted spreads (expressed in percent) by sectors trading in the overnight gilt repo market for the US turmoil. The sector is a borrower for the repo spread and a lender for the reverse repo spread.

Sector	N. of inst.	Rev. Repo volumes	Repo volumes	Net volumes	Repo spread	Reverse repo spread
MMF	6	4.16	0.00	4.16		0.01
CCP	3	35.63	31.34	4.30	0.01	0.02
Fund	12	2.27	0.07	2.19	−0.03	0.01
Pension fund	5	2.36	0.62	1.73	0.08	−0.02
Insurer	4	1.79	0.43	1.36	0.02	0.02
Hedge Fund	12	1.74	2.10	−0.36	0.03	−0.04
UK Gilt dealer	5	17.20	17.25	−0.05	0.00	0.02
Other Gilt dealer	7	7.79	11.08	−3.29	0.03	−0.00
US Gilt dealer	5	6.39	13.01	−6.62	0.03	−0.04
Bank	14	4.93	8.75	−3.82	−0.02	0.03

US, COVID-19 periods). The reverse repo average spread for sector i during normal times is given by:

$$\sum_{j=1}^{N^S}[\beta_{ij}^{(\mathrm{Normal,\ Spread})}\mathbb{I}_{\{i\ \text{lending sector}\}}\mathbb{I}_{\{j\ \text{borrowing sector}\}}].$$

The reverse repo average daily spread for sector i during COVID-19 are given by:

$$\sum_{j=1}^{N^S}[\beta_{ij}^{(\mathrm{Normal,\ Spread})}\mathbb{I}_{\{i\ \text{lending sector}\}}\mathbb{I}_{\{j\ \text{borrowing sector}\}} + \beta_{ij}^{(\mathrm{COVID\text{-}19,\ Spread})}\mathbb{I}_{\{i\ \text{lending sector}\}}\mathbb{I}_{\{j\ \text{borrowing sector}\}}\mathbb{I}_{\{t\in\mathcal{T}^{\mathrm{COVID\text{-}19}}\}}].$$

Similarly, the reverse repo average spread for sector i during the US stress episode is given by:

$$\sum_{j=1}^{N^S}[\beta_{ij}^{(\mathrm{Normal,\ Spread})}\mathbb{I}_{\{i\ \text{lending sector}\}}\mathbb{I}_{\{j\ \text{borrowing sector}\}} + \beta_{ij}^{(\mathrm{US,\ Spread})}\mathbb{I}_{\{i\ \text{lending sector}\}}\mathbb{I}_{\{j\ \text{borrowing sector}\}}\mathbb{I}_{\{t\in\mathcal{T}^{\mathrm{US}}\}}].$$

Analogous definitions apply to average repo spreads.

Appendix E. Statistical significance based on bootstrap

We use a bootstrapping approach to determine whether the different effects that we observed during the two stress episodes are statistically 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 (5) to the new time series. We repeat this process $R = 1000$ times and therefore obtain R estimates of our model parameter. The heatmaps in Figs. 14 and 15 are the same as in Figs. 6 and 7 with the only difference that the cells 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. We have also looked at the classical p-values for our parameter estimates. We find that the bootstrap approach results in far fewer estimates flagged as significant than the standard p-values obtained from classical hypothesis testing in the linear model.

References

Aikman, D., Chichkanov, P., Douglas, G., Georgiev, Y., Howat, J., King, B., 2019. System-wide Stress Simulation. Bank of England Staff Working Paper No. 809.

Anbil, S., Anderson, A.G., Senyuz, Z., 2021. Are Repo Markets Fragile? Evidence from September 2019. FEDS Working Paper.

Anbil, S., Senyuz, Z., 2018. Window-dressing and the Fed's RRP Facility in the Repo Market. Finance and Economics Discussion Paper, No. 2018-027.

Anderson, A.G., Kandrac, J., 2018. Monetary policy implementation and financial vulnerability: Evidence from the overnight reverse repurchase facility. Rev. Financ. Stud. 31, 3643–3686.

Avalos, F., Ehlers, T., Eren, E., 2019. September Stress in Dollar Repo Markets: Passing or Structural? BIS Quarterly Review December 2019.

Baklanova, V., Caglio, C., Cipriani, M., Copeland, A., 2019. The use of collateral in bilateral repurchase and securities lending agreements. Rev. Econ. Dyn. 33, 228–249.
Baklanova, V., Copeland, A.M., McCaughrin, R., 2015. Reference Guide to U.S. Repo and Securities Lending Markets. FRB of New York Staff Report No. 740, Available at SSRN: https://ssrn.com/abstract=2664283.
Bank of England, 2018. Financial Stability Report, November 2018.
Bank of England, 2019. Financial Stability Report, December 2019.
Bank of England, 2020. Interim Financial Stability Report, May 2020.
Baranova, Y., Holbrook, E., MacDonald, D., Rawstorne, W., Vause, N., Waddington, G., 2023. The Potential Impact of Broader Central Clearing on Dealer Balance Sheet Capacity: A Case Study of UK Gilt and Gilt Repo Markets. Bank of England Staff Working Paper No. 1026.
Benos, E., Ferrara, G., Ranaldo, A., 2023. Collateral Cycles. Bank of England Working Paper No. 966.
Bicu-Lieb, A., Chen, L., Elliott, D., 2020. The leverage ratio and liquidity in the gilt and gilt repo markets. J. Financial Mark. 48, 100510.
Boissel, C., Derrien, F., Ors, E., Thesmar, D., 2017. Systemic risk in clearing houses: Evidence from the European repo market. J. Financ. Econ. 125, 511–536.
Capponi, A., Cheng, W.A., Rajan, S., 2015. Systemic Risk: The Dynamics Under Central Clearing. Working Paper (7 May 2015), Office of Financial Research.
CGFS, 2017. Repo Market Functioning. Committee on the Global Financial System (CGFS) Papers No 59.
Copeland, A., Martin, A., Walker, M., 2014. Repo runs: Evidence from the tri-party repo market. J. Finance 69, 2343–2380.
CPSS, 2010. Strengthening Repo Clearing and Settlement Arrangements. Committee on Payment and Settlement Systems.
Craig, B., Von Peter, G., 2014. Interbank tiering and money center banks. J. Financ. Intermediation 23, 322–347.
Cunliffe, J., 2020. Financial system resilience: Lessons from a real stress. Speech given by Sir Jon Cunliffe, Deputy Governor Financial Stability, Member of the Monetary Policy Committee, Member of the Financial Policy Committee and Member of the Prudential Regulation Committee Investment Association Webinar, London Tuesday 9 June 2020.
Czech, R., Gual-Ricart, B., Lillis, J., Worlidge, J., 2021. The Role of Non-bank Financial Intermediaries in the Dash for Cash in Sterling Markets. Bank of England Financial Stability Paper No. 47.
Duffie, D., Scheicher, M., Vuillemey, G., 2015. Central clearing and collateral demand. J. Financ. Econ. 116, 237–256.
Duffie, D., Zhu, H., 2011. Does a central clearing counterparty reduce counterparty risk? Rev. Asset Pricing Stud. 1, 74–95.
Duncan, E., Horvath, A., Iercosan, D., Loudis, B., Maddrey, A., Martinez, F., Mooney, T., Ranish, B., Wang, K., Warusawitharana, M., Wix, C., 2022. COVID-19 as a stress test: Assessing the bank regulatory framework. J. Financ. Stab. 61, 101016.
Dunne, P.G., Fleming, M.J., Zholos, A., 2013. ECB Monetary Operations and the Interbank Repo Market. FRB of New York Staff Report No. 654.
Eren, E., Schrimpf, A., Sushko, V., 2020. US Dollar Funding Markets during the COVID-19 Crisis - the Money Market Fund Turmoil. Bank for International Settlements, Bank for International Settlements, BIS Bulletin No 14.
European Commission, 2013. Commission delegated regulation (EU) no 153/2013. Off. J. Eur. Union 52, 41–74.
Farmer, J.D., Kleinnijenhuis, A.M., Nahai-Williamson, P., Wetzer, T., 2020. Foundations of System-wide Financial Stress Testing with Heterogeneous Institutions. Bank of England Staff Working Paper No. 861.
Gai, P., Haldane, A., Kapadia, S., 2011. Complexity, concentration and contagion. J. Monetary Econ. 58, 453–470.
Gerba, E., Katsoulis, P., 2021. The Repo Market under Basel III. Bank of England Staff Working Paper No. 809.
Ghamami, S., Glasserman, P., Young, H.P., 2022. Collateralized networks. Manage. Sci. 68, 2202–2225.
Giese, J., Haldane, A., 2020. COVID-19 and the financial system: A tale of two crises. Oxf. Rev. Econ. Policy 36, S200–S214.
Glasserman, P., Young, H.P., 2016. Contagion in financial networks. J. Econ. Lit. 54, 779–831.
Gorton, G., Laarits, T., Metrick, A., 2020. The run on repo and the Fed's response. J. Financ. Stab. 100744.
Gorton, G., Metrick, A., 2012. Securitized banking and the run on repo. J. Financ. Econ. 104, 425–451.
Hall, J., 2021. Building financial market resilience: From diagnosis to prescription. Speech given by Jonathan Hall, Member of the Financial Policy Committee of the Bank of England, at Cardiff Business School, 19 May 2021.
Han, S., Nikolaou, K., Tase, M., 2022. Trading relationships in secured markets: Evidence from triparty repos. J. Bank. Financ. 139, 106486.
Harris, R., Taylor, T., 2018. Sterling money markets: Beneath the surface. Bank Engl. Q. Bull. 58, 1–14.
Hauser, A., 2020. Seven moments in spring: COVID-19, financial markets and the Bank of England's balance sheet operations. Speech given by A. Hauser, Executive Director for Markets, Bank of England, on 4 June 2020, hosted by Bloomberg, London via webinar.
Hauser, A., 2021. From lender of last resort to market maker of last resort via the dash for cash: Why central banks need new tools for dealing with market dysfunction. Speech given by A. Hauser, Executive Director for Markets, Bank of England, on 7 of Januray 2021, London.
He, Z., Nagel, S., Song, Z., 2022. Treasury inconvenience yields during the COVID-19 crisis. J. Financ. Econ. 143, 57–79.
Hempel, S.J., Kahn, R.J., Nguyen, V., Ross, S.Y., 2022. Non-centrally cleared bilateral repo. The OFR Blog.
Huang, W., Takáts, E., 2020. The CCP-Bank Nexus in the Time of COVID-19. Bank for International Settlements, Bank for International Settlements, BIS Bulletin No 13.
Hüser, A.-C., 2015. Too interconnected to fail: A survey of the interbank networks literature. J. Netw. Theory Finance 1, 1–50.
Hüser, A.-C., Lepore, C., Veraart, L.A.M., 2021. How Do Secured Funding Markets Behave Under Stress? Evidence from the Gilt Repo Market. Bank of England Working Paper No. 910.
Julliard, C., Pinter, G., Todorov, K., Yuan, K., 2022. What Drives Repo Haircuts? Evidence from the UK Market, Bank of England Working Paper No. 985.
Kotidis, A., Van Horen, N., 2018. Repo Market Functioning: The Role of Capital Regulation. Bank of England Staff Working Paper No. 746.
Kotidis, A., Van Horen, N., 2019. Repo Market Functioning: The Role of Capital Regulation. Bank of England Staff Working Paper No. 746.
Krishnamurthy, A., Nagel, S., Orlov, D., 2014. Sizing up repo. J. Finance 69, 2381–2417.
Kusnetsov, M., Veraart, L.A.M., 2019. Interbank clearing in financial networks with multiple maturities. SIAM J. Financial Math. 10, 37–67.
Langfield, S., Liu, Z., Ota, T., 2014. Mapping the UK interbank system. J. Bank. Financ. 45, 288–303.
Luu, D.T., Napoletano, M., Barucca, P., Battiston, S., 2020. Collateral unchained: Rehypothecation networks, concentration and systemic effects. J. Financ. Stab. 100811.
Macchiavelli, M., Zhou, X., 2022. Funding liquidity and market liquidity: The broker-dealer perspective. Manage. Sci. 68, 3379–3398.
Mancini, L., Ranaldo, A., Wrampelmeyer, J., 2016. The Euro interbank repo market. Rev. Financ. Stud. 29, 1747–1779.
Martin, A., Skeie, D., Thadden, E.-L.v., 2014. Repo runs. Rev. Financ. Stud. 27, 957–989.
Mazzarisi, P., Barucca, P., Lillo, F., Tantari, D., 2020. A dynamic network model with persistent links and node-specific latent variables, with an application to the interbank market. European J. Oper. Res. 281, 50–65.
Munyan, B., 2017. Regulatory Arbitrage in Repo Markets. Office of Financial Research Working Paper. 15–22.
Noss, J., Patel, R., 2019. Decomposing Changes in the Functioning of the Sterling Repo Market. Bank of England Staff Working Paper No. 797.
Paddrik, M.E., Ramirez, C.A., McCormick, M., 2021. The Dynamics of the U.S. Overnight Triparty Repo Market. FEDS Notes.
Ranaldo, A., Schaffner, P., Vasios, M., 2019. Regulatory Effects on Short-Term Interest Rates. Bank of England Staff Working Paper No. 801.
Roberts-Sklar, M., Baines, T., 2020. Have Hedge Funds Increased Their Use of Repo Borrowing? Bank of England Overground Article.
Schrimpf, A., Shin, H.S., Sushko, V., 2020. Leverage and Margin Spirals in Fixed Income Markets During the COVID-19 Crisis. Bank for International Settlements, Bank for International Settlements, BIS Bulletin No 2.
U.K. DMO, 2021. GEMM guidebook, a guide to the roles of the DMO and Primary Dealers (GEMMs) in the UK government bond market. Publication by the UK Debt Management Office (DMO).