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Abstract

We examine how the overnight gilt repo market operates during three episodes of liquidity stress, using novel transaction-level data on repurchase agreements on gilts. Using network analysis we document that the structure of the repo market significantly changes during stress relative to normal times, with a focus on how sectors adjust volumes, spreads and haircuts in their repo transactions. We find several common patterns in the two most recent stress episodes (the US repo turmoil in 2019 and the Covid-19 crisis in 2020): a preference for dealers and banks to transact in the cleared rather than the bilateral segment of the market, increased usage of the market by hedge funds and central counterparties increasing their reinvestment of cash margin into reverse repo.

Key words: Repo market, liquidity risk, financial networks, market microstructure, Brexit referendum, US repo turmoil, Covid-19 crisis.

JEL classification: D85, G01, G21, G23.

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1 Introduction

The repo market is key to the provision of short-term liquidity in the financial system. Since the global financial crisis (GFC), it has been characterized by weakened market functioning (CGFS, 2017). Recent spikes in repo rates, such as in September 2019 in the US and the COVID-19 "dash for cash" in March 2020, have added evidence of dysfunctionality in this market. Our current understanding of market structure and dynamics during a liquidity stress is still very limited, not least due to scarce data (Gorton et al., 2020). However, Martin et al. (2014) show in a theoretical model how important the microstructure is for the fragility of secured funding markets. Studies of previous repo turmoils during the GFC and the European sovereign debt crisis highlight that different repo market segments and participants can behave very differently during times of stress (Gorton & Metrick, 2012; Copeland et al., 2014; Krishnamurthy et al., 2014; Mancini et al., 2016; Boissel et al., 2017),[1] pointing to the importance of empirically capturing the heterogeneity of the repo market structure. Besides Gorton & Metrick (2012) who study the bilateral segment but using proxy data, all of the above studies are based on an analysis of the cleared or tri-party segment of the market. As Krishnamurthy et al. (2014) points out, they "lack data on the bilateral repo market, and thus the full picture on repo is yet to be assembled."

We fill this gap by providing a joint empirical analysis of the bilateral and cleared segment of the repo market and offering a unique window into the current structure and functioning of the market, both in normal and stress times. We apply network analysis to unique granular transaction data of the gilt repo market[2] to study the market structure at institutional and sectoral level. Our sample period from June 2016 to May 2020 covers both a normal regime and three stress episodes: the referendum on the UK's EU membership in June 2016, the US repo turmoil in September 2019 and the COVID-19 "dash for cash" in March 2020.[3] Using a simple econometric model, we find that trading relationships between sectors, in terms of volumes, spreads and haircuts, significantly change during the stress episodes relative to normal times. Most notably, there are several common patterns in the two most recent stress episodes: a preference for dealers and banks to transact in the cleared rather than the bilateral segment of the market, increased usage of the market by hedge funds and central counterparties increasing their reinvestment of cash margin into reverse repo.

In terms of market structure we find that the repo network, as characterized by the transaction links, has a strong core-periphery structure. Banks and gilt dealers[4] form the network's core. They are the key intermediaries and transact amongst each other as well as with all the other sectors active in the market. Non-banking sectors are located in the periphery,[5] only

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

[2] 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.

[3] The three stress episodes represent a domestic, international and global shock respectively. Please refer to Section 2.5 for a more detailed description of these episodes.

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

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

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.

In terms of market functioning in times of stress, our analysis of transaction volumes shows that core sectors have a preference to transact with each other via the CCP rather than bilaterally. This trend, already noted in a report by the Committee of the Global Financial System (2017), is likely to be driven by the option to net transactions with a CCP, thereby not affecting the size of a bank's balance sheet as reported for regulatory purposes.[6] Previous empirical research, conducted on data for normal times, highlights that the introduction of the UK leverage ratio affected the capacity of dealers to intermediate in the gilt repo market (Bicu-Lieb et al., 2020; Kotidis & Van Horen, 2018).

We are able to show empirically that volumes traded by banks and dealers via the CCP significantly increase during stress compared to normal times. Indeed, during the two more recent stress episodes, the US repo turmoil and the COVID-19 crisis, we find that core sectors increase their lending via cleared markets during stress. This finding is in line with the conclusion reached by Noss & Patel (2019) that cleared repo transactions are better able to absorb an increase in demand for liquidity because of their netting benefits[7]. At the same time, we find that lending from the core to most non-bank sectors decreases relative to normal times. Further, when looking at repo spreads, we find that in times of stress they tend to increase the most when gilt dealers and banks are the lenders. This empirically confirms theoretical findings that, in a context of post-crisis regulation, dealers demand compensation for the shadow cost of balance sheet expansion via repo in the form of higher repo rates (He et al., 2020). Taken together, these results suggest that the banking sector has a preference for the cleared segment of the market and has become less able or willing to accommodate an increase in demand for liquidity in the bilateral segment.

A second driver of the significant increase in trading in the cleared segment during stress is that CCPs invest the additional cash margin they collect during periods of increased volatility. Taking the case of the COVID-19 stress in particular, 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 & 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.

Further, our analysis provides results on non-banks behaviour in the repo market. First, we confirm that hedge funds' increased reliance on the repo market, as highlighted by other recent studies (see for instance Roberts-Sklar & Baines (2020) and Schrimpf et al. (2020)). In particular, we find that hedge funds increase their net borrowing positions during the US repo turmoil and even more so during the COVID-19 crisis. Second, we find that MMFs increase cash investments in overnight gilt repo market, relative to normal times, placing them with gilt dealers. It is interesting that this pattern is present during the COVID-19 stress, despite MMFs

[6] CGFS (2017) defines netting in the following terms: "Although netting rules differ in their details, they generally provide for a cash receivable due from a counterparty to be presented net of a cash payable due back to the same counterparty, provided that the payment dates and settlement mechanisms match. As such, two matching repo/reverse repo transactions, with different underlying bonds but the same settlement date and identical opposing cash flows, do not affect the size of a bank's balance sheet as reported for regulatory purposes."

[7] They reach this conclusion using a simulation on gilt repo market data in normal times. By contrast, we empirically investigate stress periods.

[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.

experiencing large outflows during the "dash-for-cash" episode in March 2020. In particular, during this episode, MMFs display a preference for investing cash in the overnight gilt repo market relative to longer maturities. This result indicates their preference for short-term safe investments, in line with findings on US MMFs behaviour during the COVID-19 stress (Eren et al., 2020).

Finally, we provide an aggregate analysis of the resilience of the UK repo market by analysing aggregate volumes, spreads and haircuts and their relationship with systemic risk and other key macro-economic variables. Following Mancini et al. (2016) we study the sensitivity of aggregate repo market activity to systemic risk, as measured by the Composite Indicator of Systemic Stress (CISS) developed by Hollo et al. (2012). We find that the cost of repo is positively related to risk, hence the UK repo market does not act as a shock absorber. However, aggregate volumes and haircuts are not significantly affected by risk and hence can be considered as resilient.

Our results contribute to the existing literature in several ways. First, we contribute to the literature that empirically analyses repo markets during stress periods. Our uniquely granular dataset covers almost the entire universe of transactions in the gilt repo market, including different segments, market participants and their repo trades volumes, rates and haircuts. As a result, we are, to the best of our knowledge, the first to jointly analyse the bilateral and the cleared segment of the repo market and to quantify empirically inter-sectoral changes in repo market activity in these segments during times of stress. Indeed, previous empirical studies using detailed repo market data either focused on the US tri-party market (Copeland et al., 2014; Krishnamurthy et al., 2014) or on the CCP-based euro interbank repo market (Mancini et al., 2016; Boissel et al., 2017). We add to this literature by looking at the bilateral segment, as well as cleared, of the gilt repo market in stress, which is one of the world's core repo markets[9]. Furthermore, we study the dynamics of the COVID-19 "dash for cash" in March 2020 in the repo market and the impact of the US repo turmoil in September 2019 on a non-dollar repo market, whereas previous studies focused on its impact on the US repo market (Avalos et al., 2019; Correa et al., 2020). Hence, we fill a gap in the literature here too.

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

Finally, given the scarcity of data on repo markets (Gorton et al., 2020), we provide a unique insight for the theoretical debates on repo market structure (Martin et al., 2014), central clearing (Duffie & Zhu, 2011; Capponi et al., 2015; Duffie et al., 2015) and the modelling of its network dynamics (Luu et al., 2020; Ghamami et al., 2020+). Regarding the latter, while most of the existing approaches consider models of a dynamic contagion process on a static network[10], 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

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

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

to the importance of developing dynamic network models to assess financial stability.[11]

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

More generally, our paper sheds light on the behaviour of non-banks under stress. This is an area of the financial system in need of further consideration as recommended by Giese & Haldane (2020). The COVID-19 crisis has re-emphasized the importance of non-banks and their potential to generate systemic risk. In a recent speech (Cunliffe, 2020) the Bank of England deputy governor for financial stability John Cunliffe asked: "do we need more resilience, particularly liquidity resilience, in the non-bank parts of the financial system?" While we cannot offer a complete answer, we document important patterns in non-bank behaviour during recent stress episodes in the overnight repo market. In particular, hedge funds increased their borrowing relative to normal times, signalling an increasing reliance on this market for short-term funding in stress. A policy implication following from this result is that broadening liquidity facilities to non-banks participants in times of stress could produce positive spillovers to other sectors in gilt repo markets and further enhance its resilience.

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. Section 2 provides an overview of the gilt repo market and zooms in the overnight segment in more details. Furthermore, this section introduces the three stress episodes we will focus on. Section 3 analyses the network structure of the market, and how it evolves under stress. Section 4 provides an analysis of how repo market activity, in terms of volumes, spreads and haircuts between sectors react to the stress episodes. Finally, Section 5 looks into the question of aggregate resilience of the gilt repo market and Section 6 concludes.

2 The gilt repo market

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. Throughout this paper we focus on the 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*.

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

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

transaction. We denote by $h = 1 - V/g \in \mathbb{R}$ the *haircut*.[12] This implies that $V = (1 - h)g$. 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*. 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.

In this section we provide an overview of the gilt repo market, and in particular its overnight segment, using the Bank of England Sterling Money Market (SMM) data. We then discuss three episodes of stress, which will be analysed in detail in the rest of the paper.

2.1 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 potential 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 June 2016 until 11 May 2020.

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

2.2 Settlement

Trades in the repo market can be settled in three ways: bilaterally, tri-party and through a central counterparty (CCP). In the UK, only 1% of the UK gilt repo market is settled tri-party.[14][15] CCPs have a special role in the repo market. They do not actively provide liquidity. They do two things. First, they clear trades between counterparties. In that sense they neither provide nor demand liquidity themselves but may make it easier or less risky for clearing members to do so. Haircuts on cleared repo trades are determined by the original counterparties to the trade - details are then simply passed to the CCP, which novates the trade and replaces it with two equal and opposite trades with the two counterparties. The haircut therefore just reflects market dynamics, in much the same way as for bilateral repo. Margins are determined independently by the CCP, and paid by both counterparties. Second, the CCP sector lends cash collected from margin payments[16] as reverse repo, purely as a cash management process. 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. Figure 1 shows that on average 37% of total repo volumes across all maturities are traded with the CCP sector and 63% with other sectors in our sample. We will go into more detail on the other sectors in Section 3.

[12] Sometimes an accrued interest of the collateral is included in this definition.

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

[14] This figure excludes trades settled through the CREST delivery-by-value (DBV) mechanism.

[15] By contrast, in the US half of the dealer-client market is settled tri-party via a clearing bank. The other half is settled bilaterally.

[16] CCPs typically accept cash or government bonds (and sometimes a few other assets) as margin collateral, so it does not automatically follow that an increase in margin requirements will feed through 1:1 to increased cash reinvestment, e.g. if the additional margin is paid in non-cash collateral.

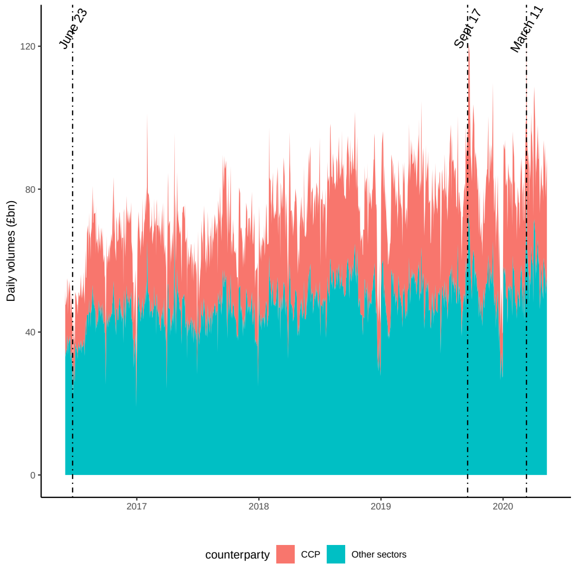
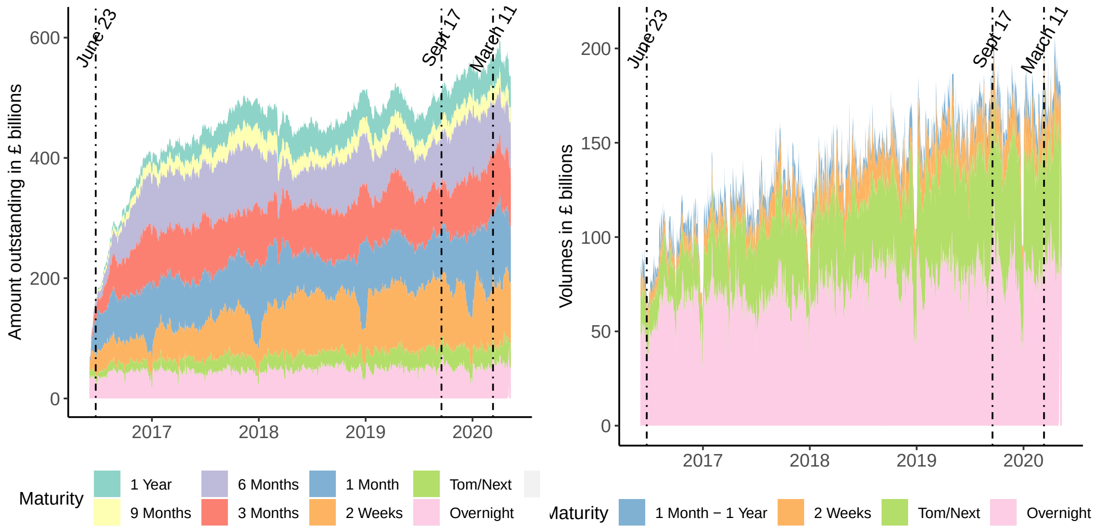


Figure 1: Aggregate repo volumes traded with the CCP and other sectors.

2.3 Outstanding amounts and volumes by maturity

In the sample, the total amount outstanding[17] across all maturities in the repo and reverse repo has been on average £548 billion. The value of transactions outstanding is quite evenly spread across different maturities, see Figure 2(a). Even though it might appear in Figure 2(a) that contracts between 2 Weeks and 6 Months increase most in terms of amount outstanding over time, this is not necessarily the case. For the longer maturities, the stock will need longer to build up in the data set, since they are traded less on a daily basis. This can be seen in Figure 2(b) which shows the daily volumes traded in each maturity.



(a) Amount outstanding of repo by maturity buckets in bn £.

(b) Volumes by maturity buckets in bn £.

Figure 2: Amount outstanding and volumes for different original maturities.

[17] To compute the total repo amount outstanding we have excluded from the repo data set the reverse repo trades where the counterparty is a CCP, so that a transaction that goes through a CCP is counted only once and not twice.

Transaction volumes are highly concentrated at shorter maturities (Figure 2(b)). The overnight segment attracts on average daily 73 bn £ and the Tom/Next segment 43 bn £ out of a total daily average of 137 bn £. 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 is 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. This is in line with other studies on repo market resilience, such as Mancini et al. (2016).

2.4 The overnight repo market

We will now zoom into the overnight segment of the gilt repo market, which is the focus of the remainder of the paper, providing an overview of market activity in terms of volumes, rates and haircuts.

A total of 247 institutions trade in the overnight repo market between June 2016 and May 2020. The daily average number of institutions active is 60, with large fluctuations of market participation around key reporting dates at quarter- and year-ends, as shown in Figure 3(a). These are well-known period of window dressing for banks and dealers, as documented in Kotidis & Van Horen (2018) for the UK repo market and by the BIS for the US.[18]

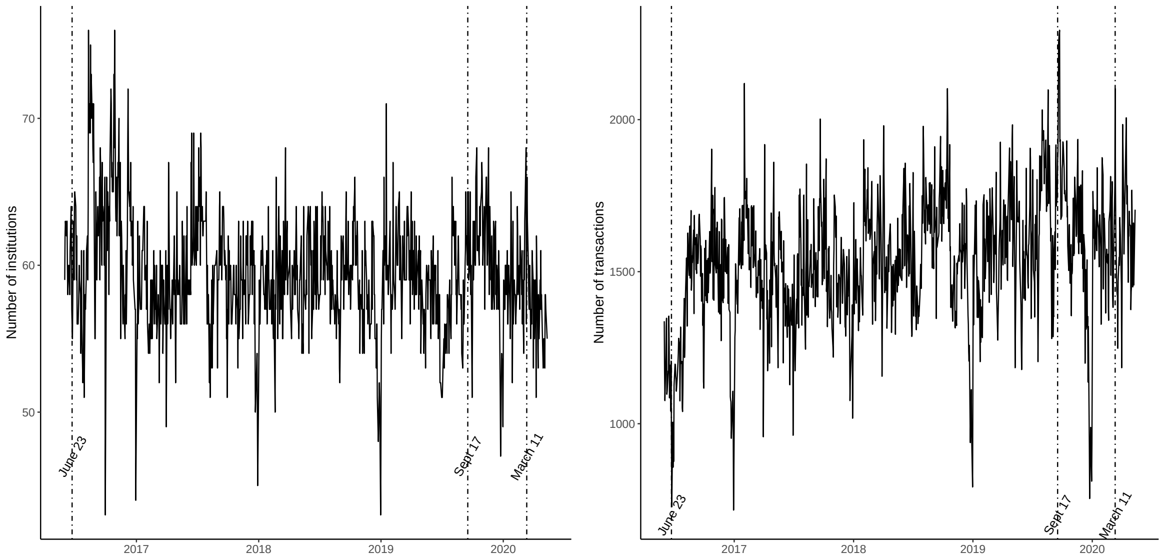
Furthermore, while the average number of participants is broadly constant over time, the number of transactions in the overnight market shows a slight upward trend, suggesting an increase in trading activity, see Figure 3(b). Within our sample period, there was also an increase in volumes, as shown in Figure 4(a). This is a relatively new trend, following a transitional phase prior to 2016 when the post-crisis environment had affected repo market functioning and consequently volumes traded, as documented in CGFS (2017) for different jurisdictions. For the UK, Bicu-Lieb et al. (2020) show that gilt repo liquidity worsened during the period when the leverage ratio policy was announced (2010-2015) and that gilt repo liquidity had become less resilient. Noss & Patel (2019) find that there was a reduction in intermediation by dealers between 2014 and 2016, followed by an improvement between 2016 and 2018.

The cost of repo transactions are typically represented as a spread above the relevant monetary policy rate. In the following we will compute the spread as the overnight repo rate minus the Bank of England's policy rate. The repo rate is the interest rate on the transaction. Figure 4(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. As highlighted in Harris & Taylor (2018), due to the different usages of the repo market from several sectors, the repo market structure is complex. Therefore, movement in rates can be caused by a variety of reasons. Spreads tend to show large negative spikes at year-end and quarter-end, in line with the movements observed in the volumes.

Spreads are more volatile and negatively skewed in the first part of our sample (from 2016 to 2018). This period has been characterized by high market uncertainty, in particular around key Brexit dates, changes in regulations (in particular the leverage ratio) and monetary policy interventions. Spreads have been less volatile in 2019, with some exceptions,[19] consistent with the view that repo market functioning has been stabilizing in recent years. However, the COVID-19 crisis has sparked new volatility in repo rates, with rates becoming elevated in mid-March 2020. As explained in the Bank of England (2020), "the cost of repo borrowing increased as

[18] See https://www.bis.org/publ/arpdf/ar2018e3.pdf

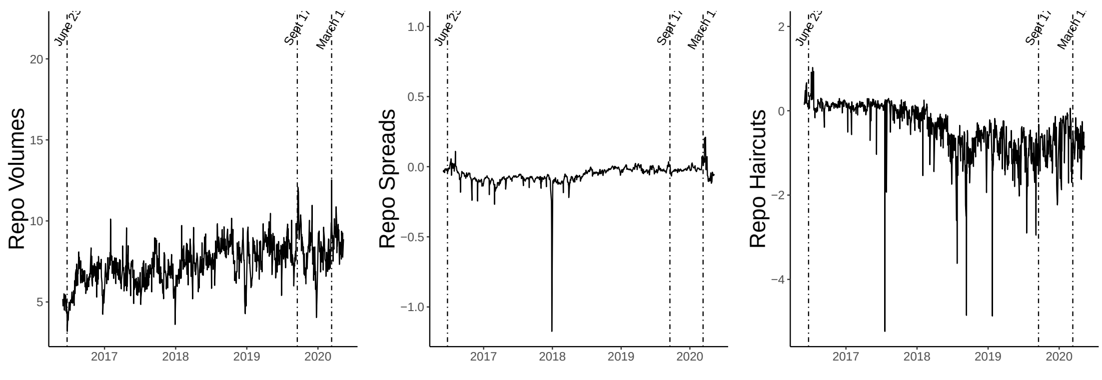
[19] One exception is , e.g., the period around the international developments in the US repo market, as explored in more details in Section 4.



(a) Number of daily active institutions.

(b) Number of daily transactions.

Figure 3: Times series of market participation.



(a) Aggregate average volume in overnight market (in £ billions).

(b) Aggregate average volume weighted repo spread in overnight market (in percentage).

(c) Aggregate average volume weighted haircut in overnight market (in percentage).

Figure 4: Average overnight repo volume, volume weighted spread and volume weighted haircut.

demand increased, and dealers' ability and willingness to intermediate was constrained." The subsequent policy interventions, both domestic and international, effectively stabilized short-term repo rates.

Similarly, when looking at the volume-weighted distribution of haircuts in our sample, we can observe two different regimes in the distribution of haircuts. The first regime between 2016 until early 2018, characterized by higher haircuts with a wider variation, followed by the second regime of smaller and less volatile haircuts. Overall, in recent years the average haircut has decreased as shown in Figure 4(c).

2.5 Three periods of stress in the repo market

Next, we will provide background information on the three time periods of stress that we will analyse.

Our first case study is the period around the referendum on the UK's membership of the EU that took place on 23 June 2016. The UK voted to leave the EU, which triggered significant market volatility and economic uncertainty. As reported in Bank of England (2016) market falls in a range of UK assets reflected "an increase in risk premia on UK assets, a perceived weaker growth outlook, and anticipation of some future deterioration in the United Kingdom's terms of trade and supply capacity." In this environment, an ensuing flight to safety led gilt yields to fall. Figure 5(a) shows that yields on 10-year gilts decreased 8 bps in the week before the EU Referendum, and by 50 bps straight after the EU Referendum vote, between 23/06 and 30/06. In the overnight gilt repo market, Figure 4(a) illustrates that aggregate volumes declined sharply around the event and repo spreads rose in its aftermath (Figure 4(b)). The decline in volumes, however, was continuing a previous trend of declining market activity (as documented in Noss & Patel (2019)). Figure 4(c) shows that haircuts are markedly higher around the EU referendum compared to the rest of the sample. Overall, this was a period of heightened volatility, but its impact on the repo market was contained and temporary. Secured lending markets were considered to be resilient (Bank of England, 2016).

The second case study is around the period of high volatility in the US repo market in mid-September 2019. On 17th September, the secured overnight funding rate (SOFR) - the new repo market-based US dollar overnight reference rate[20] - more than doubled[21] reaching 3.15% above the interest paid on reserves (IOR)[22], see Figure 5(b). 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. The first change is that the Fed has been reducing the size of its balance sheet, which implies a reduction of cash reserves banks hold at the Fed. Ultimately this implies that banks have less cash directly available to cover short-term funding stress. A second change is the increased demand for funding from leveraged financial institutions such as hedge funds via Treasury repos (Avalos et al., 2019). A third change is due to liquidity and leverage regulations which might constrain banks' ability to lend out large amounts of cash for example in the repo market. In line with this explanation, Kotidis & Van Horen (2018) have shown that dealers subject to a more binding leverage ratio have reduced liquidity supply in the UK repo market after a tightening of reporting requirements in January 2017. While this stress episode did not originate in the UK, we are interested in understanding the potential spillovers to the gilt repo market. Figure 4(a) shows that aggregate gilt repo volumes in the

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

[21] 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).

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

overnight market spiked on September 17, indicating a large temporary increase in borrowing volumes. The Federal Reserve launched a number of operations, aimed at returning the market to conditions consistent with its target monetary policy range. These policy measures "stabilised the market [...] and helped to limit spillovers to broader market conditions", as reported in Bank of England (2019).

Finally, our third case study considers the COVID-19 pandemic with a particular focus on the period of March 2020 where volatility in financial markets and economic uncertainty was particularly pronounced. The episode has been described as an extreme "dash for cash" by the Bank of England (2020). As in financial market asset prices adjusted very sharply, margin calls on derivative exposures went up sharply as well. The need to post additional margin generated sharp 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. This development is shown in Figure 5(a) for the 10-year gilt yield. However, as reported in Bank of England (2020), "in mid-March even safe, typically highly liquid assets, such as government bonds, came under forced selling pressure and saw little demand, as markets became characterised by exceptionally high demand for cash and near-cash short-dated assets." This rise in demand for cash particularly affected MMFs. Sterling MMFs saw outflows of 10% of their total assets in the eight days between 12 and 20 March. Overnight repo rates rose sharply, as shown in Figure 4(b), interpreted as a "particularly serious sign of dysfunction" (Hauser, 2020). Figure 4(a) shows that repo volumes were increasing sharply up to March 11, as demand for liquidity built up.

Several sets of policy actions helped to ease pressure on money market rates and gilt markets. On March 11, the Bank of England reduced the Bank Rate by 50 basis points to 0.25%. On March 19, the Bank of England decided to buy gilts in large size – coupled with similar policy actions by other central banks, which helped stabilise broader markets. And, 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.

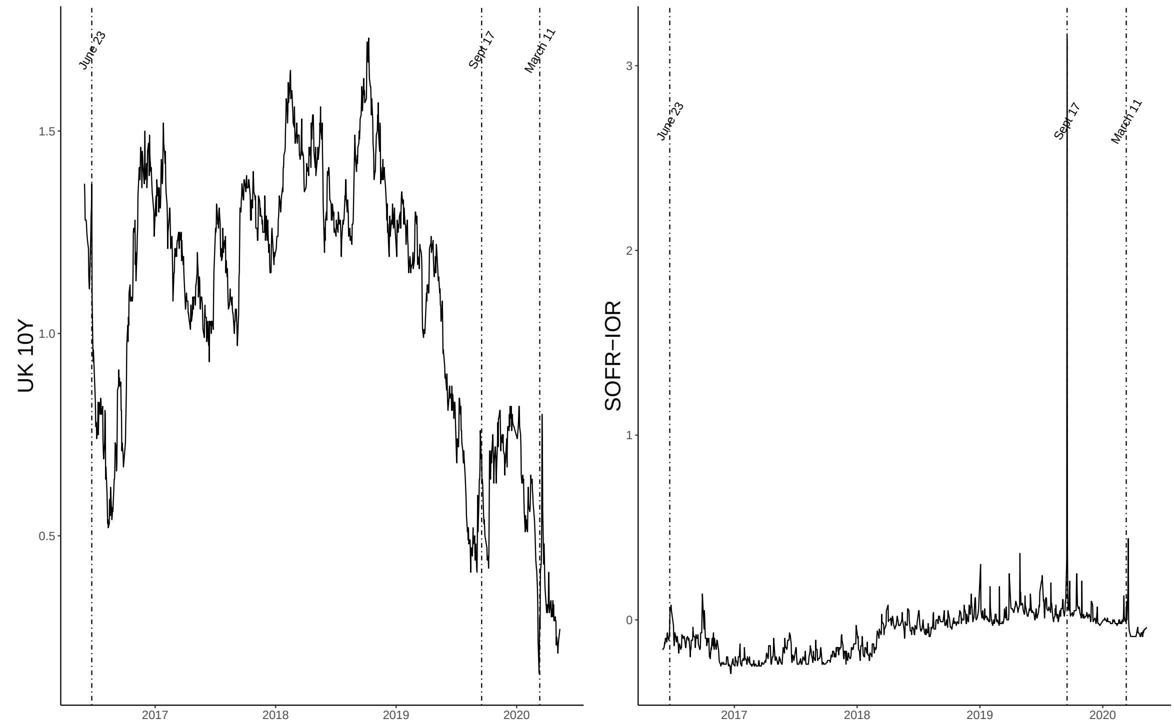
These episodes are all different in nature and therefore represent interesting case studies to analyse how the gilt repo market reacts to a domestic, international and global shock respectively. Let us now introduce some notation for these time periods of stress, which will be useful in our statistical analysis.

Definition 2.1 (Time windows for case studies). *Throughout this paper we will denote by* $\mathcal{T} = \{t_0, t_1, \ldots, t_T\}$ *the set of all discrete time points (i.e., days) considered in our analysis of the overnight repo market. We have* $t_0 = 1$ *June* 2016, $t_T = 11$ *May* 2020 *and* $T + 1 = 998$. *We will denote by* $\mathcal{T}^{CS1} \subset \mathcal{T}$ *the dates associated with our first case study, i.e., 20 June 2016 - 8 July 2016, by* $\mathcal{T}^{CS2} \subset \mathcal{T}$ *the dates associated with our second case study, i.e., 03 September 2019 - 17 September 2019 and by* $\mathcal{T}^{CS3} \subset \mathcal{T}$ *the dates associated with our third case study, i.e., 03 March 2020 - 23 March 2020.*

3 How does the network structure change under stress?

Having described the aggregate market dynamics in periods of stress, we are interested in delving deeper into the sectoral and institutional behaviour, exploiting the granularity of our unique data set. In particular, in this section we will analyse how the structure of the overnight gilt repo market changes under stress using a network perspective.

To do so we define a set of nodes which will remain constant over time. We will distinguish between the *institutional* and the *sectoral network*. In the institutional network the nodes



(a) 10-year gilts yields (in percentage).

(b) SOFR-IOR spread (in percentage).

Figure 5: Time series of the 10-year gilts yield and SOFR-IOR spread.

represent individual institutions, whereas in the sectoral network the nodes represent different sectors, e.g., banks, hedge funds etc. Any institution or sector that is involved in a repo or reverse repo agreement at least once during our sample period is included in the set of nodes representing institutions or sectors, respectively.

We also define a set of edges for each time-point (trading day). The edges are weighted and directed. Throughout this paper we will consider three different interpretations of an edge: edges either represent the volume of cash borrowed between two nodes in an overnight repo agreement on a given day, the corresponding repo spread (volume-weighted in the sectoral network) or the corresponding haircut (volume weighted in the sectoral network) of the agreement. Throughout this section edges will represent volumes. We will start by considering the institutional network.

3.1 The institutional network

3.1.1 General characteristics

We define the institutional networks of volumes as follows.

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

1. *The* institutional network of volumes *consists of a set of nodes denoted by* $\mathcal{N}^{(I)} = \{1, \dots, N^{(I)}\}$, $N^{(I)} = 225$, *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* $A^{(I)}(t) = (A^{(I)}_{ij}(t))_{i,j\in\mathcal{N}^{(I)}} \in \{0,1\}^{N^{(I)}\times N^{(I)}}$ *the adjacency matrix at time* t *that corresponds to the network of cash lent in the institutional network, i.e.,*

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

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, $V^{(I)}_{ij}(t)$ represents the sum of the corresponding notional amounts of cash, i.e., the total amount of cash traded on day t. In the following, we will illustrate the main general features of the institutional network of volumes. First, we consider the transaction volumes between each pair of institutions averaged over the whole sample period. These can be represented by the matrix $\bar{V}^{(I)} = (\bar{V}^{(I)}_{ij})_{i,j\in\mathcal{N}^{(I)}} \in [0,\infty)^{N^{(I)}\times N^{(I)}}$, where

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

Figure 6(a) shows the heatmap of $\bar{V}^{(I)}$, i.e., each coloured cell represents the average transaction volume between two institutions in the overnight gilt repo market over the whole sample. The rows show the average volumes lent in the overnight gilt repo market over the whole sample for each institution. The columns show the average volumes borrowed in the overnight gilt repo market over the whole sample for each institution. The institutions are ordered by the sum of average repo and reverse transactions (in other words by the sum of their column and row aggregates), with the institution with the largest average volumes traded located in the lower left corner. The coloured scale represents the average transaction volume of each institution for the whole sample. The darker the red, the larger the average transaction volume of that institution.

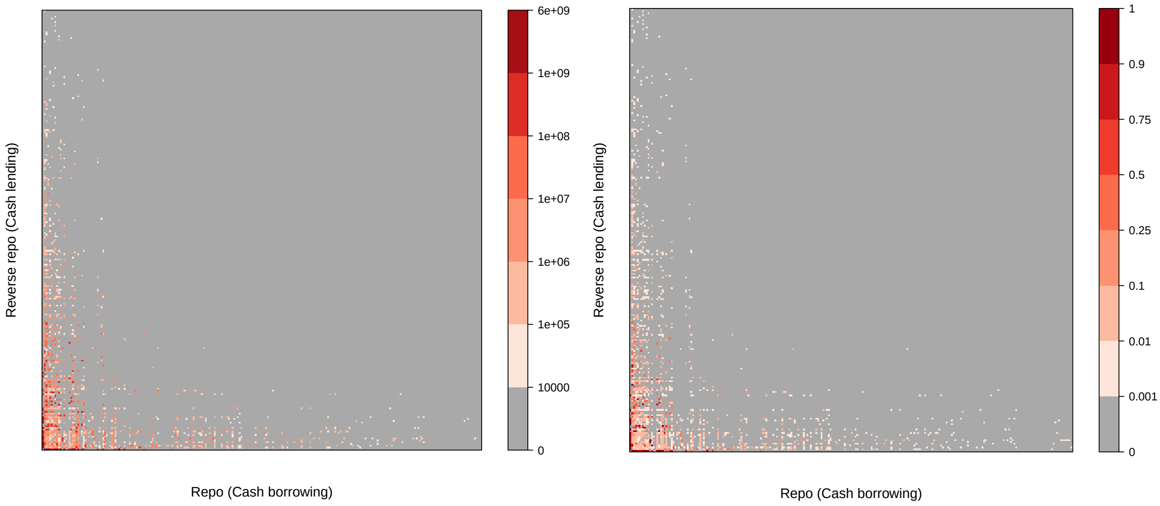
We see that the overnight gilt repo market exhibits a core-periphery structure. In the lower left corner of Figure 6(a) we can identify a cluster, as well as more scattered elements in the left most columns and the last few rows of the heatmap. The cluster in the lower left corner is the core of institutions which transact repo amongst themselves as well as with the periphery, which are the more scattered elements extending top and right of the cluster. It is interesting to note that the cluster in the lower left corner is redder, 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, see e.g. Craig & Von Peter (2014), 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.

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

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

Hence, $\bar{A}^{(I)}_{ij}$ represents the empirical probability that institution i lends institution j cash in a repo transaction on a given day. Figure 6(b) shows a heatmap of $\bar{A}^{(I)}$. For ease of comparison, the institutions are ordered in the same way as in Figure 6(a). Each cell represents the probability that two institutions trade with each other on any given day in the whole sample. The darker the red of the cell, the higher is the likelihood that these two institutions trade on any given day. The darkest red ranges from 0.9 to 1 and means that two institutions trade between 90 and 100 percent of days in our sample, implying an almost continuous daily roll-over of trades.

Figure 6(b) shows that overall the empirical transaction probabilities corresponding to the lower left corner, i.e., the core, are still rather low for the majority of institution pairs. This implies, that there is no daily roll-over of overnight repo (not even in the core) for the majority of core institution pairs for the whole sample. 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 observe almost daily roll-over for the whole period.



(a) $\bar{V}^{(I)}$.

(b) $\bar{A}^{(I)}$.

Figure 6: Heatmap of average transaction volume $\bar{V}^{(I)}$ (defined in (2)) and the observed transaction probability $\bar{A}^{(I)}$ (defined in (3)).

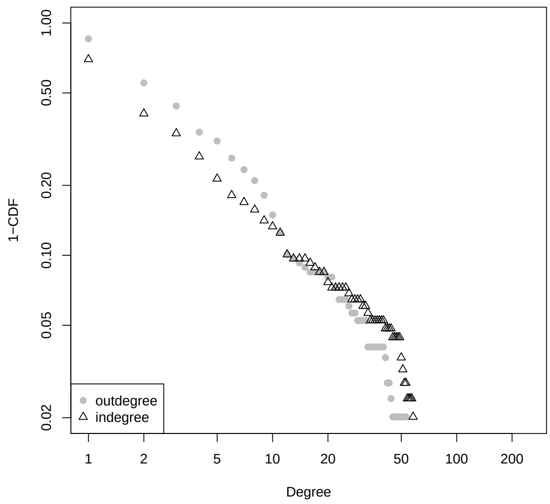


Figure 7: Empirical survival function of the average in- and outdegrees.

Figure 7 provides further evidence that the network has a core periphery structure. 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[23] and $d \in \{1, \ldots, N^{(I)} - 1\}$) 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 $N^{(I)} = 225$ 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 our data set, nodes in the periphery, do not have repo or reverse repo agreements with other nodes in the periphery but only with banks or gilt dealers in the core. This substantially lowers the possible number of connections for peripheral nodes. For the y-axis we consider all values in $[0, 1]$ since we are interested in a probability, i.e., the empirical survival function. The empirical survival function (indicated by the label 1-CDF) represents the probability that a node in our sample has a strictly larger (in- or out-) degree than the number indicated on the $x-$axis. For example, when we consider the (in- or out-) degree of 5 on the x-axis, we see in Figure 7, 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 60 on the x-axis, then the probability that a node has an (in- or out-) degree larger than 60 is 0. We find that the maximum number of incoming or outgoing edges is around 60. 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.

Note that Figure 7 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.

3.1.2 Changes under stress

We will now analyse how some network characteristics change over time and in particular during the three stress episodes. Figure 8 shows time dependent network characteristics.

Figure 8(a) shows the average degree over time. 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. This confirms our findings from Figure 6 that the network is very sparse.

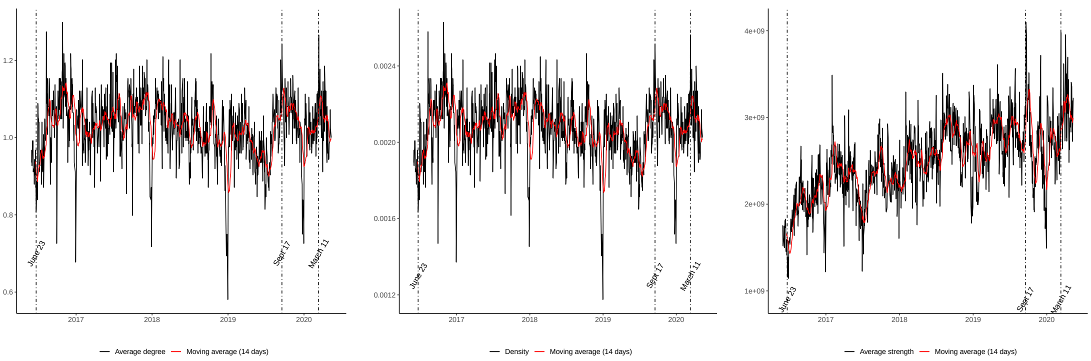
Very much related is Figure 8(b) which plots the density of the network of all institutions over time. The density of a network is the ratio of existing links between nodes out of all the possible links that could exist between the nodes in the network. Mathematically, the time-t density at time t for the institutional network is defined as $\frac{1}{N^{(I)}(N^{(I)}-1)} \sum_{i=1}^{N^{(I)}} \sum_{j=1}^{N^{(I)}} A_{ij}^{(I)}$. The average density for the whole sample is very low: 0.002. It means that on average, 0.2% of the possible edges are present in the network, again confirming the sparsity result.

In both Figures 8(a) and 8(b) we see clear dips at year ends and some smaller dips at quarter ends which is in line with the window dressing effects observed at these times discussed earlier. We also find that during the EU referendum the network is generally less connected than for later parts of the sample. This is in line with the general decline of activity in the repo market around that time. For the US repo crisis and the COVID-19 stress episode, however, we find clear evidence that the density of the network increases during these time periods, i.e., the network becomes more connected during these stress periods.

Figure 8(c) shows the average strength of the active nodes over time. The strength of the node is a volume-weighted degree, meaning that the volumes corresponding to the transaction

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

links are included. We denote the number of active nodes at time t by $n^{(a)}(t) \leq N^{(I)}$ and we say that a node is active if it has at least one incoming or one outgoing edge. Then the average strength of active nodes at time t is given by $\frac{2\sum_{i,j=1}^{N^{(I)}} V_{ij}^{(I)}(t)}{n^{(a)}(t)}$ and therefore a scaled version of the aggregate volume. We see that it increases over time, with some clear dips at quarter- and year-ends. During the EU referendum it is still low, consistent with generally lower volumes. As pointed out in Noss & Patel (2019), between January 2014 and June 2016, “there has been a sharp deterioration, followed by a subsequent improvement, in the functioning of the gilt repo market [...] However, between July 2016 and April 2018, some of this deterioration reversed”. This is consistent with our observations. More recently, during the US repo crisis and the COVID-19 stress period we find that the average strength increases significantly indicating higher transaction volumes per node.



(a) Average degree. (b) Density. (c) Average strength.

Figure 8: Time series of descriptive statistics for the institutional network of volumes.

We will now investigate whether some pairs of nodes trades mainly trade during stress episodes, to help us understand if some institutions turn to the overnight gilt repo market especially during liquidity stress. To do this, we consider the matrix $Y^{\text{CS}} = (Y_{ij}^{\text{CS}})_{i,j \in N^{(I)}} \in [0,1]^{N^{(I)} \times N^{(I)}}$, where for $i, j \in \mathcal{N}^{(I)}$

$$Y_{ij}^{\text{CS}} = \begin{cases} \frac{\sum_{t \in \mathcal{T}^{\text{CS1}} \cup \mathcal{T}^{\text{CS2}} \cup \mathcal{T}^{\text{CS3}}} A_{ij}^{(I)}(t)}{\sum_{t \in \mathcal{T}} A_{ij}^{(I)}(t)}, & \text{if } \sum_{t \in \mathcal{T}} A_{ij}^{(I)}(t) > 0, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Hence, the element in the ith row and the jth column represents the proportion of agreements in which i lent cash to j anytime during our three case studies relative to the total number of agreements they engaged in over the whole sample period. If the pair (i, j) never trades with each other the corresponding entry in the matrix is just set to 0. If these proportions are close to 1 this means, that these pairs trade (almost) exclusively during stress episodes. Lower numbers imply that these are trading relationships that are also present outside a particular case study period and are not unique to crises. Figure 9 shows the heatmap representing the matrix Y^{CS}. The darker the red of the cell, the higher is the proportion of trades occurring during stress between that pair of institutions. The darkest red ranges from 0.9 to 1 and means that between 90 and 100 percent of the trades take place during the stress episodes. We do observe some dark red spots indicating that indeed some trade relationships are active almost exclusively during stress episodes. Most of these new edges appear in the periphery and seem to suggest that some institutions do turn to the overnight gilt repo market especially during liquidity stress. In the following we will explore in more detail which sectors drive the observed changes in the repo network. To do this, we will analyse the sectoral network of volumes in the overnight repo market.

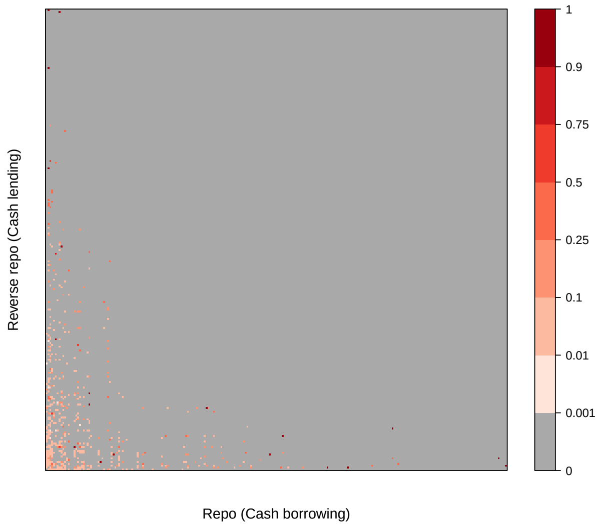


Figure 9: Heatmap of Y^{CS} (defined in (4)).

Note: The figure shows for each pair of nodes the number of their trades that took place during the three stress periods divided by the total number of trades between this pair over the full observation period.

3.2 The sectoral network

3.2.1 General characteristics

We define the sectoral network of volumes in the overnight repo market.

Definition 3.2 (Sectoral network of volumes)**.**

1. *The* sectoral network of volumes *consists of a set of nodes denoted by* $\mathcal{N}^{(S)} = \{1, \dots, N^{(S)}\}$, $N^{(S)} = 12$, *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.,*

$$A_{ij}^{(S)}(t) = \begin{cases} 1, & \text{if } V_{ij}^{(S)}(t) > 0, \\ 0, & \text{else.} \end{cases} \tag{5}$$

Repo markets bring together two types of end users that interact through intermediaries (CGFS, 2017). The first type includes those sectors that provide collateral in return for cash, such as funds, pension funds, hedge funds and insurance companies. The second type of end users is those sectors investing in cash while receiving collateral, such as money market funds

(MMFs), hedge funds[24] or corporate treasurers. Figure 10 illustrates the structure of the sectoral overnight gilt repo network. High-level observations are that gilt dealers and banks are the only sectors that have trade relationships with all the other sectors, they are the intermediaries connecting all the sectors in the repo market together. Therefore the only nodes in the sectoral network that have self-loops are the gilt dealers and the banks - meaning that gilt dealers have repo/reverse repo agreements with gilt dealers and banks have repo/reverse repo agreements with banks. Gilt dealers and banks are the only two sectors that are clearing members and hence are the only ones interacting with the CCP sector. The non-banks only trade bilaterally with the gilt dealers and the banks, but not amongst each other shown in the network visualization. We will describe the role of each of these sectors in more detail below, starting with the intermediaries.

Gilt dealers are the banks that are Gilt-Edged Market Makers (GEMMs) as classified by the UK Debt Management Office (DMO), which means they are the primary dealers in the UK sterling government bond market. All the banks that are not GEMMs are grouped in the banking sector as opposed to the gilt dealer sector in the following. For dealers, repo lending to clients is a core part of their business and a large part of their repo borrowing is to finance that lending (the so-called 'matched book') CGFS (2017). Most of the rest of their repo borrowing is to finance inventories for market-making and to source short-term funding. Gilt dealers have reserve accounts at the Bank of England, hence they can benefit from the spread on Bank reserves relative to the repo rate. Overall, the gilt dealers sector is the largest net borrower in the overnight gilt repo market (see Table 1), although there is some heterogeneity in the net lending position if we distinguish gilt dealers by the location of their headquarters. Table 1 illustrates that UK gilt dealers have a larger net borrowing position relative to US gilt dealers and other gilt dealers (headquartered neither in the UK nor the US). The introduction of the leverage requirement has affected dealers' behaviour in the repo market and has incentivised a more pro-active management of their balance sheets, including by limiting repo activity.[25] Banks use the repo market to earn a return on their liquid assets and to source short-term funding. Banks also have reserve accounts at the Bank of England, hence they can also benefit from the spread on Bank reserves relative to the repo rate. Overall, banks are the second largest net borrowers on average in the overnight gilt repo market (see Table 1).

As described in Section 2, the CCP sector has a special role in the repo market. In particular, the CCPs do not actively provide liquidity. They do two things. First, they clear trades between their members, which in this market are the gilt dealers and the banks. Second, they lend cash collected from margin payments as reverse repo to gilt dealers and banks. These are indeed the only sectors trading with them in the overnight gilt repo market (see Figure 10). We cannot distinguish in the data whether a *reverse* repo by a CCP is traded as part of their clearing business or their cash management. In those cases we will refer to these as trades with *the CCP sector*. A repo transaction however should only be performed as part of their clearing business and we will refer to these as trades via *cleared markets*. As shown in Ranaldo et al. (2019), CCPs' incentives to invest cash in the repo market have been strengthened by EMIR which requires CCPs to continually acquire safe assets, thus expanding the supply of cash in repo markets. As Table 1 shows, the CCP sector is one of the largest net lender. Since the CCP sector should have a net zero position on their clearing business, the net lending is likely to reflect the average daily investment of cash margin into the overnight gilt repo market.

We will now describe how non-banking sectors at the periphery of the market use its bilateral segment to trade with banks and gilt dealers. MMFs, insurers and pension funds are net lenders in the overnight gilt repo market.[26] These sectors are indeed cash rich and use the

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

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

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

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. Investors in MMFs include non-financial corporations, public authorities, insurers, pension funds, investment funds and households. MMFs invest in short-term money market instruments and are key providers of short-term funding to financial institutions (particularly banks), corporates and governments.

Hedge funds are instead net borrowers on average, as reported in Table 1, although only marginally as their repo borrowing is largely matched by cash lending. They use the repo market both to borrow cash, by placing securities as collateral with dealers, and to borrow securities from dealers, offering cash in return. Hedge funds can use repo to increase their leverage, which magnifies both their potential gains and their potential losses. They borrow cash, secured against gilts, in order to buy other assets and thereby obtain leverage.

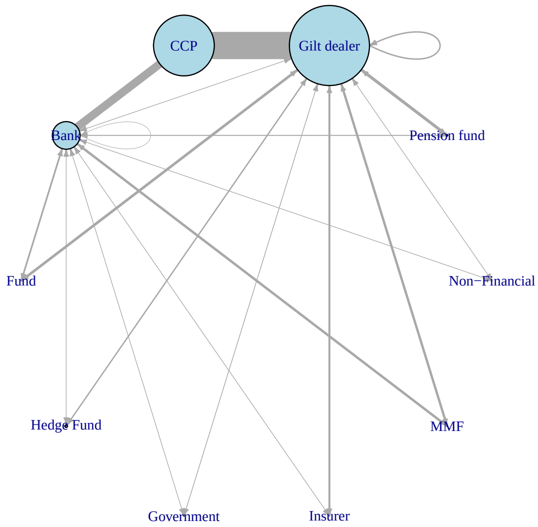


Figure 10: Sectoral network.

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

reported in Bank of England (2018).

Sector	n. of inst.	Av. lend	Av. borrow	Av. net lend	Av. repo trans	AV. rev. repo trans
All Gilt dealer	18	25.81	34.09	-8.28	627	599
Bank	45	3.95	11.81	-7.86	186	145
CCP	7	29.49	25.84	3.65	656	670
Fund	38	3.62	0.05	3.58	2	30
Government	10	0.56	0.17	0.39	3	4
Hedge Fund	47	0.87	1.12	-0.25	22	18
Insurer	8	2.09	0.05	2.04	2	24
MMF	18	4.03	0.05	3.98	1	18
Non-Financial	6	0.11	0.00	0.10	0	1
Other Gilt dealer	7	5.45	7.89	-2.44	198	199
Pension fund	50	3.28	0.62	2.66	34	23
UK Gilt dealer	6	11.97	16.19	-4.22	223	221
US Gilt dealer	5	8.39	10.00	-1.61	206	180

Table 1: Overview of the sectors trading in the overnight gilt repo market for the whole sample, volumes are expressed in £billion.

Note: Other Gilt dealers represent the Gilt dealers that are neither based in the UK nor in the US.

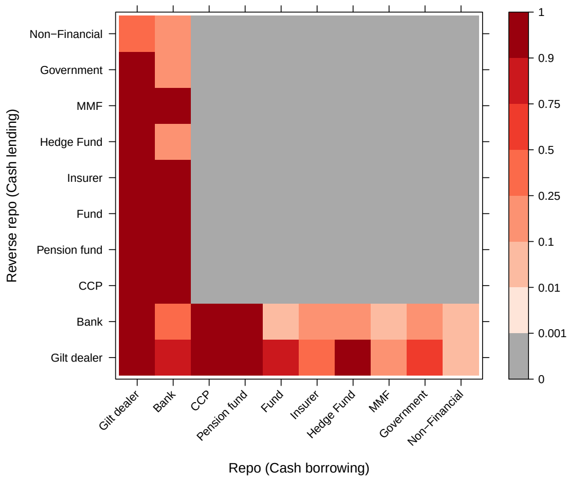


Figure 11: Observed transaction probability $\bar{A}^{(S)}$ in the sectoral network.

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

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

Here $\bar{A}^{(S)}_{ij}$ represents the empirically observed probability that sector i lends sector j cash in a repo transaction on a given day. Figure 11[27] shows a heatmap of this matrix $\bar{A}^{(S)}$. Each cell represents the probability that two sectors trade with each other on any given day in the whole sample. The darker the red of the cell, the higher is the likelihood that these two sectors trade on any given day. The darkest red ranges from 0.9 to 1 and means that two sectors trade between 90 and 100 percent of days in our sample, implying an almost continuous daily roll-over

[27] This is the sector-level version of Figure 6(a).

of trades. It is striking that gilt dealers will almost certainly borrow from all sectors except one (non-financial sector) on any given day in the sample. In terms of lending, this is more heterogeneous, but gilt dealers will almost certainly lend to the CCP sector, pension funds and hedge funds. For banks, the patterns are more heterogeneous on both sides of the market. Also note that the grey square in the top right represents the fact we observed in Figure 10 already: the CCP sector and the non-banks do not trade with each other or amongst each other in our data set.

3.2.2 Changes under stress

How does the sectoral network change under stress? First, we consider the average density of the sectoral network over time. In the institutional network we have seen that the network density has increased during the US repo crisis and the COVID-19 stress period indicating that institutions have established new trading relationships or re-established old ones. By analysing the density of the sectoral network we can identify whether these trading relationships are established between new pairs of sectors or whether these new trading relationships are formed between existing pairs of sectors.

Figure 12 shows the average density of the sectoral network over time. We observe a slight increase in this density following the Brexit referendum indicating that new pairs of sectors start trading or that previous trading relationships are re-established. The most significant change can be seen during the US repo stress, where the average density peaks in our sample period. The absolute level of this density indicates that all possible sector combinations in our data set trade with each other both in repo and in reverse repo transactions. This means that gilt dealers and banks have repo and reverse repo agreements between each other and with all other sectors; peripheral sectors still cannot have any repo or reverse repo agreements among themselves in our data set.

During the COVID-19 stress the density of the sectoral level is slightly increased indicating that some pairs of sectors re-establish trading relationships or form new ones. Since the density in the institutional network increases more significantly than the density in the sectoral network during COVID-19, the majority of the new or re-established trading relationships during the COVID-19 stress period seems to be between existing pairs of sectors.

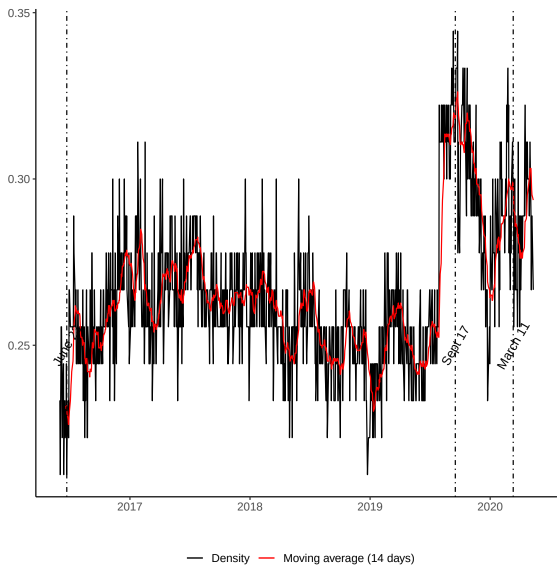
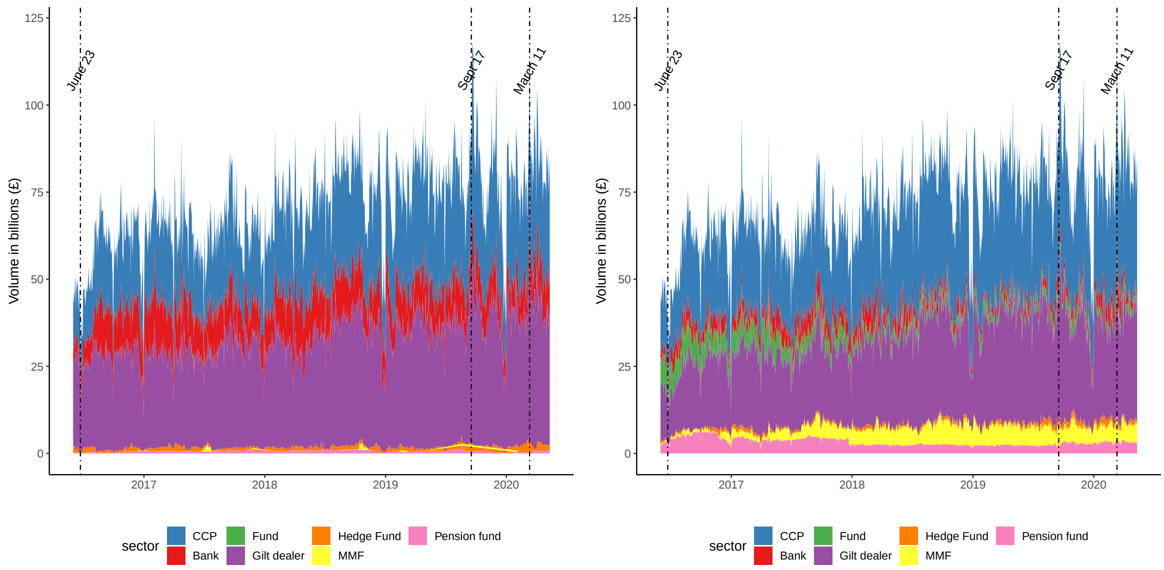


Figure 12: Density of the sectoral network.

Finally, Figure 13 shows how the total volumes borrowed (repo) and lent (reverse repo)



(a) Total volumes borrowed by sectors (in £ billions). (b) Total volumes lent by sectors (in £ billions).

Figure 13: Total volume borrowed (repo) by and lent (reverse repo) to different sectors.

evolve over time by sectors for the largest sectors.[28] That is, we plot in 13(a) the total volume that sector j borrowed as a function in time, i.e., $t \mapsto \sum_{i=1}^{N^{(S)}} V_{ij}^{(S)}(t)$ and in 13(b)the total volume that sector j lent as a function in time, i.e., $t \mapsto \sum_{i=1}^{N^{(S)}} V_{ji}^{(S)}(t)$.

We see that aggregate volumes tend to increase over time and this seems to be driven by increased transaction volumes by gilt dealers and the CCP sector which are the two sectors with the highest market share in both repo and reverse repo. Banks trade higher volumes in repo transactions than they do in reverse repo, they are indeed net borrowers. It seems that banks decreased their reverse repo activities slightly over time. Funds and MMFs trade higher volumes in reverse repo than they trade in repo, they are indeed net lenders. Pension funds seem to have decreased lending (reverse repo) from the end of 2017. As noted before, we clearly see the quarter ends and year ends as time points where volumes go down significantly usually across all sectors.

4 How do sectors adjust volumes, spreads and haircuts under stress?

Next, we statistically analyse changes in repo market activity between sectors during the three stress episodes.

4.1 Model

We fit three linear models to analyse the effect of the three periods of stress on the three variables of interest: volumes, spreads and haircuts. The analysis of this section is done at sectoral level.

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 $i, j \in \{1, \ldots, N^{(S)}\}$ and $t \in \tilde{\mathcal{T}}$. Here $\tilde{\mathcal{T}}$ denotes the set of time points $\mathcal{T}$ in which the quarter ends were removed

[28]Specifically we have excluded insurers, government and non-financial because they are relatively small.

from the time series.[29] In our data we have $N^{(S)} = 12$ and $\tilde{T} = |\tilde{\mathcal{T}}| = 965$. Hence, we have $12^2 \cdot 965 = 138{,}960$ observations to fit the model.[30] We then consider the following linear model with only categorical explanatory variables:

$$\begin{aligned} Y_{ijt} = &\beta_{ij}^{(\text{Normal, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \\ &+ \beta_{ij}^{(\text{CS1, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{CS1}}\}} \\ &+ \beta_{ij}^{(\text{CS2, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{CS2}}\}} \\ &+ \beta_{ij}^{(\text{CS3, Vol})} \mathbb{I}_{\{i \text{ lending sector}\}} \mathbb{I}_{\{j \text{ borrowing sector}\}} \mathbb{I}_{\{t \in \mathcal{T}^{\text{CS3}}\}} + \epsilon_{ijt}, \end{aligned} \tag{7}$$

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 $4(N^{(S)})^2 = 576$ model parameters that can be represented as four $(N^{(S)} \times N^{(S)})$-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 three stress periods, i.e., $\beta_{ij}^{(\text{Normal, Vol})}$ is the average daily volume lent from sector i to sector j for $t \in \tilde{\mathcal{T}} \setminus (\mathcal{T}^{\text{CS1}} \cup \mathcal{T}^{\text{CS2}} \cup \mathcal{T}^{\text{CS3}})$.

- $\beta^{(\text{CS1, Vol})} = (\beta_{ij}^{(\text{CS1, Vol})})_{i,j \in \{1,\dots,N^{(S)}\}} \in \mathbb{R}^{N^{(S)} \times N^{(S)}}$ represents the change in the average daily volume between the sector pairs during the time period of case study 1. More specifically, $\beta_{ij}^{(\text{CS1, Vol})}$ is the change in average daily volume lent from sector i to sector j during case study 1. Hence, the average daily volume lent from sector i to sector j at a time $t \in \mathcal{T}^{\text{CS1}}$ would be given by the model as $\beta_{ij}^{(\text{Normal, Vol})} + \beta_{ij}^{(\text{CS1, Vol})}$.

- $\beta^{(\text{CS2, Vol})}$ and $\beta^{(\text{CS3, Vol})}$ can be defined and interpreted along the lines of the definitions and interpretations of $\beta^{(\text{CS1, Vol})}$ but represent case study 2 and case study 3 respectively.

Second, we consider the sectoral network of repo spreads. The linear model for the repo spreads is the same as (7), 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 volume $V_{ij}^{(S)}(t)$. We will denote the corresponding four matrices of parameters that we estimate by $\beta^{(\text{Normal, Spread})}$, $\beta^{(\text{CS1, Spread})}$, $\beta^{(\text{CS2, Spread})}$ and $\beta^{(\text{CS3, Spread})}$.

Third, we consider the sectoral network of haircuts. Again, the linear model for the haircuts is the same as (7), with the only difference that the observations are no longer the volumes, but the haircuts, i.e., the observations Y_{ijt} are the volume weighted haircuts associated with the repo transaction with volume $V_{ij}^{(S)}(t)$. We will denote the corresponding four matrices of parameters that we estimate by $\beta^{(\text{Normal, HC})}$, $\beta^{(\text{CS1, HC})}$, $\beta^{(\text{CS2, HC})}$ and $\beta^{(\text{CS3, HC})}$.

Figures 14, 15 and 16 show heatmaps of the four estimated parameter matrices for each of the model for volumes, spreads and haircuts. The colour scale represents the level of the parameter estimate, where warm/cold colours indicate an increase/decrease in average volumes, spreads or haircuts during stress relative to normal times. Repo spreads and haircuts are reported in percentages.

[29]We removed the quarter ends from the time series by removing the two first days and the two last days in 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 on repo market data, see e.g. Mancini et al. (2016).

[30]If we do not observe a repo/reverse repo transaction between a pair of sectors on a given day, we set the corresponding observation for volumes to be equal to zero. For repo spreads and haircuts, 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.

Before we discuss the market reactions in more detail below we look into the significance of our model parameters. To do this we use a bootstrapping approach to determine whether the different effects that we observed during the three case studies are indeed significant. Our time series consists of $\tilde{T}$ data points representing days. 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 (7) to the new time series. We repeat this process $R = 1000$ times and therefore obtain R estimates of our model parameter. Figures 14, 15 and 16 all have numbers in the coloured fields taking values between 0 and 100. These represent the percentile of the parameter estimate corresponding to the observed time series relative to the empirical cumulative distribution generated by the bootstrap. If these numbers are very high (i.e., 99 or 100) this indicates that these parameter estimates are in the right tail of the bootstrap distribution and therefore highly significant. Similarly, very low numbers such as 0 or 1 indicate that these parameter estimates are in the left tail of the bootstrap distribution and also highly significant.

4.2 Estimation results

4.2.1 Volumes

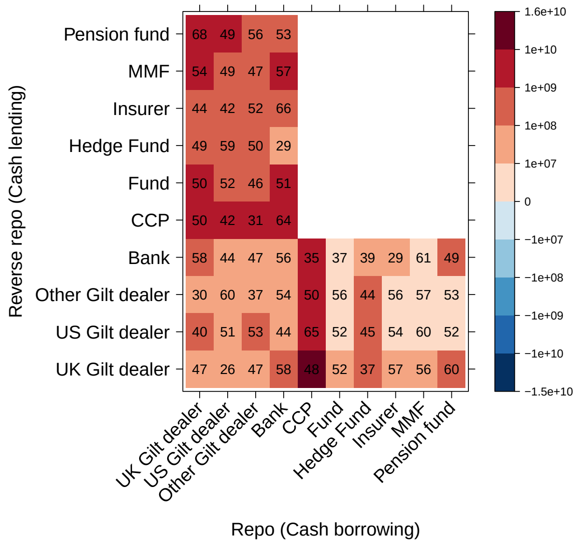
Figure 14(a) shows the heatmaps for the average volumes in normal times and is based on the estimates for the parameter matrix $\beta^{(\text{Normal, Vol})}$ generated by the linear regression model for volumes (7). Figures 14(b), 14(c) and 14(d) show the changes in average volumes during the three stress episodes relative to normal times and are respectively based on estimates for the parameter matrices $\beta^{(\text{CS1, Vol})}$, $\beta^{(\text{CS2, Vol})}$ and $\beta^{(\text{CS3, Vol})}$. The colour legend of the heatmaps represents the value of those estimates in pound sterling. The numbers printed in the heatmaps represent the percentile of where the parameter estimate falls within the empirical cumulative distribution function generated by the 1000 estimates we get from the bootstrap described above. In addition, in Appendix A, Figure 18 reports the heatmaps that correspond to average volumes during normal times and during each of the three stress periods. In the following we describe the results in normal times and for the case studies.

Normal times. Figure 14(a) reports the model estimates for the whole sample excluding the three case studies. First, we observe that in normal times the largest volumes are traded between the CCP sector and gilt dealers and banks. In particular, UK gilt dealers are lending large volumes in the centrally cleared segment of the market. Since CCPs can only do reverse repo as proprietary trading for cash margin management, this large supply of cash of UK gilt dealers to cleared markets goes to gilt dealers and banks.

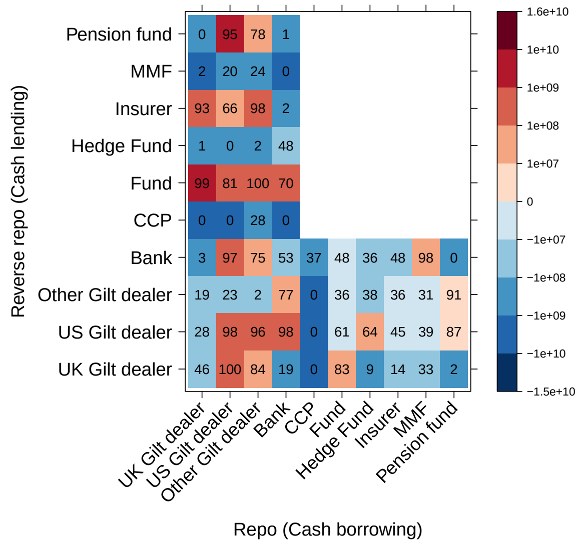
Within the core, banks are net borrowers (see Table 2) and they borrow the largest quantities from the CCP sector, funds and MMFs. Gilt dealers are also net borrowers, but to different degrees. UK gilt dealers are the largest net borrowers, relative to US and other gilt dealers. They borrow the largest amounts from the CCP sector and from non-banking sectors, namely funds, MMF, and pension funds. UK gilt dealers also lend significant volumes to cleared markets. US gilt dealers borrow the largest amounts from the CCP sector and pension funds. Other gilt dealers borrow the largest amount from the CCP sector.

In the periphery, hedge funds are the only net borrowers, albeit only by a small margin. They borrow and lend rather similar volumes to and from all gilt dealers and banks. As explained in Section 3.2 hedge funds are active in both sides of the market. All other institutions in the periphery are net lenders. Pension funds lend substantial amounts to UK and US gilt dealers, while MMFs and funds lend substantial amounts to UK gilt dealers and banks.

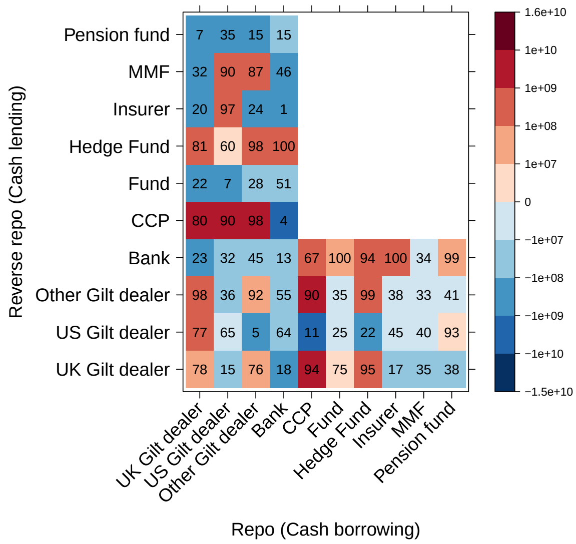
Comparison across episodes. A high level comparison between Figures 14(b),14(c) and 14(d) shows that there are common patterns between the two most recent crisis episodes, but



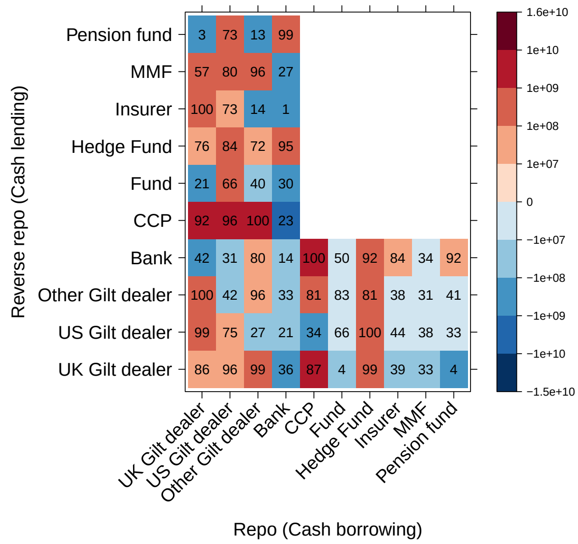
(a) Normal times: Estimate of $\beta^{(\text{Normal, Vol})}$.



(b) EU referendum: Estimate of $\beta^{(\text{CS1, Vol})}$.



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



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

Figure 14: Linear model for volumes: Parameter estimates (represented by colours) and their percentiles in the distribution generated by bootstrap (represented by numbers). The estimates represent the average volume in normal times (14(a)) and the changes in the average volume during each of the three stress periods compared to normal times (14(b), 14(c), 14(d)).

Sector	Whole sample	EU referendum	US turmoil	COVID-19
Bank	-7.86	-2.01	-3.82	-3.18
CCP	3.65	1.44	4.30	7.64
Fund	3.58	6.91	2.19	2.72
Government	0.39	0.29	0.18	0.31
Hedge Fund	-0.25	-0.66	-0.36	-1.28
Insurer	2.04	2.68	1.36	2.25
MMF	3.98	0.43	4.16	4.39
Non-Financial	0.10	0.27	0.22	0.08
Other Gilt dealer	-2.44	-4.19	-3.29	-6.00
Pension fund	2.66	3.02	1.73	3.04
UK Gilt dealer	-4.22	-5.41	-0.05	-3.74
US Gilt dealer	-1.61	-2.75	-6.62	-6.23

Table 2: Average daily net lending of sectors in whole sample and during the stress episodes, in £billion.

that these are very different from the EU referendum. [31]

Relative to normal times, overall volumes traded with the CCP sector during the US repo turmoil and COVID-19 episodes increase. The same sectoral patterns appear in both stress episodes. The first pattern is that banks lend more cash through cleared markets during the US repo turmoil and even more so during the COVID-19 episode, compared to normal times. At the same time banks lend less bilaterally to gilt dealers, and decrease borrowing from almost all sectors.[32] While banks are still net borrowers during both episodes (see 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 Figures 14(c) and 14(d). Indeed, Giese & Haldane (2020) argue that banks were a shock-absorber during the COVID-19 crisis given banks' strong capital and liquidity positions before the crisis struck. The additional liquidity provided by banks via cleared markets ends up with sectors that are clearing members. We can narrow this down even further given that gilt dealers borrow higher volumes from the CCP sector, whereas banks do not. Hence the increased repo lending of banks into cleared markets goes to gilt dealers.

A possible explanation for this striking preference of banks to lend via cleared markets rather than bilaterally during the COVID-19 episode is that the cleared segment is more attractive because it is less capital-intensive due to the ability to net trades. Indeed, transacting repos through a CCP creates opportunities for banks to net their repo transactions because doing so increases the proportion of trades on which banks face a single counterparty. As a result of these netting benefits, cleared trades reduce the impact of repo market intermediation on bank's balance sheet as reported for regulatory purposes.[33] Balance sheet netting has been identified as an important driver of repo market intermediation by CGFS (2017). In line with our findings, Eren et al. (2020) also find evidence of dealers' marked preference for cleared markets in the US dollar funding markets during the "dash for cash".[34] Another possible reason to prefer trading with CCPs during the "dash for cash" are that the settlement of trades might have been perceived as easier and less risky than trading bilaterally.

[31]Interestingly, Figures 18(b),18(c) and 18(d) in levels show one clear common pattern across the three stress episodes, namely that there is almost no reverse repo by the core to MMF and insurers. We also find very limited reverse repo from the core to other non-banks such as funds and pension funds during the stress episodes.

[32]The only exceptions are hedge funds during both episodes and pension funds during the COVID-19 stress episode.

[33]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.

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

A second pattern we see in both episodes is that the CCP sector increases reverse repo trades with gilt dealers.[35] Besides banks lending more into cleared markets, another source of this increase in cash supply are the CCPs investing the additional cash margin they collected during this period of increased volatility.[36] 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).[37] We also know that the average net lending by the CCP sector during COVID-19 was 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[38]. It is impossible to say whether the additional cash from initial margin would have ended up in the repo market in any case, since the main intermediaries in this market were among those firms strongly hit by the increase in margin calls (Bank of England, 2020; Huang & Takáts, 2020). Nonetheless, our analysis shows how the shift in liquid assets from dealers to CCPs, due to large margin calls, affects volumes traded between sectors in the overnight gilt repo market.

A third pattern present in both episodes is that UK and other gilt dealers also lend higher volumes via cleared markets. By contrast, US gilt dealers decrease their lending through cleared markets and seem to use the gilt repo market more to acquire sterling cash in both stress episodes. Overall, both lending and borrowing via cleared markets increases significantly during the two most recent stress episodes, whereas it decreases significantly during the EU referendum.

In the bilateral segment of the overnight market we also observe common patters across the US repo turmoil and COVID-19 episodes. First, in terms of lending from the core to the periphery we find that the core lends more to hedge funds. Since 2018, hedge funds have significantly increased their reliance on short-term funding via repo (Roberts-Sklar & Baines, 2020). In both stress episodes, their short-term funding needs increased, as is visible in Figures 14(c) and 14(d). During the COVID-19 episode, hedge funds' daily average net borrowing is more than five times the size of its sample average, see Table 2. 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. The increased demand for funding from these leveraged players has also been cited as a possible cause for the increased volatility in the US repo market in September (Avalos et al., 2019).

Regarding bilateral lending from the periphery to the core, selected non-banks (e.g. hedge funds, MMFs and insurers) invest more cash into the overnight segment of the repo market than in normal times, mainly lending more to gilt dealers. This pattern is even more pronounced during the COVID-19 episode, but already present during the US repo turmoil. In particular, during both stress episodes US gilt dealers become the largest net borrowers (see Table 2), increasing their reverse repo activity with most non-banks.

During the EU referendum, the patterns of bilateral trading are very different. The core

[35] In absolute terms, reverse repo by the CCP sector are also the highest volumes traded, as shown in Figures 18(c) and 18(d)

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

[37] 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.

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

lends less to non-banks in the periphery, including hedge funds. Hedge funds appear less reliant on the repo market, decreasing both lending and borrowing from the core, as also apparent from Figure 18(b). Overall the comparison across the case studies shows that the EU referendum is a very different case to the the US repo turmoil and COVID-19 episodes. While all three stress episodes are different in nature, the repo market conditions in the two more recent episodes seem to be more aligned leading to similar dynamics, see also Figure 18.

COVID-19 episode. Figure 14(d) illustrates the sectoral behaviour during the COVID-19 episode. This period is characterised by a strong "dash-for-cash" episode, with several financial institutions in need for additional liquidity. In particular, during the "dash for cash" in mid-March 2020 MMFs experience liquidity issues, due to large outflows as reported in Hauser (2020). Indeed, MMFs had to pay cash out to redeeming investors, and hence had less cash available overall to lend. Nonetheless, we find that MMFs remain net lenders in the overnight gilt repo market during COVID-19 with an average net lending higher than the sample average (see Table 2). In terms of counterparties, Figure 14(d) shows that MMFs lend more to all gilt dealers while they lend less to banks relative to normal times. Given the overall liquidity problems faced by MMFs, we analyse MMF lending behaviour in the gilt repo market at longer maturities in order to investigate whether a shortening of maturities occurred. For UK gilt dealers, MMF lending 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.[39] During the "dash for cash" period, we therefore observe a preference 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". Eren et al. (2020) found a similar dynamic for US prime MMFs during the COVID-19 stress. In order to preserve the liquidity of their portfolios, US prime MMFs shed longer-maturity assets and rolled them over into shorter maturities, which improved the liquidity and decreased the average maturity of their holdings.

US repo turmoil. During the US repo crisis in September 2019 we see that the spill over effects to the gilt repo market were visible but limited, as also explained in (Bank of England, 2019, p. 65). Figure 14(c) illustrates that overall US gilt dealers significantly increased borrowing and decreased lending, more than tripling their net borrowing position (see Table 2). As liquidity demands in the US increased, due to corporate taxes deadlines and a large US Treasury securities settlement, and rates in the US repo market spiked, US dealers have increased their demand for funding in the gilt repo market, which were accommodated from different market participants.

In particular, a significant increase in liquidity comes via the CCP sector. In the core of the market, UK and other gilt dealers significantly increased their lending through cleared markets, which can then be lent out to US gilt dealers via the CCP. Focusing on periphery to core lending, US gilt dealers' additional liquidity needs were met by increased lending from MMFs, insurers and hedge funds. Hedge funds lend at high percentiles to banks and non-US gilt dealers as well. Regarding periphery borrowing from the core, hedge funds borrow at high percentiles from gilt dealers and banks, with the exception of US gilt dealers.

EU referendum. During the Brexit referendum the repo market could cope with the stress and no policy interventions targeted at the gilt repo market were needed. Overall volumes were only slightly down which also has to be seen in the context that overall activity has decreased in previous years, see (Bank of England, 2016, p. 2).

However, looking at the volumes exchanged between different sectors reveals some interesting

[39] In addition, in the case of other gilt dealers, MMF lending at short (2 to 3 days) also completely stopped. For US gilt dealers, MMF lending at short maturities drastically declined.

dynamics which are unique to this stress episode. Most strikingly, trading via the CCP sector is extremely low. This suggests that the preference for the cleared segment of the market it is a more recent trend.

This episode particularly affects UK gilt dealers, given the perceived risk of a recession and uncertainty over the future economic outlook of the UK.[40] Even though UK dealers were resilient during this episode, having strengthened their capital and liquidity positions after the financial crisis, they did show to be less willing to extend repo financing and instead increased significantly their borrowing. This increase in net borrowing is mostly funded by funds (see Figure 14(b)), which almost double their net lending during this stress episode compared to the sample average (see Table 2).

4.2.2 Spreads

Figure 15(a) shows the heatmaps for the average spreads in normal times, i.e., it shows $\beta^{(\text{Normal, Spread})}$ generated by the linear regression model for spreads (7). Figures 15(b), 15(c) and 15(d) show the changes in average spreads during the three stress episodes relative to normal times and are respectively based on estimates for the parameter matrices $\beta^{(\text{CS1, Spread})}$, $\beta^{(\text{CS2, Spread})}$ and $\beta^{(\text{CS3, Spread})}$. The colour legend of the heatmaps represents the value of those estimates in percent. In addition, Figure 19 in Appendix A reports the heatmaps that correspond to average spreads during normal times and during each of the three stress periods.

Normal times. Figure 15(a) shows that repo spreads in normal times are small and very close to zero (see also the times series of spreads in Figure 4(b)). Overall, there is very little variation in normal times across sectors, apart from spreads on trades between the core being slightly lower and the slightly higher spreads largely occurring in trades with the periphery.

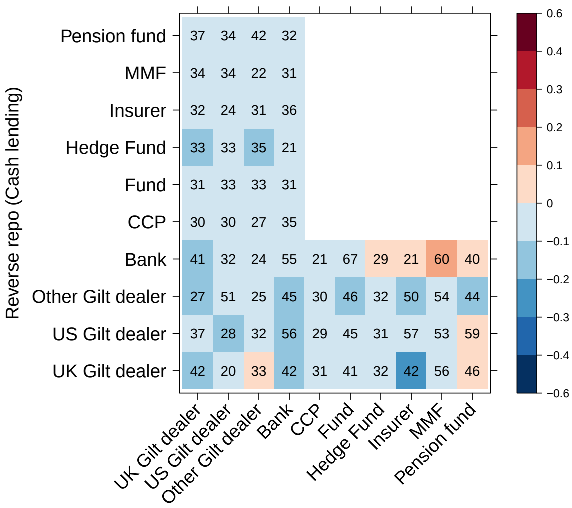
Comparison across stress episodes.[41] Overall, we find that repo spreads tend to increase across most sectors during stress episodes. Comparing Figures 15(b), 15(c) and 15(d), we can see that the COVID-19 episode displays the highest increase in the level of spreads relative to the other case studies and that most percentiles are at 100. As a result, repo spreads reached elevated levels up to 60 basis points, as reported in Figure 19(d). This was indeed the most stressful period for the gilt repo market, but also for the financial system more generally. The US repo turmoil also features high percentiles (most are between 90 and 99), suggesting that rates increased too, although without reaching more than 20 basis points, as reported in Figure 19(c). During the EU referendum, increases are less significant and levels remain small (and negative in many cases), again setting this episode apart. In general, we observe that for the sectoral pairs where repo spreads increase during stress, this tends to happen where the cash lender is an institution in the core, hence a bank or gilt dealer.[42] This result reveals a decreased willingness or ability of banks and dealers to lend in the repo market in times of stress.

COVID-19 episode. The highest level of spreads are all happening when the core sectors engage in reverse repo transactions, with a concentration of the higher spreads observed in transactions between core sectors. UK gilt dealers' spreads on reverse repo are consistently between the 98 or 100 percentiles and between 10 and 30 basis points higher than in normal times. As noted by Huang & Takáts (2020) large margin calls strained the liquidity positions of large dealer banks and possibly also led to hoarding liquid assets in anticipation of further margin calls. If one compares Figures 14(d) and 15(d), we find that there is no clear cut pattern

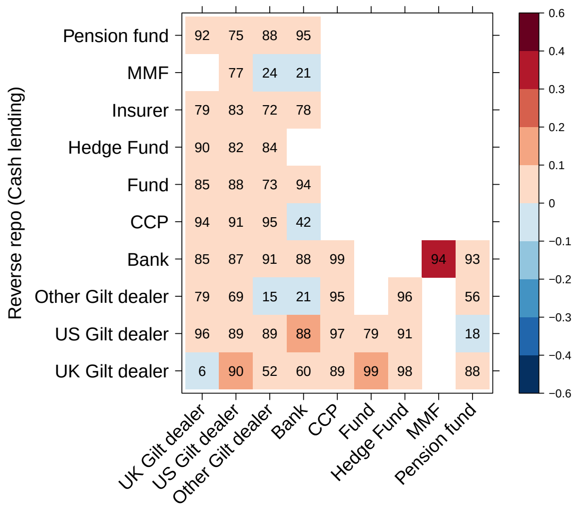
[40]As reported in Bank of England (2016) "Equity prices of UK banks have fallen on average by 20%, with UK-focused banks experiencing the largest falls. The ten-year UK government bond yield fell by 52 basis points. These moves reflect an increase in risk premia on UK assets, a perceived weaker growth outlook, and anticipation of some future deterioration in the United Kingdom's terms of trade and supply capacity".

[41]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.

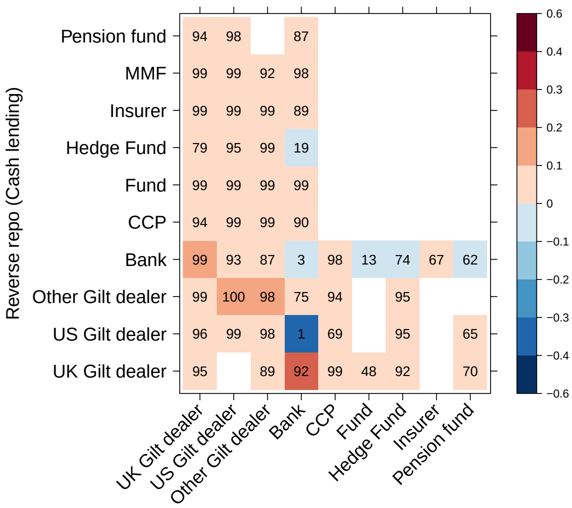
[42]In addition, we see that during the EU referendum and the COVID-19 episode, reverse repo trades of the core featured the highest spreads, whereas in the US repo turmoil the highest spreads occurred in borrowing relationship of the core.



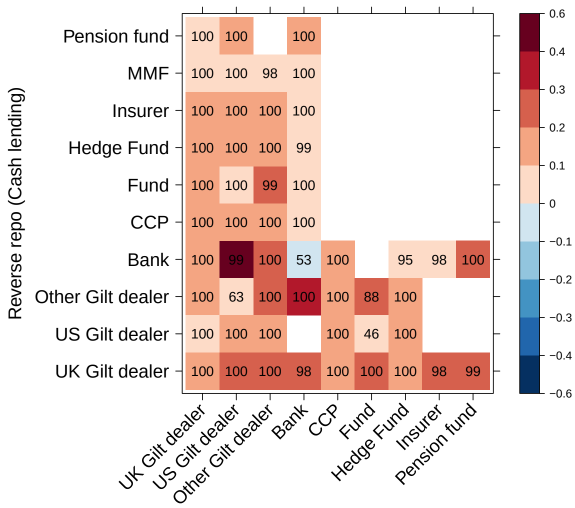
(a) Normal times: Estimate of $\beta^{(\text{Normal, Spread})}$.



(b) EU referendum: Estimate of $\beta^{(\text{CS1, Spread})}$.



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



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

Figure 15: Linear model for repo spreads: Parameter estimates (represented by colours) and their percentiles in the distribution generated by bootstrap (represented by numbers). The estimates represent the average repo spreads in normal times (15(a)) and the changes in the average repo spreads during each of the three stress periods compared to normal times (15(b), 15(c), 15(d)). All estimates are given in percent.

between an increase in spreads and a corresponding change in volumes. However, looking at increases in reverse repo by the core, a lot of the darker orange shades (corresponding to the range of 20 to 30 basis points in the colour scale) correspond to increases in volumes relative to normal times. While our analysis does not allow us to speak about causality, we can state that borrowing from the core becomes more expensive during the "dash for cash".

The highest average increase in spreads we observe across all four heatmaps is for the COVID-19 episode in Figure 15(d), confirming that this episode was the most severe liquidity stress. This corresponds to repo trades when banks are lending to US gilt dealers, which are associated with a decrease in volumes relative to normal times (located at the 37th percentile of the distribution, as reported in Figure 14(d)). Slightly lower but still high (between 0.3 and 0.4 percent) is the spread at which other gilt dealers lend to banks, which correspond to a decrease in volumes as well. Overall it is interesting to note that the largest average spread increases correspond to drops in volumes, which can be taken as a sign of strains in the market. The only mildly negative change in spreads occur in transactions between banks. The associated percentile points out that these are closer to their median bilateral spread.

US repo turmoil. First, it is important to notice that US gilt dealers do 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 percent 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.

Second, we notice that all the most elevated spreads are observed in repo transactions within the core. The highest average level of spreads is observed when banks borrow from UK gilt dealers. At a slightly lower but still elevated level, UK gilt dealers borrow at higher spreads from banks as well as non-UK gilt dealers from other gilt dealers. By contrast, banks face very low spreads when borrowing from US gilt dealers, which is significant at the 1 percentile.

EU referendum. We note that, analogously to the previous case study, UK gilt dealers increase in borrowing is not associated with extremely large increases in spreads. Although they do face higher spreads relative to normal times, they only increase up to 0.1 percentage points on average. The highest level of spreads occur in lending relationships with the core, in particular when banks lend to MMFs. Slightly lower but still standing out are US gilt dealers lending to banks and UK gilt dealers lending to US gilt dealers and funds.

4.2.3 Haircuts

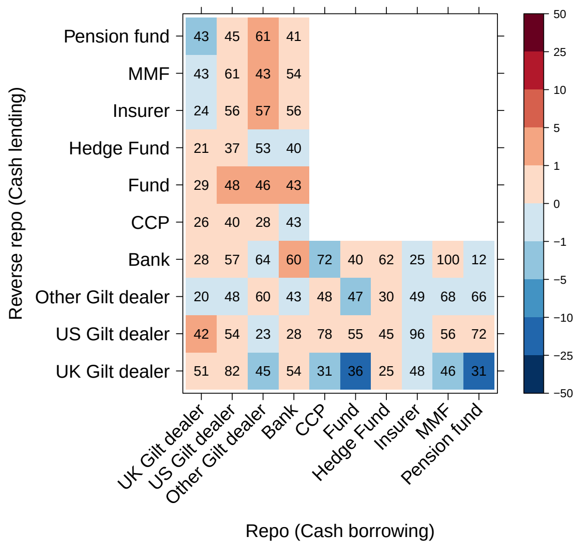
Figure 16(a) shows the heatmaps for the average haircuts[43] in normal times and is based on the estimates for parameter matrix $\beta^{(\text{Normal, HC})}$ generated by the linear regression model for haircuts (7). Figures 16(b), 16(c) and 16(d) show the changes in average haircuts during the three stress episodes relative to normal times and are respectively based on estimates for the parameter matrices $\beta^{(\text{CS1, HC})}$, $\beta^{(\text{CS2, HC})}$ and $\beta^{(\text{CS3, HC})}$. The colour legend of the heatmaps represents the value of those estimates in percent. In addition, Figure 20 in Appendix A, reports the heatmaps that correspond to average haircuts during normal times and during each of the three stress periods.

Normal times. Haircuts on repo transactions in the overnight gilt repo market on average over our sample can take positive but also negative values.[44] The size of haircuts should be a function of market liquidity risk in the underlying collateral securities, operational risk at the non-defaulting party (e.g. the efficiency of the non-defaulting party in margin maintenance settlement and custody) and legal risk (e.g. delays in collateral transfers at default due to legal challenges), as well as default risk on the collateral securities.[45] Furthermore, Julliard et al.

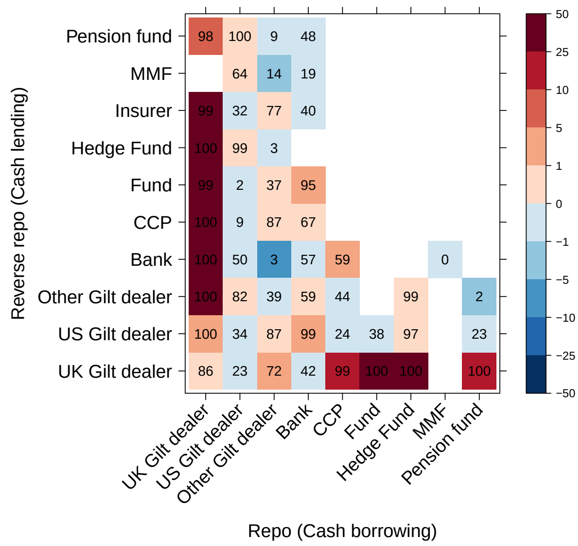
[43]See the beginning of Section 2 for the definition of haircuts.

[44]When the market value of collateral is lower than the cash exchanged the haircut is negative, i.e. the repo is under-collateralised.

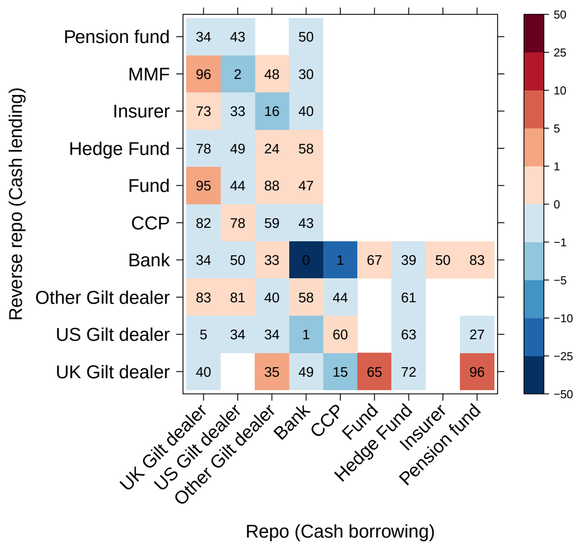
[45]We refer to The International Capital Market Association (ICMA) (2012) for more details.



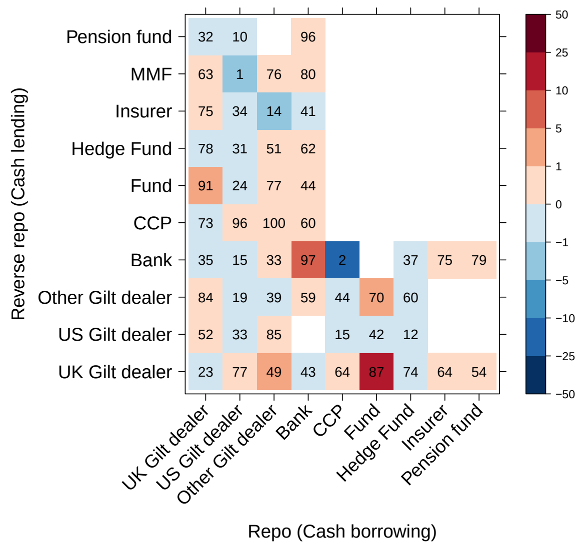
(a) Normal times: Estimate of $\beta^{(\text{Normal, HC})}$.



(b) EU referendum: Estimate of $\beta^{(\text{CS1, HC})}$.



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



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

Figure 16: Linear model for haircuts: Parameter estimates (represented by colours) and their percentiles in the distribution generated by bootstrap (represented by numbers). The estimates represent the average haircut in normal times (16(a)) and the changes in the average haircut during each of the three stress periods compared to normal times (16(b), 16(c), 16(d)). All estimates are given in percent.

(2019) finds that counterparties matter in determining haircuts in the UK repo market. This is reflected also in our findings.

Figure 16(a) shows that average haircuts are mostly between 5 and -5 percent. Haircuts demanded by the core sectors when lending to non-core counterparties are almost all negative but small.[46] By contrast, when the core sectors borrow cash, haircuts are generally positive, with few exceptions. It is also interesting to note that lending and borrowing of banks within the core mostly attracts positive haircuts, except when the counterparty is from other gilt dealers. By contrast banks lending and borrowing through cleared markets attracts negative haircuts, although ultimately reaches the exact same counterparties - gilt dealers and banks.[47] The lower haircuts might be due to the fact that repo lending through cleared markets is doubly secured: both by the collateral and by the clearing process.

Comparison across episodes. When comparing the stress episodes, it becomes clear that the EU referendum had the strongest impact on haircuts. In particular, we observe large increases in haircuts (up to 50 percentage points) for transactions intermediated by UK gilt dealers, more so for borrowing transactions. Besides the extremes values observed during the EU referendum, during the stress episodes we observe that changes in average haircuts are mostly between 5 and -5 percentage points relative to normal times. Both during the US repo turmoil and the COVID-19 episode, haircuts decrease most when banks lend to the cleared markets, which corresponds to significant increases in volumes in both cases.

COVID-19 episode. The largest decrease in haircuts occurs when banks lend to the cleared markets and one of the highest increase occurs when banks lend to banks[48] which correspond to an increase and a decrease in volumes respectively (see Figure 14(d)). These results corroborate our hypothesis that banks have a preference for the cleared segment of the repo market in this episode, as perceived safer.

Haircuts increase significantly also when UK gilt dealers lend to funds, however remaining still low at average levels (see Figure 20(d)). This also corresponds to a decrease in volumes relative to normal times.

US repo turmoil. The US gilt dealers face heterogeneous levels of haircuts, but most of them are decreasing during this episode and none are extreme in terms of levels (see Figure 20(c)). This finding reflects that this episode was not particularly stressful for gilt markets. We note that banks have the lowest haircuts when transacting with banks and when lending to the CCP. This latter result is in line with what observed in the COVID-19 episode.

EU referendum. It is striking that trading activity with UK gilt dealer involves extremely high haircuts when borrowing from most sectors and when lending to CCP, funds and hedge funds. In the period considered, there was significant market volatility and economic uncertainty, which triggered a flight to safety leading gilt yields to fall. Indeed, Figure 5(a) shows that yields on 10-year gilts decreased 8 bps in the week before the EU Referendum, and by 50 bps straight after the EU Referendum vote, between 23/06 and 30/06. Falling yields imply that the value of the gilt rose strongly.

Hence, these results are not driven by a change in collateral value per se but probably a consequence of the fact that the UK gilt sector was hit particularly hard by the UK's vote to leave the EU. Their shares dropped given markets' expectations that the vote would hit economic growth, cause bad loans to rise and push up funding costs, as also reflected in more

[46] Only haircuts on reverse repo transactions from UK gilt dealers with funds and pension funds are negative and quite large (between -10 and -25 percentage points), perhaps reflecting a preferential trading relationship between the sectors.

[47] Haircuts on cleared repo trades are determined by the original counterparties to the trade – details are then simply passed to the CCP, which novates the trade and replaces it with two equal and opposite trades with the two counterparties. So the haircut should just reflect market dynamics, in much the same way as for bilateral repo.

[48] When banks lend to banks the average haircuts level reaches up to 10 percentage points, as reported in Figure 20(d). This is still low relative to the highest levels reached during the EU referendum.

negative credit outlooks. Haircuts adjusted to reflect the higher credit risk and heightened uncertainty over the future outlook of UK dealers, and the desire of their counterparties to protect themselves from it.

4.3 Summary

To summarise, we find that there are common patterns in the way sectoral volumes change in the US repo turmoil and in the COVID-19 crisis. We find that volumes traded with the CCP sector increased. Banks increase their lending to cleared markets while mostly decreasing volumes lent and borrowed with other sectors bilaterally. Non-banks behave heterogeneously, but in both stress episodes hedge funds significantly increase their borrowing as well as lending and MMFs invest more cash with gilt dealers in the overnight repo market.

In terms of changes in the cost of repo, we find that spreads are risk-sensitive and increased the most during the COVID-19 crisis, which is testimony to the scale of the liquidity stress that occurred. In particular, repo spreads tend to increase the most in trades where the cash lender is a bank or a gilt dealer. Haircuts are instead less sensitive. However, we do observe large increases in haircuts during the EU referendum for the UK gilt dealers sector.[49]

5 Aggregate market resilience analysis

In this section, we will conclude the analysis of the paper by investigating the resilience of the gilt repo market. To do so we analyse aggregate repo volumes, spreads and haircuts for the overnight segment (see Figure 4 for their evolution over time) and their relation with key macroeconomic and financial variables.

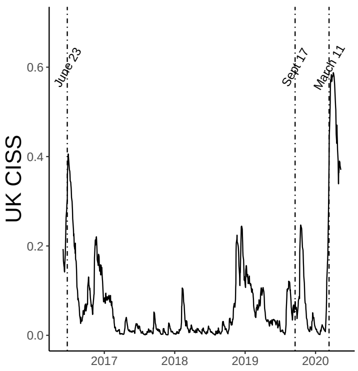
We adapt the model of Mancini et al. (2016) to the UK framework, and conduct a regression analysis for the overnight gilt repo market to investigate its relationship with (systemic) risk and central bank policy. First, to investigate the response of the overnight gilt repo market to systemic risk, we adopt the Composite Indicator of Systemic Stress (CISS), a proxy for systemic stress, calibrated for the United Kingdom. This risk indicator, first introduced in Hollo et al. (2012), is an aggregation of 15 indicators capturing financial stress symptoms in a broad range of financial market segments. In particular, CISS is constructed to put relatively more weight on situations in which stress prevails in several market segments at the same time. This is indeed reflected in Figure 17(a) which shows the CISS indicator[50] for the United Kingdom. The UK CISS indicator spikes during the stress episodes of the EU referendum and COVID-19 and declines shortly after.

Second, we also look at central bank policy measures, which can drive repo market dynamics as noted in Mancini et al. (2016), through monetary policy rates and the liquidity that credit institutions hold as reserves. As a measure of monetary policy rate we use SONIA, i.e., the reference risk-free rate for sterling markets.[51] As a measure of liquidity we use the Bank of

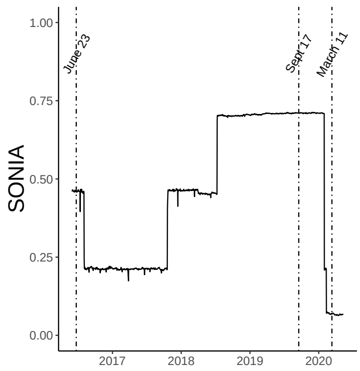
[49]These changes reflect an increase in counterparty risk as this sector was hit hard by the expectations of lower economic growth and heightened uncertainty caused from the UK's vote to leave the EU.

[50]The variables adopted to construct the UK CISS captures stress in i) money markets: volatility of 3-month LIBOR, and the differential between the 3-month LIBOR and Treasury bill rate; ii) bond markets: return volatility of the 10-year UK government bond, the 10-year swap interest rate differential vis-a-vis UK government bonds, the yield differential between the IBOXX financial corporations index at 5-10 years maturity and a 7-year government bond, and the yield differential between the IBOXX non-financial corporations index at 5-10 years maturity and a 7-year government bond; iii) equity markets: return volatilities, book-price ratios and cumulated maximum percentage index losses over a 2-year moving window (CMAX) separately for non-financial and financial corporations; and iv) foreign exchange markets: return volatility of the British Pound exchange rate vis-a-vis the Euro, the Japanese Yen, and the US Dollar. We refer to Hollo et al. (2012) for more details on the methodology adopted to aggregate these variables and compute CISS.

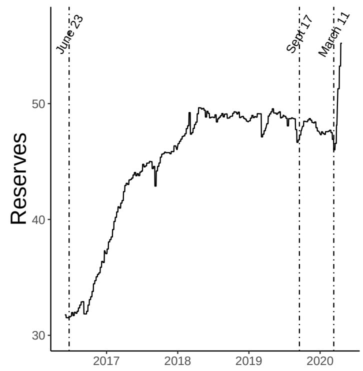
[51]Note that while Mancini et al. (2016) choose a measure of monetary policy expectations, we do not have data available to replicate such measure in the UK for our sample. The future contract on SONIA only have become



(a) CISS_UK.



(b) SONIA.



(c) Reserves.

Figure 17: Explanatory variables: the UK Composite Indicator of Systemic Stress (CISS_UK), SONIA and Bank of England Reserves.

England reserves[52], i.e. the current account balances held by commercial banks and building societies at the Bank paying the Bank rate.[53] As explained in Bank of England (2010), reserve balances can be varied freely to meet day to day liquidity needs, and under the current framework banks are not required to set targets for their reserve balances. As shown in Figure 17(c), there has been a steady increase in recent years in reserve balances at the Bank of England. This is part of a long term trend since March 2009, where the increase in reserve balances reflects the fact that asset purchases under the Bank of England's programme of quantitative easing have been financed by increasing reserves balances. Furthermore, we have seen a much steeper increase since mid March 2020, during the stress period of COVID-19. This sharp increase could reflect a preference to hold central bank reserves over other assets to manage liquidity and mitigate the stress.

We study the overnight gilt repo market activity throughout our sample[54], regressing repo volumes, spreads and haircuts on the variables discussed above. To allow for linear growth we include a time trend. Furthermore, we include lagged repo spreads, volumes and haircuts to account for interactions amongst repo market activity variables.[55]

In particular, the regression model is given by

$$\begin{aligned} Y_t = \gamma_0 + \gamma_1 t + \gamma_2 \text{CISS\_UK}_{t-1} + \gamma_3 \text{SONIA}_{t-1} + \gamma_4 \text{Reserves}_{t-1} + \gamma_5 \text{Volumes}_{t-1} \\ + \gamma_6 \text{Spreads}_{t-1} + \gamma_7 \text{Haircuts}_{t-1} + \epsilon_t, \end{aligned}$$

where $Y_t \in \{\text{Volumes}_t, \text{Spreads}_t, \text{Haircuts}_t\}$.[56] Furthermore, $\gamma = (\gamma_0, \ldots, \gamma_7)^\top$ are the eight model parameters that we estimate for each model corresponding to volumes, spreads and haircuts. Here, ϵ_t denotes the random noise term.

The results of these regressions for the overnight gilt repo market are reported in Table 5.

available from December 2017.

[52]'BOE reserve balances in Sterling' weekly time series from Datastream.

[53]This measure is also different from the one used in Mancini et al. (2016), i.e., reserves in excess of the ECB requirement, reflecting the different monetary frameworks.

[54]The whole sample is from 01-06-2016 to 11-05-2020.

[55]Note that our definition of repo spreads and haircuts differ from Mancini et al. (2016) We define repo spreads as the difference between repo rates and the Bank of England rate, while they adopt the ratio between the repo rates and the ECB deposit rate, relative to the ECB interest rate corridor. Further while repo haircuts are not reported in their data set, they need to rely on average haircuts applied at the ECB and Eurex, we construct haircuts directly from reported variables in our data set.

[56]Here, $\text{Volumes}_t = \sum_{i=1}^{\mathcal{N}^{(I)}} \sum_{i=1}^{\mathcal{N}^{(I)}} V_{ij}^{(I)}(t)$ from Definition 3.1 and the definitions for Spreads_t, Haircuts_t are analogue.

First, we discuss the results on the key repo market activity variables.[57] Repo volumes have a positive impact on volumes and a negative impact on spreads. These results are in line with the findings in Mancini et al. (2016) for the Euro repo market when liquidity is high,[58] confirming that in this case cash providers have more market power than cash takers. Similarly, repo spreads have a positive impact on spreads, and a negative impact on volumes. Hence a spread increase tends to be associated with a decrease in repo volumes.[59]

Most importantly, we find that CISS UK is positively related to repo spreads while it has a negative but not significant relation with repo volumes. Hence systemic stress leads to an increase in costs of repo funding. However, repo volumes are relatively unaffected by systemic risk in aggregate. This is indeed broadly in line with what we observed during the COVID-19 crisis when systemic risk, as captured by the CISS UK indicator, become elevated. Further, CISS UK has no significant relation with repo haircuts. This result is in line with some of the literature on the US repo market during the global financial crisis (see Copeland et al. (2014) and Krishnamurthy et al. (2014)). For the UK repo market, we have indeed observed in Section 4 that haircuts did not increase significantly across the board during the COVID-19 crisis.[60]

In Mancini et al. (2016) a repo market is defined as resilient, "if the lending volume and maturity are non-decreasing and repo rates and haircuts are non-increasing during crisis periods". Under their resilience definition, risk is neither positively related to repo spread and haircuts nor is it negatively related to repo volume and maturity. Further, under their shock absorber hypothesis, repo market activity is positively impacted by risk. As in their analysis CISS is positively related to repo volumes but has no positive effect on repo spreads and no negative effect on volumes, they conclude that the Euro repo market acted as a shock absorber.

In contrast to the results reported by Mancini et al. (2016) for the Euro repo market, we find that the gilt repo market did not act as a shock absorber in aggregate in our sample. The cost of repo funding in the UK is increasing with financial stress, highlighting some fragilities. This risk-sensitivity of the cost of repo funding could be driven by a decrease in the ability or willingness by banks and gilt dealers to intermediate the market, at least bilaterally, as suggested by our case studies analysis. However, as aggregate haircuts and volumes remained relatively stable we did not observe a market-wide freeze.

[57]The results on monetary policy variables are as expected: we find no significant impact on repo volumes, while there is a significant relation with repo spreads and haircuts. In particular, SONIA has a positive impact on spreads while it has a negative impact on haircuts. Central bank reserves have a negative impact on spreads. This latter result is in line with the supply and demand dynamic in the market, as also observed for the Euro repo market in Mancini et al. (2016) in times of moderate excess liquidity. Instead, a higher SONIA rate is followed by higher repo spreads but lower haircuts. SONIA is based on actual transactions and reflects the average of the interest rates that banks pay to borrow sterling overnight from other financial institutions, which is therefore positively related to repo cost.

[58]Note that in Mancini et al. (2016) excess liquidity is considered to be high if it exceeds 300 EUR billion, which approximately corresponds to the total single-counted volume of secured and unsecured lending in the euro area.

[59]By contrast, repo spreads and volumes do not significantly affect haircuts. However, haircuts have a negative impact on volumes. This result highlights a negative effect, where higher haircuts lead to lower repo funding. This effect could be driven by financial institutions' liquidity hoarding, as aggregate haircuts increase and investors face liquidity shortfalls, they respond by hoarding liquidity in the repo market. This channel has been explored in network contagion models such as Gai et al. (2011).

[60]However, haircuts reached extreme values during the EU Referendum for UK gilt dealers. Thus suggesting that the counterparties might be a more important driver than systemic risk.

	Dependent variable:		
	Volumes	Spreads	Haircuts
	(1)	(2)	(3)
Intercept	2.775***	0.045***	0.496***
	(0.319)	(0.017)	(0.177)
Trend	0.001***	0.0001***	−0.001***
	(0.0002)	(0.00001)	(0.0001)
CISS_UK_{t-1}	−0.284	0.047***	0.057
	(0.263)	(0.014)	(0.146)
SONIA_{t-1}	−0.135	0.031***	−0.478***
	(0.144)	(0.008)	(0.080)
Reserves_{t-1}	−0.012	−0.002***	−0.005
	(0.008)	(0.0004)	(0.005)
Volumes_{t-1}	0.616***	−0.003**	−0.005
	(0.025)	(0.001)	(0.014)
Spreads_{t-1}	−0.925*	0.546***	−0.363
	(0.506)	(0.027)	(0.282)
Haircuts_{t-1}	−0.099*	−0.004	0.345***
	(0.055)	(0.003)	(0.030)
Observations	967	967	967
R^2	0.618	0.535	0.548
Adjusted R^2	0.615	0.532	0.544
Residual Std. Error (df = 959)	0.769	0.041	0.428
F Statistic (df = 7; 959)	221.273***	157.568***	165.796***

Table 3: This table reports the results of regressing repo volumes, spreads and haircuts for the aggregate overnight gilt repo market on various explanatory variables reported in the first column. It states the estimates of γ_i corresponding to the explanatory variables specified in the rows and the corresponding standard errors in brackets below. Regressions are based on daily data for the period from 01-06-2016 to 11-05-2020. Significance levels corresponds to *p<0.1; **p<0.05; ***p<0.01 respectively.

6 Conclusions

The repo market has shown signs of strain in recent stress episodes. In particular, overnight repo rates spiked in the "dash-for-cash" episode during the COVID-19 crisis, and the US turmoil in mid-September 2019, raising questions on repo market functioning. Given its critical importance 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. At an aggregate level, we find that repo spreads are sensitive to stress, but volumes and haircuts are not significantly affected by risk and hence can be considered as resilient. Our sectoral analysis can help understand why, by shedding light on important common dynamics of market participants during the US repo market turmoil and the COVID-19 crisis.

One key result of our paper is concerned with the role of the non-banking sectors in the repo market under stress. These sectors are an increasingly important part of the financial system and their behaviour a crucial driver of its performance under stress. Our analysis reveals some common patterns for non-banks in the repo market during these two stress episodes. In particular, hedge funds significantly increased trading in the repo market. Hedge funds are net borrowers throughout our sample, but particularly during the COVID-19 stress episode, they satisfy short-term funding needs by increasing their use of the overnight gilt repo market. By contrast, MMFs, which are net lenders throughout our sample, increase their lending in the overnight repo market even further. Specifically, MMFs placed more cash with gilt dealers relative to normal times. During COVID-19 this latter result reflects a preference for safe short-term investment, as MMFs decreased lending to gilt dealers at longer maturities.

Another key result is that volumes traded by the CCP sector increase relative to normal times. This finding is likely driven by post-crisis regulation. It reflects a preference of the core sectors, i.e. gilt dealers and the banking sector, to intermediate volumes through the cleared segment of the market due to netting benefits. Further, the CCP sector increased their investment of cash margins collected during times of stress in the repo market via reverse repos. The increased importance of the CCP sector in the repo market, a trend already highlighted by CGFS (2017), deserves close monitoring and raises some important questions for policy makers. As we show, CCPs can increase funding during stress. Hence, policymakers could consider further broadening access to CCPs beyond banks and dealers to repo end users, such as non-bank financial institutions. However, increasing concentration on CCPs has its own risks[61] 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.

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

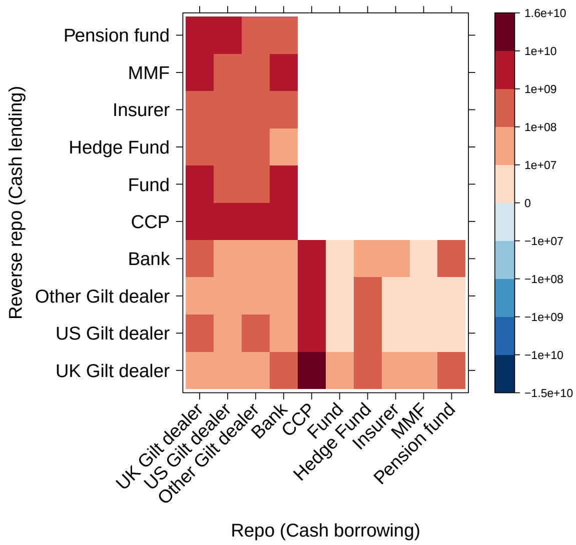
Appendix

A Additional figures for analysis in Section 4

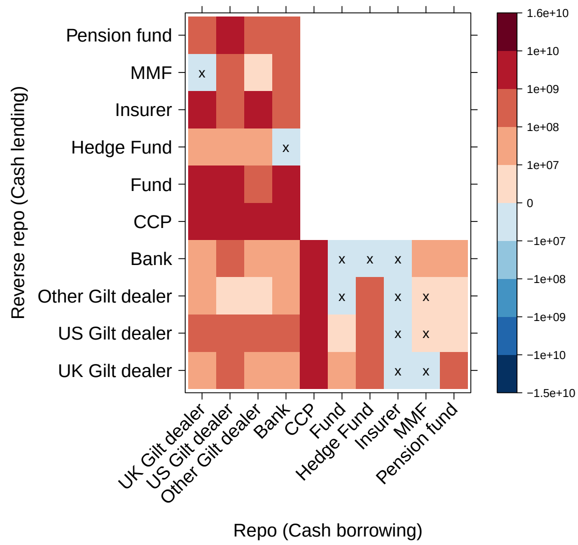
In Subsection 4.1 we have introduced the linear model (7) for volumes, spreads and haircuts. For volumes, for example, we estimate four $(N^{(S)} \times N^{(S)})$-dimensional matrices, where $\beta^{(\text{Normal, Vol})} = (\beta_{ij}^{(\text{Normal, Vol})})_{i,j \in \{1,\dots,N^{(S)}\}} \in \mathbb{R}^{N^{(S)} \times N^{(S)}}$ represents the average daily volume that is being traded between the sector pairs outside the three stress periods and $\beta^{(\text{CS1, Vol})}$, $\beta^{(\text{CS2, Vol})}$ and $\beta^{(\text{CS3, Vol})}$ represent the changes in the average daily volume between the sector pairs during the time period of case study 1, 2 and 3, respectively. Hence, from these estimates of the changes, we obtain the average daily volume lent from sector i to sector j at a time $t \in \mathcal{T}^{\text{CS1}}$ by considering $\beta_{ij}^{(\text{Normal, Vol})} + \beta_{ij}^{(\text{CS1, Vol})}$. Figures 18, 19, 20, show the corresponding heatmaps for the estimates of the average volumes, spreads and haircuts during normal times and during each of the three stress episodes. These are in contrast to Figures 14, 15 and 16, representing the changes during a stress episode and not the level during the stress episode.

The black crosses in Figures 18, 19, 20, indicate that the corresponding estimate is approximately 0. Due to rounding errors, it is not exactly zero and therefore some of the cells appear light blue (or light red), even though, obviously, there is no negative volume when considering average volumes rather than changes in volumes. These cells correspond to sector pairs that did not engage in repo or reverse repo transactions during some of the stress episodes.

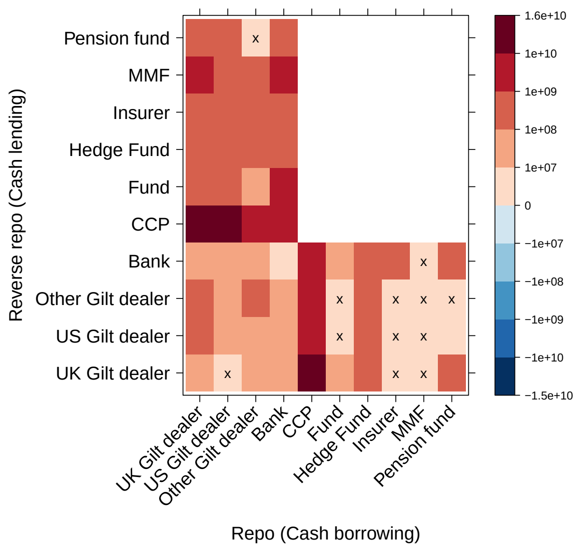
While we can assign a volume of zero to a sector pair, that did not report a single trade during one of the stress episodes, we cannot assign a corresponding repo spread or haircut. Hence, for the matrices that represent the level of spreads and haircuts, reported in Figures 19, 20, the "NA" in the corresponding cell indicates that this estimate does not exist since there are no observations to estimate it.



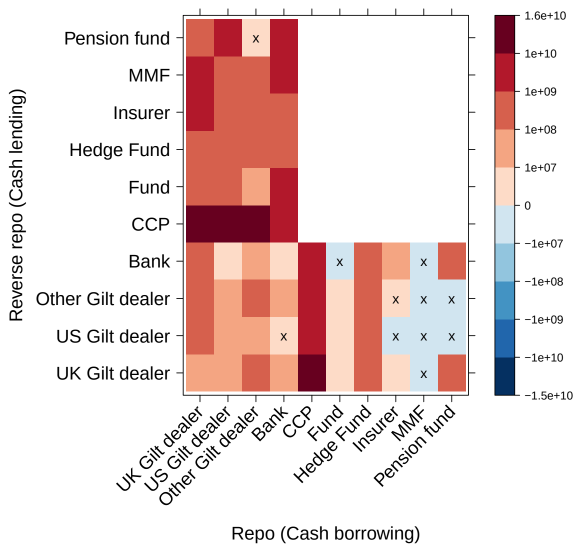
(a) Normal times: Estimate of $\beta^{(\text{Normal, Vol})}$.



(b) EU referendum: Estimate of $\beta^{(\text{Normal, Vol})} + \beta^{(\text{CS1, Vol})}$.

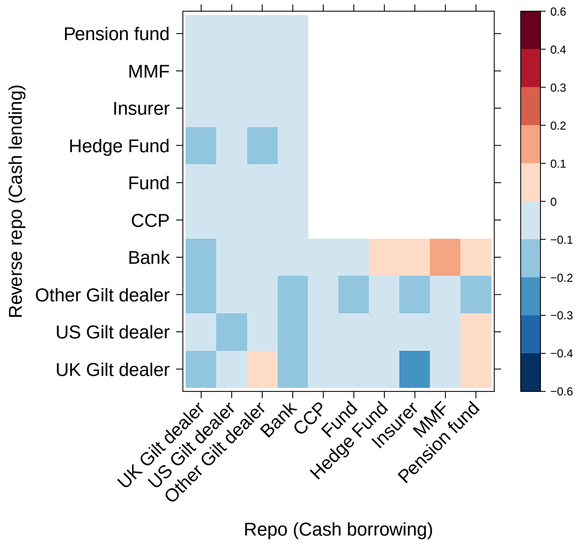


(c) US turmoil: Estimate of $\beta^{(\text{Normal, Vol})} + \beta^{(\text{CS2, Vol})}$.

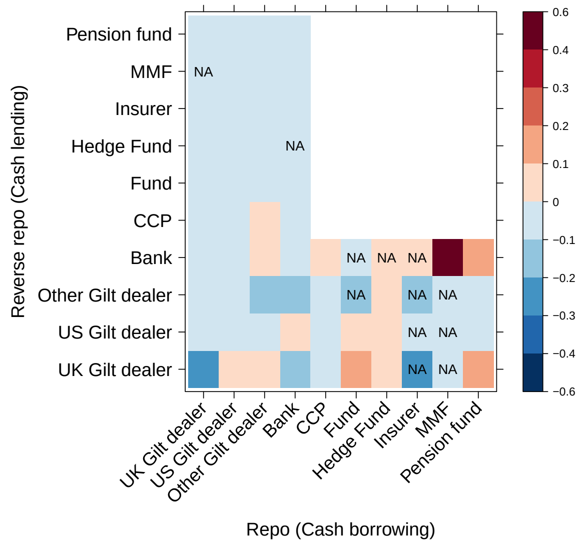


(d) COVID: Estimate of $\beta^{(\text{Normal, Vol})} + \beta^{(\text{CS3, Vol})}$.

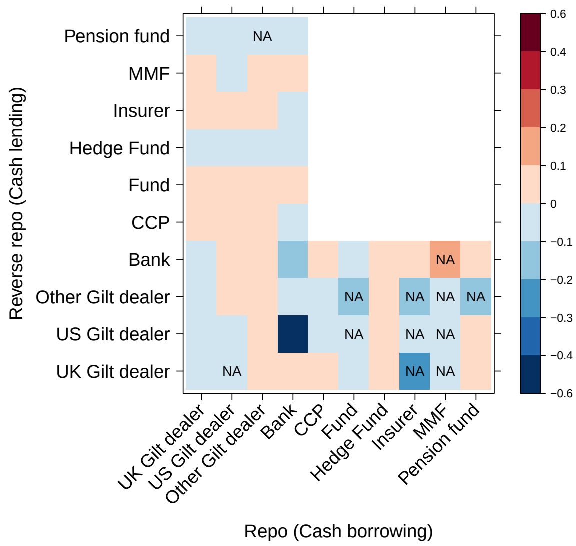
Figure 18: Parameter estimates for the average volume in normal times and the average volumes during each of the three stress periods. Crosses indicate that the corresponding sector pairs did not transact during the corresponding stress episode and hence the corresponding estimates are (almost) zero.



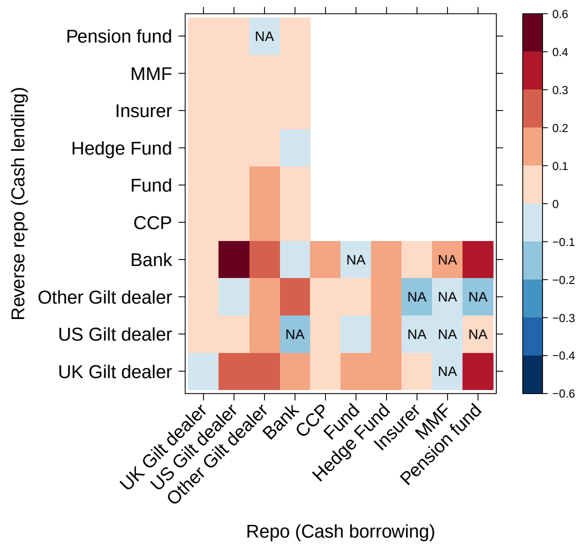
(a) Normal times: Estimate of $\beta^{(\text{Normal, Spread})}$.



(b) EU referendum: Estimate of $\beta^{(\text{Normal, Spread})} + \beta^{(\text{CS1, Spread})}$.

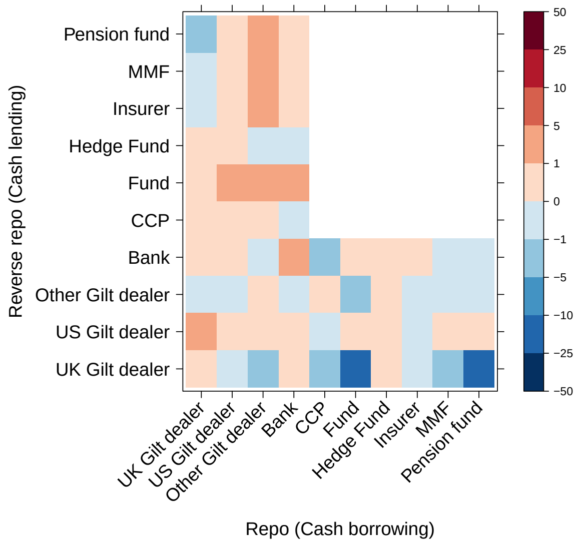


(c) US turmoil: Estimate of $\beta^{(\text{Normal, Spread})} + \beta^{(\text{CS2, Spread})}$.

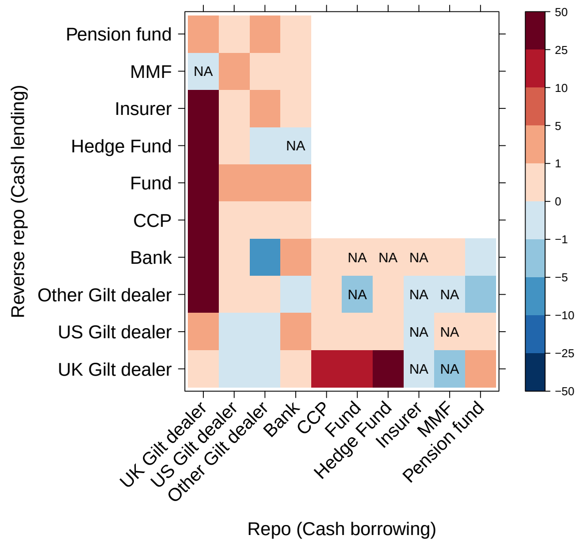


(d) COVID: Estimate of $\beta^{(\text{Normal, Spread})} + \beta^{(\text{CS3, Spread})}$.

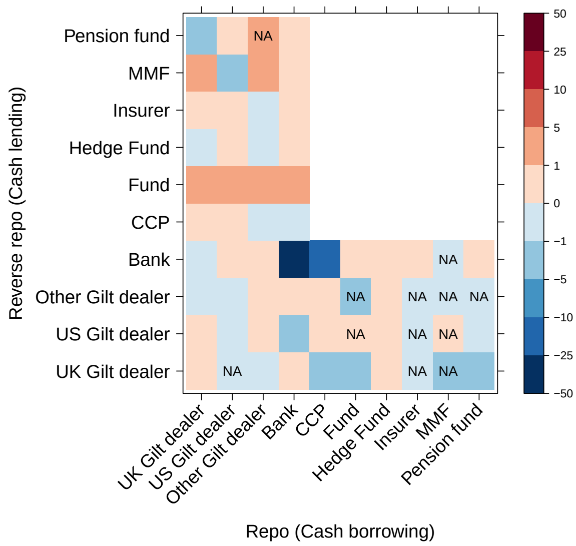
Figure 19: Parameter estimates for the average repo spread in normal times and the average repo spread during each of the three stress periods. All estimates are given in percent. "NA" indicates that the corresponding sector pair did not transact during the corresponding stress episode and hence the corresponding estimate does not exist.



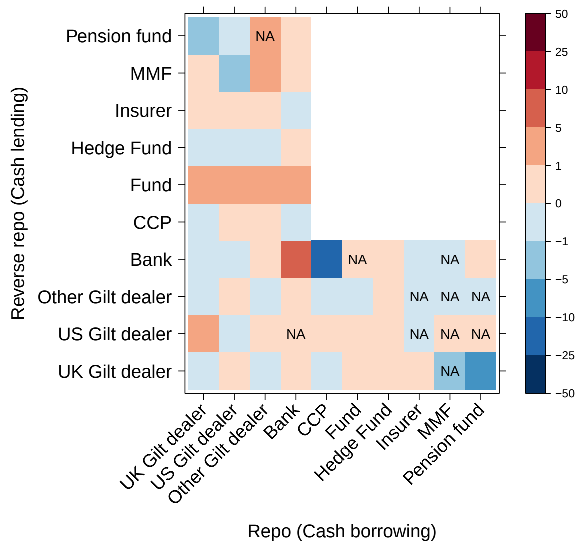
(a) Normal times: Estimate of $\beta^{(\text{Normal, HC})}$.



(b) EU referendum: Estimate of $\beta^{(\text{Normal, HC})} + \beta^{(\text{CS1, HC})}$.



(c) US turmoil: Estimate of $\beta^{(\text{Normal, HC})} + \beta^{(\text{CS2, HC})}$.



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

Figure 20: Parameter estimates for the average haircut in normal times and the average haircut during each of the three stress periods. All estimates are given in percent. "NA" indicates that the corresponding sector pair did not transact during the corresponding stress episode and hence the corresponding estimate does not exist.

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