Outages in Sovereign Bond Markets

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February 2025

Abstract

We use outages as natural experiments to study sovereign bond market functioning. When the futures market goes down, cash market trading declines, liquidity evaporates, and prices deviate from fundamentals. At the micro level, outages reduce dealers' intermediation capacity and exacerbate information asymmetries. Dealers reliant on bond futures withdraw, forcing clients to accept higher markups or to trade directly with other clients, causing mispricing. In contrast, cash market outages barely affect futures trading, implying one-way price formation. Our findings reveal trade-offs between a (de)centralized market structure, support cross-asset learning models, and show how financial intermediaries impose limits to arbitrage.

Keywords: Yield curve, market microstructure, natural experiment.

JEL classification: G12, G14, G23

Contact address: mark.kerssenfischer@bundesbank.de and caspar.helmus@bundesbank.de. We thank Gabor Pinter (discussant), Davide Tomio (discussant), Samuel Rosen (discussant), Martin Scheicher (discussant), Darrell Duffie, Albert Menkveld, Peter Hoffmann, Jean-Edouard Colliard, Refet Gürkaynak, Dobrislav Dobrev, Marius Zoican, Emanuel Moench, Michael Weber, Yuriy Gorodnichenko, Harald Uhlig, Steven Ongena, Rainer Haselmann, Niklas Kroner, Andriy Shkilko, Milena Wittwer, Johannes Breckenfelder, Jean-David Sigaux, Thierry Foucault, Alexander Düring, Maik Schmeling, Rajkamal Iyer, Frank Keane, Bernd Schwaab, Claus Brand, an anonymous referee and seminar participants at ESMA, Deutsche Finanzagentur, The Microstructure Exchange, the 19th Central Bank Conference on the Microstructure of Financial Markets, the 51st EFA Annual Meeting, the 99th WEAI conference, the 12th Annual EBA Research Workshop, the 12th Bundesbank Term Structure Workshop, the 2024 Tri-City Day-Ahead Workshop on the Future of Financial Intermediation, the 9th Research Workshop of the ECB's Monetary Policy Committee Task Force on Banking Analysis, and the ECB's Market Operations Committee, for valuable feedback. The views expressed in this paper are those of the authors and do not necessarily coincide with the views of the Deutsche Bundesbank or the Eurosystem.

1 Introduction

The risk-free yield curve builds the foundation for asset pricing and the literature has made considerable progress understanding *why* bond yields change.[1] This paper provides new evidence on *how* price formation takes place by exploiting market outages as natural experiments. These outages were unanticipated and for all intents and purposes exogenous. Hence, how different investors reacted to these outages across trading venues and across financial instruments provides a rare glimpse into the price formation process underlying the risk-free yield curve.

Our first key contribution is to highlight the role of bond futures. We focus on two days in 2020, 14 April and 1 July, when technical glitches abruptly halted trading on the euro area futures exchange Eurex for several hours.[2] To study the effects on the cash market for sovereign bonds, we combine regulatory non-anonymous transaction-level data and data sourced directly from major trading platforms, interdealer brokers, and indicative quote providers. Thanks to the sharp discontinuities caused by the outages, we can identify causal effects with straightforward methods. In particular, we compare key variables in tight windows around the outages. To account for time-fixed effects, we also compare outage days with similar 'control' days, usually the same day of the week one week before and after. We document dramatic macro-level effects of Eurex outages and trace these back to the underlying micro-level mechanisms.

Trading volumes on the cash market drop sharply for government bonds of all four euro area countries we study (Germany, France, Italy, Spain). The decline is particularly strong for bonds with longer maturity. Market liquidity also declines dramatically during outages, with some differential effects across countries. Executable quotes on MTS's dealer-to-dealer platform vanish almost entirely for Germany, France and Spain. Liquidity is most robust for Italy, where MTS is the main cash trading venue, but even for Italian bonds, quoted bid-ask spreads spike and the quoted volume declines by more than half when Eurex is down. Just as for trading volumes, the liquidity dry-up is more pronounced for bonds with longer maturity. Indicative quotes, which usually provide a guidepost to negotiate trades in the over-the-counter (OTC) market, become stale as soon as bond futures become unavailable. This is true for quotes from all three different data providers we study (Bloomberg, Refinitiv, and TPICAP). While the exact calculation methods behind these indicative quotes are not disclosed, our results show that bond future prices are a vital input.

Finally, futures market outages cause a large spike in mispricing on the cash bond market. Focusing on German bonds, the euro area's risk-free benchmark, we show that the remaining cash market transactions during outages occur at prices far from fundamental values. Under normal conditions, arbitrage forces keep observed market yields closely aligned with a smooth

[1] The literature has identified two major drivers of yields: *news*, such as monetary policy announcements or macroeconomic data releases, see e.g. Fleming and Remolona (1999), Andersen, Bollerslev, Diebold, and Vega (2003, 2007), Gürkaynak, Kısacıkoğlu, and Wright (2020), Kerssenfischer and Schmeling (2024) and *flows*, see e.g. Brandt and Kavajecz (2004), Green (2004), Pasquariello and Vega (2007), Deuskar and Johnson (2011) and Gabaix and Koijen (2021).

[2] Regarding the nature of those glitches, Deutsche Börse commented: *'The disruption in the T7 system in April and today's failure had the same origin. They were due to faulty third-party software that is part of the trading system. [..] External causes can be ruled out.'* Appendix B contains further narrative evidence on the outages.

fitted yield curve. When Eurex goes down, however, pricing errors – the difference between observed and fitted yields – increase sharply and are many times higher than normal. The root mean squared pricing error – Hu, Pan, and Wang (2013)'s noise measure – matches or exceeds levels observed during the peak of the Covid-19 market turmoil in March 2020. Pricing errors spike immediately after the outage and quickly recede once Eurex is back online. Small trades in short-term bonds become particularly mispriced.

Taken together, these *macro*-level results suggest that bond futures are vital for the euro area fixed-income market to function smoothly. As our second major contribution, we exploit the granularity of our transaction dataset to identify the *micro*-level mechanisms causing the cash market to break down. Dealers sharply reduce their market presence during Eurex outages but their remaining trades remain fairly priced, at least when trading with other dealers. Consequently, trading volumes and market liquidity drop more but pricing errors increase less at the long end of the yield curve, where dealers are more active. Small transactions become most mispriced, as these are predominantly executed between clients without dealer involvement. This evidence suggests that dealers are better informed than clients and rely less on bond futures to accurately price the risk-free yield curve. Dealers are, however, more reliant on the futures market for hedging purposes. As bond futures become unavailable, dealers are less willing to intermediate bond trades on the cash market. Exploiting the heterogeneity in hedging strategies we uncover, we show that dealers with the most intense use of bond futures often cease to intermediate trades altogether, forcing clients to trade directly with each other, usually at prices far from fundamental values. Dealers with a more moderate use of bond futures retain some intermediation capacity during Eurex outages, but they demand higher markups when trading with clients, particularly for large trades in long-term bonds. Lastly, clients with more and stronger dealer connections fare better during outages, indicating that outages exacerbate information asymmetries and increase the importance of client-dealer relationships.

Our third and final major contribution is to document how unique the effects of futures market outages on the cash market are. We first show that outages on cash trading platforms have much smaller effects, both on the aggregate cash market and on the futures market. We found five such outages affecting four different platforms, but three outages are particularly informative. First, on 12 January 2010 a technical glitch delayed the market opening on MTS by roughly two and a half hours. This outage has almost no discernible impact on bond futures traded on Eurex, in stark contrast to the widespread breakdown of MTS during Eurex outages. Second, on 17 April 2015, Bloomberg terminals worldwide were inaccessible for about two hours. This outage significantly reduces trading volumes on the futures market, but barely affects market functioning. Standard illiquidity measures rise by less than a tenth of a standard deviation. The third major cash market outage affected the Brokertec platform for about two hours on 11 January 2019. Again, this outage reduces trading volumes but barely affects the liquidity on the futures market. Importantly, this null effect also holds for US Treasury futures, despite the fact that Brokertec is the dominant electronic trading platform for US Treasuries. Taken together, we document very asymmetric effects of outages. Price discovery and liquidity provision seem to be more of a one-way street from the futures to the cash market than previously thought.

Lastly, we show that outages on the euro area futures market do not spill over to the US futures market and vice versa. Specifically, the order book depth of US Treasury futures does not decrease when Eurex goes down. Likewise, we exploit seven outages on the US futures market and find no systematic decrease in liquidity or trading activity on the euro area futures market. This lack of liquidity spillovers stands in stark contrast to the strong price spillovers documented in the literature, particularly from the US to Europe (see e.g. Boehm and Kroner, 2024). Market participants seem to provide bond liquidity purely 'domestically', not conditionally on a foreign risk-free yield curve.

Our quasi-experimental evidence is informative for three major strands in the literature. It highlights the trade-offs between a (de)centralized market structure, distinguishes competing theories about the link between liquidity and arbitrage and lastly, and it shows how financial intermediaries create limits to arbitrage.

Market Structure (On vs. Off-Exchange Trading). A key issue in market microstructure is the prevalence and desirability of trading outside of exchanges. Positive network effects push trading towards a single central exchange, but information asymmetries pull in the opposite direction. In particular, because more informed and faster traders impose adverse-selection costs on liquidity suppliers, these liquidity suppliers have an incentive to trade with uninformed traders off-exchange, potentially at a discount.[3] Lee and Wang (2024) formalize this intuition. In their model, less informed traders optimally choose the OTC market. Nonetheless, closing the OTC market raises welfare, particularly for assets traded mostly OTC. Allen and Wittwer (2023a) use transaction-level data to estimate a structural model of the Canadian government bond market. They find that shifting trades to a centralized platform could decrease welfare, unless competition among dealers is sufficiently strong.[4]

Our results provide an important qualifier. On the decentralized cash market, investors – particularly clients – free-ride on the price discovery provided by the centralized futures market. Bond futures serve as benchmarks, which have positive externalities for the wider market (Duffie, Dworzcak, and Zhu, 2017). Welfare calculations should take this point into account. Centralizing the OTC market would have additional benefits, insofar as it leads to more liquidity and self-sustained price discovery. This is in line with Kutai, Nathan, and Wittwer (2025), who document that the Israeli bond market, the only major government bond market operating on an exchange, performed better during the Covid-19 crisis than most other markets operating OTC. We find similar results across euro area countries: the liquidity in Italian bonds drops least during futures market outages, in line with the fact that most cash trading is centralized in a single limit order book. At the same time, our results show that full market centralization comes at the cost of introducing systemic risks.

[3] de Roure, Moench, Pelizzon, and Schneider (2025) provide empirical evidence in line with the price discrimination channel. They document that for German government bonds, transaction prices in the OTC market are favorable compared to the centralized MTS exchange. This 'OTC discount' is in line with the fact that most German bonds are traded off-exchange.

[4] Dugast, Üslü, and Weill (2022) provide a model for on vs. off-exchange trading and show that, depending on their trading capacity, some market participants benefit from a decentralized OTC market. Biais and Green (2019) provide historical context and document that up until World War II, most US bond trading occurred on-exchange.

Liquidity and Arbitrage. We use our natural experiments to test competing theories of liquidity provision. In models of *cross-asset arbitrage*, arbitrageurs such as high-frequency traders exploit mispricings of similar securities across different exchanges (see Gromb and Vayanos, 2010, 2018). Hence, they provide liquidity on one exchange conditional on the availability of another. Harding and Ma (2010) e.g. show that outages on the main US Treasury futures exchange (CBOT, Chicago Board of Trade) lead to a dramatic fall in liquidity on a major electronic cash market trading platform (Espeed). This is similar to our finding that liquidity on MTS evaporates when Eurex is down.

However, the underlying mechanism is assumed to be symmetric. In our case, cross-asset arbitrage models predict that cash market outages should have equally dramatic effects on the futures market. Harding and Ma (2010) do not directly test this prediction, probably because there have been no suitable outages of the Espeed platform. We do test and reject this prediction. We find much smaller effects of cash market outages on the futures market, suggesting that price formation and liquidity provision is more of a one-way street from the futures to the cash market.

Hence, our evidence is more in line with *cross-asset learning* models (see e.g. Admati, 1985; Veldkamp, 2006; Cespa and Foucault, 2014; Asriyan, Fuchs, and Green, 2017). The key idea of these models is that liquidity providers use some particularly informative asset prices to trade further assets. Applied to our case, bond futures are used to price and provide liquidity in other fixed-income instruments, such as sovereign bonds and interest rate swaps.[5]

Intermediary Asset Pricing and Limits to Arbitrage. A closely related literature studies the role of intermediaries in financial markets and the limits to arbitrage they impose (see Long, Shleifer, Summers, and Waldmann, 1990; Shleifer and Vishny, 1997; Gromb and Vayanos, 2002; Mitchell, Pedersen, and Pulvino, 2007; Brunnermeier and Pedersen, 2008; Gabaix and Maggiori, 2015; He and Krishnamurthy, 2013; Allen and Wittwer, 2023b; Bräuning and Stein, 2024). In a recent paper on the U.S. Treasury market, e.g., Duffie, Fleming, Keane, Nelson, Shachar, and Van Tassel (2023) show that expected volatility explains most of the time variation in Treasury market liquidity, but when dealers exhaust their balance sheet capacity – as observed in March 2020 – market functionality gets impaired. The outages we study provide a clear natural experiment that corroborates this functional chain. The Eurex outages diminish dealers' capacity to intermediate bond trades on the cash market, since they are unable to hedge their inventory risk on the futures market. Consequently, clients with an urge to trade have to trade directly with other clients, pushing prices away from fundamental values. Crucially, our evidence is not subject to the usual endogeneity concerns between expected volatility, market

[5]Numerous papers employ vector error correction models to show that bond futures 'lead' in price discovery, i.e. they reflect new information faster than bonds on the cash market, see e.g. Mizrach and Neely (2008) and Dobreva and Schaumburg (2023) for US Treasuries, Upper and Werner (2007) for German bonds and Jappelli, Lucke, and Pelizzon (2022) for German, French and Italian bonds. We document an even more pivotal role for bond futures: they are a prerequisite for the fixed-income market to function smoothly. This result also relates to the literature on dominant vs. satellite markets, which usually looks at stocks traded on multiple exchanges (cross-listed instruments) and finds that price discovery occurs mostly on the primary stock exchange (see e.g. Hasbrouck, 1995; Guillaumie, Loiacono, Winkler, and Kern, 2020; Hagströmer and Menkveld, 2023). Cast in these terms, we show that for bonds, the futures market is the dominant market while the different cash market trading venues are satellite markets.

liquidity, and dealer capacity.

2 European Government Bond Market Structure

This section briefly outlines the market microstructure for euro area government bonds (EGBs) on the cash and futures market, see Appendix A for further details. Our analysis covers the four largest euro area member states: Germany, France, Italy and Spain. They are also the only countries with corresponding bond futures.

The futures market for EGBs is highly homogeneous and centralized, as these futures are traded exclusively on Eurex's central limit order book (CLOB). There are only a handful of bond futures covering selected maturity segments. A 10-year bond future exists for all four countries. For Italy, also a 2-year bond future is actively traded while for Germany, bond futures are also available for the 2-, 5-, and 30-year segment. Together, the trading volume in German bonds is roughly ten times larger on the futures than the cash market in terms of underlying value. For France and Italy, the two markets are of comparable size, while for Spain, where a future was introduced last, trading volumes in futures are only about 1% of the cash market volume.

In terms of market participants, the futures market is rather concentrated, with relatively few high frequency trading firms dominating trading activity (Hautsch, Noé, and Zhang, 2017; Kirilenko, Kyle, Samadi, and Tuzun, 2017). The cash market, in contrast, has the typical dealer-client and core-periphery structure (see e.g. Di Maggio, Kermani, and Song, 2017; Li and Schürhoff, 2019; Bessembinder, Spatt, and Venkataraman, 2020; Allen and Wittwer, 2023a).

The cash market for EGBs is also much more fragmented and opaque compared to the futures market. There are hundreds of individual bonds outstanding at any point in time and these can be traded on very different venues. Trading on these venues differs along multiple dimensions, which are best explained with concrete examples from two polar opposites. On the one side, bonds can be traded anonymously and immediately in a CLOB, just like bond futures. MTS is the dominant platform in this regard, but it is for the most part only accessible to dealers, i.e. large banks. Bonds can also be traded in a CLOB on regular stock exchanges, which are open also to small retail traders. But out of the multitude of exchanges, no single exchange captures a significant market share and the order book for most bonds is correspondingly thin. Some exchanges offer incentive programs for designated market makers to improve this poor liquidity. Importantly, on-exchange trading is 'lit', i.e. all market participants can observe quotes and transaction prices and volumes.

On the other side, bonds can be traded over-the-counter (OTC). Bilateral OTC trades are neither anonymous nor immediate. Such trades are typically negotiated by voice or chat and they remain common since bonds are less standardized and generally traded less frequently, but in larger size, compared to other financial instruments. To preserve some anonymity and to reduce search costs, market participants can also trade OTC via a broker. In this case, the initiating party communicates its trade request to a broker, who then tries to find a suitable counterparty on a 'matched principal' basis, see de Roure et al. (2025) for a detailed description of this market segment. This way, the two counterparties do not have to reveal their identity to each other. Yet another venue on the OTC market are systematic internalisers (also called single-dealer platforms). On these platforms, large dealer banks act as a central counterparty for trades initiated by their clients. Compared to on-exchange trades, all three types of OTC trades are comparatively 'dark', i.e. there is little pre- and post-trade transparency.

In between these two extremes, another increasingly important market segment for EGB trading are electronic trading platforms, which dominate the dealer-to-client segment. Examples for such platforms are Tradeweb and Bloomberg, which use a request-for-quote (RFQ) mechanism, i.e. clients request quotes for a certain bond from multiple dealers.

Moreover, to facilitate the matching process between buyers and sellers, various companies – e.g. trading platforms themselves – provide indicative quotes for European government bonds. These quotes are often available only for specific bonds, e.g. 'benchmark' bonds of selected maturities, and the exact calculation methods behind those quotes are not disclosed.

Lastly, the market structure of EGBs differs substantially across countries. Italian bonds, e.g., are predominantly traded 'on-exchange' (on MTS), whereas German bonds are traded more on electronic trading platforms and OTC.[6] To capture this heterogeneous bond market as much as possible, we combine various data sources, as explained in the following subsections.

2.1 Cash Market Transactions

For EGB transactions on the cash market, we start with the non-anonymous MiFIR dataset, which contains information on bond transactions since 2018 and which is collected under the MiFID II regulation. For each transaction, this dataset contains the ISIN, price, volume, time, the involved counterparties, as well as the venue on which the trade was executed. This dataset has been made available relatively recently and to the best of our knowledge, we are the first to use it for academic research. While relatively new, the dataset can be seen as an extended version of the Bafin dataset used in prior work (see e.g. de Roure et al., 2025), which was collected under the MiFID I regulation during 2008-2017, see Bundesbank website and German Securities Trading Act.

An important caveat for our purposes is that the regulatory data only covers trades in which a German security is traded or where at least one of the involved parties – the buyer or seller, the trading venue, or a central counterparty (CCP) – is domiciled in Germany. This is why trades in German bonds are overrepresented.

For the six most important days in our sample – the two Eurex outage days and the respective control days – we address this limitation by complementing the regulatory dataset with data sourced directly from trading platforms (MTS, MTS BondVision, Tradeweb) and interdealer brokers (TPICAP, BGC, GFI, Aurel). This way we are able to capture also a large share of transactions in French, Italian and Spanish government bonds. In contrast to the regulatory data, however, these datasets are anonymous, i.e. they do not contain information about the involved counterparties. Appendix A.5 describes our transaction-level data in detail.

[6] Our distinction of trading venue types (on-exchange, electronic platforms, OTC) differs somewhat from the MiFID II regulation, see Appendix A.3 for details.

Besides the transaction data, we also use quote data. In particular, we have executable quotes and volumes from MTS's CLOB and indicative quotes from Bloomberg, Refinitiv and TPICAP.

2.2 Futures Market Transactions

For bond futures, we exploit three different datasets. First, for futures traded on Eurex, we have the full history of transaction prices and volumes at the millisecond frequency going back to 2002. Second, we have the full intraday order book data, i.e. bid and ask quotes and volumes for all order book levels, going back to April 2019 for Eurex and February 2019 for CME (Chicago Mercantile Exchange). The latter datasets come from Deutsche Boerse's A7 platform. Third and lastly, we have non-anonymous investor-level data on bond future transactions since 2019. These data come from the European Market Infrastructure Regulation (EMIR) dataset.

2.3 Investor-Level Data

The two regulatory datasets mentioned above (MiFIR and EMIR) are non-anonymous, they contain a unique legal identifier (LEI) for the counterparties involved in each transaction. To classify investors into different sectors, we can thus use supervisory lists and the Register of Institutions and Affiliates Database (RIAD, see Perrella and Catz, 2020). We differentiate between banks, non-bank financial institutions (NBFI), investment funds, hedge funds, insurance companies and pensions funds (ICPF), non-financial corporations (NFC), an official sector (including central banks), and households (retail investors). We further identify whether an investor is a dealer and whether the investor is usually active also on the bond futures market or only the cash market. Appendix A.6 provides details.

3 Macro-Level Effects of Futures Market Outages

On 14 April 2020 and 1 July 2020, technical glitches caused outages on Eurex, the leading futures market exchange in the euro area. The first outage lasted approximately four and a half hours, from 9:25 a.m. to 2:00 p.m. while the second outage lasted less than three hours, from 8:49 a.m. to 11:31 a.m. (all in local time). In both cases, Eurex blamed 'faulty third-party software' as the root cause. We use these outages as natural experiments to study the role of the futures market for the broader fixed-income market in the euro area.

Figure 1 shows cumulative trading volumes in 10-year government bond futures. These futures are available for all of the four biggest euro area member states and are usually the most heavily traded maturity. To put the events into perspective, we compare outage days with the previous and subsequent week. The figure confirms that during both outages, trading indeed stopped across all futures.

We will show how these outages affect the *cash* market for EGBs, namely in terms of trading activity (Section 3.1), market liquidity (Section 3.2), and pricing (Section 3.3).

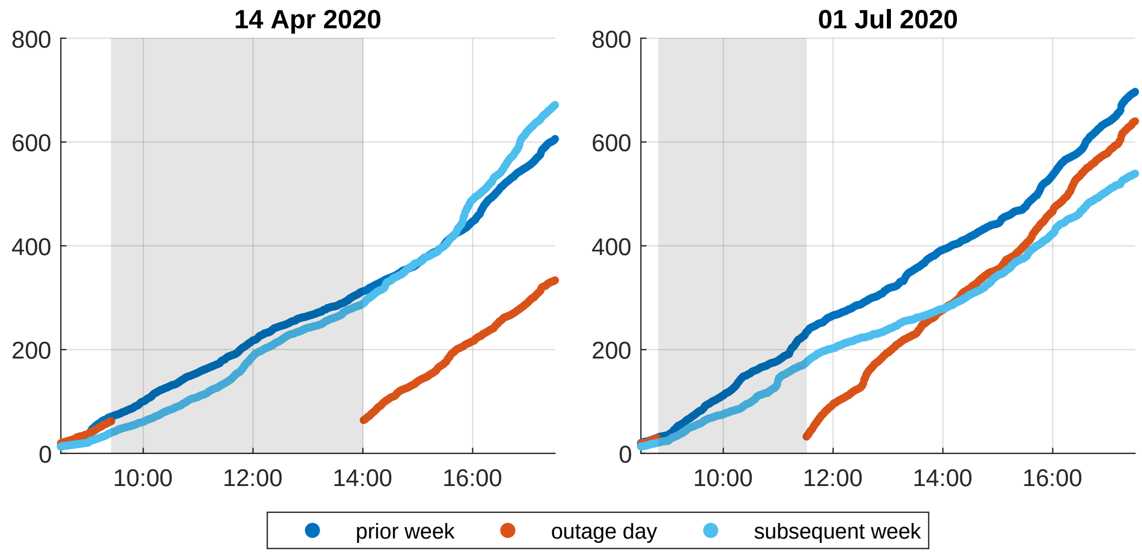

Figure 1: Trading Volume in 10-year Bond Futures. This figure shows the cumulative number of traded contracts (in thousands). Red dots refer to the outage day, dark and light blue dots refer to the previous and subsequent week.

3.1 Trading Activity

Figure 2 plots the cumulative bond trading volume on the cash market, based on our extensive transaction-level dataset. Trading volumes drop while Eurex is offline and surge once it comes back online.[7]

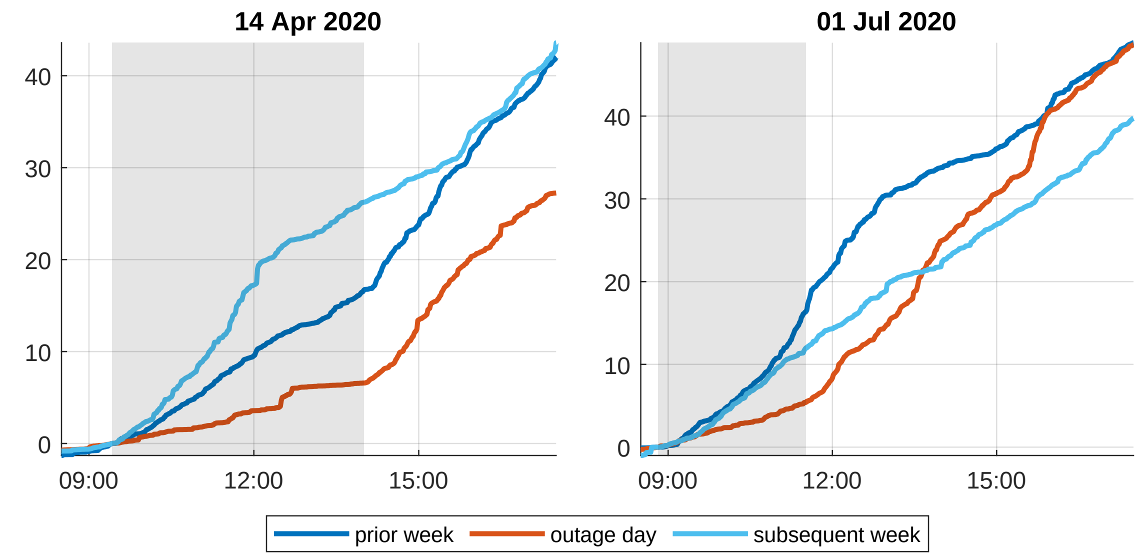

Figure 2: Trading Volume in EGBs on the Cash Market. This figure shows the cumulative trading volume in all German, French, Italian and Spanish sovereign bonds (in billions of Euro, normalized to zero at the intraday time of the outage). Red dots refer to outage days, dark and light blue dots to the previous and subsequent week.

[7]In Appendix D.1, we confirm that trading volumes catch up significantly after the outages, suggesting that some investors are forced to or choose to delay their trades.

To investigate this more formally, we estimate the following dummy regression:

$$log(1 + Volume_{cmt}) = \alpha + \beta \times D_t + \gamma \times FE + \epsilon_t \tag{1}$$

where $Volume_{cmt}$ is the total trading volume in bonds of country c and maturity bucket m in the 30-minute time interval t. D_t is a dummy that equals one during the Eurex outages and is zero otherwise, and FE captures fixed effects. We include six days (the two outage days plus the preceding and subsequent week) and 15 intraday observations per day (from 08:30 a.m. to 4:00 p.m.). We use $log(1 + Volume_t)$ to account for periods with zero trading volume.[8]

Table 1 reports the results.[9] Model (1) confirms that trading volumes on the cash market decrease dramatically during the futures market outages. Model (2) shows that trading volumes drop particularly for bonds above 2.5 years of maturity, while model (3) shows that all four euro area countries are affected similarly by the outage.

	(1) Average	(2) Maturities	(3) Countries
Outage	-3.10*** [0.56]		
Outage × <2.5y		-1.07** [0.35]	
Outage × 2.5-5.5y		-3.69*** [0.47]	
Outage × 5.5-10.5y		-3.81*** [0.64]	
Outage × >10.5y		-3.83** [1.01]	
Outage × DE			-2.75*** [0.36]
Outage × FR			-3.36** [1.03]
Outage × IT			-3.24*** [0.16]
Outage × ES			-3.05** [0.88]
FE Day	✓	✓	✓
FE Time	✓	✓	✓
FE Country	✓	✓	
FE Maturity Bucket	✓		✓
Observations	1440	1440	1440
Adjusted R^2	0.324	0.335	0.323

Table 1: Effect of Eurex Outages on Cash Trading Volume. Each column shows results of a different regression, see Equation 1. The dependent variable is the log of the transaction volume in bonds of a given country and maturity bucket, in 30-minute intervals. Model (2) adds an interaction term between the outage dummy and the maturity buckets, model (3) does the same for countries.

One obvious explanation for why long-term bonds are traded particularly rarely is that Eurex outages increase the uncertainty about the 'fair' risk-free rate, particularly at the long end of the yield curve. Hence, market participants become reluctant to trade long-term bonds. We

[8]Chen and Roth (2023) show that the regression coefficients in this setting should not be interpreted as approximate percentage effects. The maturity buckets c cover bonds of less than 2.5 years to maturity, 2.5 to 5.5 years, 5.5 to 10.5 years, and more than 10.5 years, see Appendix A.4 for details. Appendix D.6 reports results for regressions at the individual bond level. Trading volumes fall particularly sharply for on-the-run bonds and slightly less for zero-coupon bonds.

[9]Throughout this paper, *,**,*** indicates statistical significance at the 10%, 5% and 1% level, respectively and standard errors (shown in brackets) are clustered at the daily level.

will come back to this question in Section 4.

3.2 Market Liquidity

3.2.1 Executable Quotes

MTS is the only major trading venue for euro area sovereign bonds with a central limit order book, i.e. immediately executable quotes. In this regard, MTS is the closest alternative to Eurex to trade fixed-income securities. So does trading transition to MTS when Eurex goes down? For simplicity and maximum comparability, we first look at a single bond per country, namely the cheapest-to-deliver (CTD) bond underlying the 10-year bond future.[10]

Figure 3 shows that trading in these bonds effectively freezes on MTS during the Eurex blackout. Roughly three minutes after Eurex went down on 14 April 2020, virtually all quotes vanish from the MTS platform, resulting in an order book depth of zero. The first quotes reappear only at 14:06, six minutes after trading on Eurex resumed. The same is true for the second outage. While trading usually starts before 9:00 a.m. on MTS, most quotes appear only at 11:43 a.m. on 1 July 2020, 12 minutes after Eurex was back online. These results suggest that the MTS cash market platform functions properly only if the futures market is active. One might think this is true only for CTD bonds, due to their close connection to the futures traded on Eurex, but we will show that the breakdown on MTS extends far beyond these specific bonds.

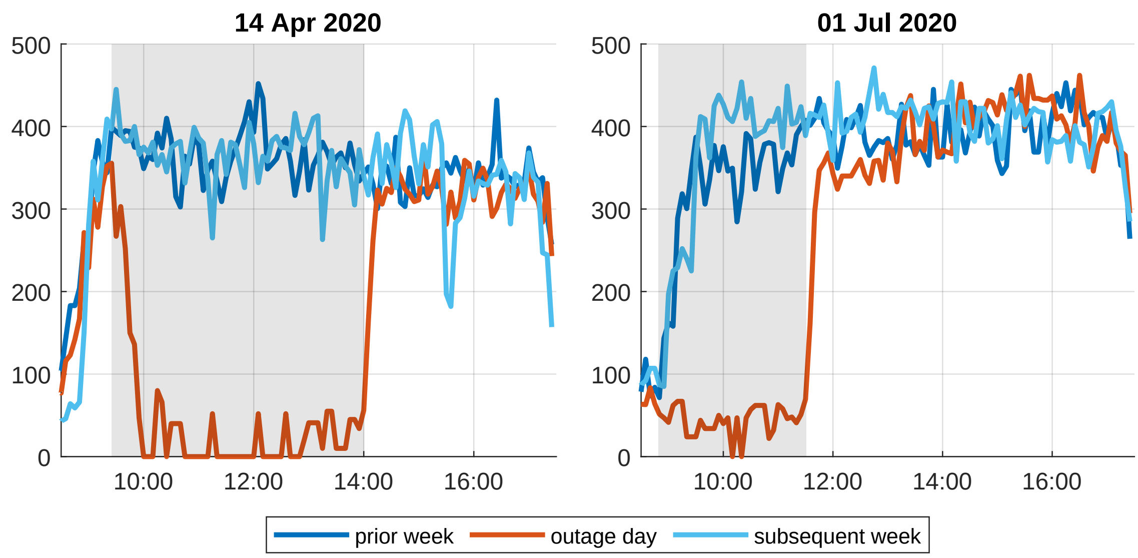

Figure 3: Order Book Depth on MTS. This figure shows the total quoted volume for German, French, Italian and Spanish 10-year CTD bonds (in million €) across all three levels and both sides of the order book, at 5-minute snapshots.

Before delving into further details, recall that Harding and Ma (2010) report broadly similar results to what we find here: outages of the main US futures exchange (CBOT) lead to a

[10] See Appendix A.4 for the ISIN of each CTD bond. Appendix D.4 confirms that the results presented here are not confined to these particular bonds.

dramatic fall in trading and quoting activity on a major electronic cash market trading platform (Espeed). They attribute this finding to high-frequency trading firms that are only active on the cash market if the futures market is online and vice versa. However, we can rule out this explanation in our setting, because only dealers are allowed to trade on MTS.[11] The fact that liquidity on MTS evaporates regardless suggests that the forces at work are more general. We will show that the more likely explanation is simply that price discovery and liquidity provision crucially depend on an active futures market. Without bond futures as a hedging instrument and pricing signal, market functioning on the cash market deteriorates dramatically.

To study the dependency of MTS on Eurex in more detail, we estimate dummy regressions of the following form:

$$log(1 + OBdepth_{cmt}) = \alpha + \beta \times D_t + \gamma \times FE + \epsilon_t \tag{2}$$

where $OBdepth_{cmt}$ is the order book depth (in €) of all bonds of country c and maturity bucket m at time t, measured at 5-minute snapshots. D_t is a dummy that equals one during Eurex outages and zero otherwise, and FE captures fixed effects. We include six days (the two outage days plus the preceding and subsequent week) and 91 intraday observations per day (5-minute intervals from 08:30 a.m. to 4:00 p.m.). We use $log(1 + OBdepth_{cmt})$ to account for periods with empty order books.[12]

Table 2 shows the results. For most countries and maturity buckets, the order book depth on MTS drops dramatically when Eurex goes down, see model (1). Model (2) shows that liquidity drops more for bonds with longer maturity, in line with the trading volume results above.

Before examining the differential effect across countries, recall that MTS is the main trading platform for Italian bonds and aggregate trading volumes in Italian bonds have a similar magnitude on the cash and futures market. This is in stark contrast to Germany e.g., where trading volumes on the futures market are roughly ten times larger than on the cash market and where MTS has only a negligible cash market share (see Appendix A.3 for details). Hence, we would expect that Italian bonds are less affected by the Eurex blackout. And indeed, model (3) confirms that while liquidity in German bonds evaporates entirely during Eurex outages, other countries are less affected. The liquidity in Italian bonds is most robust, followed by Spanish and French bonds. Still, our results suggest that market functioning on MTS is severely impaired during Eurex blackouts even for Italian bonds.

3.2.2 Indicative Quotes

Apart from the executable quotes on MTS, there are several providers of indicative quotes for EGBs. We obtained data from three different providers, namely Bloomberg, Refinitiv and TP-ICAP. Bloomberg terminals and Refinitiv's Eikon application are the two most widely used

[11]The current list of members is available on the MTS website.

[12]Appendix D.6 reports results for similar regressions at the individual bond level. Eurex outages cause liquidity to fall particularly sharply for cheapest-to-deliver, on-the-run, and zero coupon bonds. The same is true for bonds with a longer time since issuance and a longer time to maturity.

	(1) Average	(2) Maturities	(3) Countries
Outage	-10.86*** [0.42]		
Outage × <2.5y		-4.95*** [0.21]	
Outage × 2.5-5.5y		-13.45*** [0.32]	
Outage × 5.5-10.5y		-12.68*** [0.62]	
Outage × >10.5y		-12.35*** [0.71]	
Outage × DE			-18.03*** [0.43]
Outage × ES			-9.46*** [2.04]
Outage × FR			-14.15*** [0.44]
Outage × IT			-1.79** [0.52]
FE Day	✓	✓	✓
FE Time	✓	✓	✓
FE Country	✓	✓	
FE Maturity Bucket	✓		✓
Observations	8736	8736	8736
Adjusted R^2	0.518	0.558	0.644

Table 2: Effect of Eurex Outages on MTS Order Book Depth. Each column shows results of a different regression, see Equation 2. Throughout, the dependent variable is the log of the quoted bid and ask volume of all bonds of a given country and maturity bucket, at 5-minute snapshots. All explanatory variables are dummies, either for the maturity bucket or for different countries.

sources for real-time financial information. Both provide indicative quotes for EGBs, but the exact calculation methods behind those quotes are proprietary and hence not disclosed.[13] TP-ICAP, lastly, is an interdealer broker. To facilitate the intermediation of trades between two dealers, TPICAP surveys trading interests and publishes indicative prices for individual bonds.

Figure 4 shows that across all three data providers, indicative quotes become stale when Eurex suffers an outage. The number of quote updates drops dramatically the moment Eurex goes down and quickly recovers once trading resumes.[14]

Taken together, the indicative quote data are consistent with our claim that price discovery on the euro area fixed-income market hinges on bond futures. More generally, the results raise some doubts about the reliability of this type of data. Indicative intraday quotes on European government bonds appear to largely mirror bond future prices on Eurex, with little value added.

[13] Schestag, Schuster, and Uhrig-Homburg (2016), e.g., explain that Bloomberg's BGN prices 'are computed as a weighted average of quotes from participating dealers' and Bloomberg itself describes BGN as 'a real-time composite based on executable and indicative quotes from multiple contributors' which is 'indicative of available consensus-forming prices, and designed for broad terminal use' (see Bloomberg website). In fact, these indicative quotes are often used to negotiate and execute trades directly on Bloomberg terminals. Similarly, Refinitiv's 'Tick History' database contains the real-time feed updates shown on Eikon. For German and French bonds, quotes are from multiple 'pricing contributors', all of which are major European banks. For Italian and Spanish bonds, only a 'composite price', computed by Refinitiv, is available.

[14] Appendix D.7 confirms that these results hold across countries.

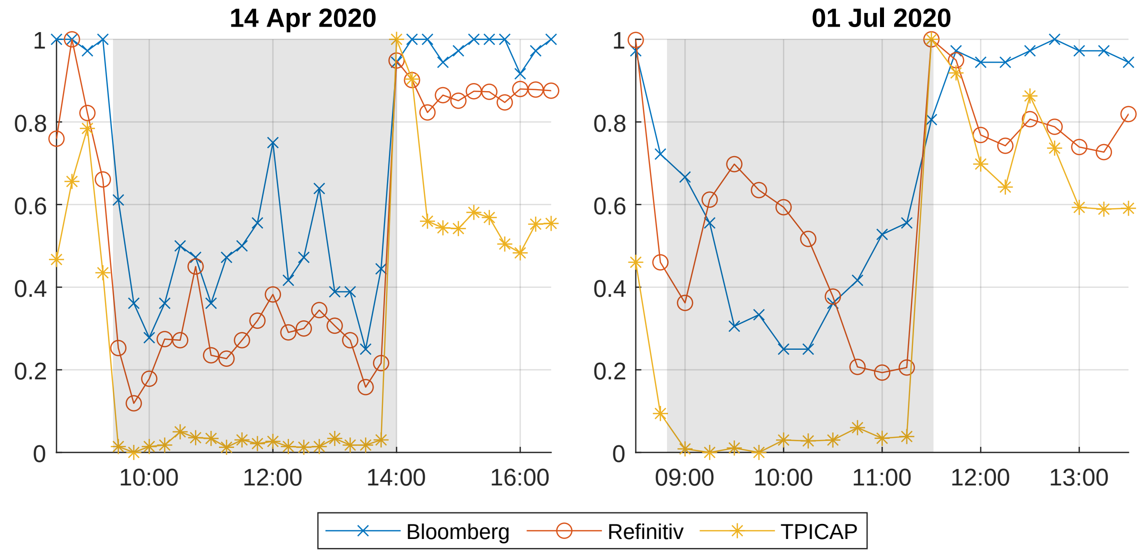

Figure 4: Quote Update Frequency for 10-Year Government Bonds on Different Platforms. Bloomberg and TPICAP data refer to quote updates in the cheapest-to-deliver bond, Refinitiv data to quote updates in the on-the-run ('benchmark') bond. Results for TPICAP and Refinitiv are based on the exact number of new quotes per bond. For Bloomberg, we approximate the number of new quotes as the number of tick-by-tick price changes. To show all series on a single scale, we aggregate the number of quote updates in 15-minute windows and normalize them to a 0-1 range for each data provider.

3.3 Pricing

We have documented that futures market outages lead to lower trading volumes and lower liquidity on the cash market for euro area government bonds. What we are ultimately interested in, however, is whether the price discovery process for EGBs is actually impaired due to the unavailability of bond futures.

Some prima facie evidence points in this direction: on 14 April 2020, the Dutch State Treasury Agency cancelled three bond auctions planned for that day, citing the Eurex outage as the reason.[15] The auctions were postponed to the next day, when Eurex was back online. This is particularly noteworthy since Dutch bonds are considered safe (rated AAA by all major rating agencies) and since the three bonds had an initial maturity of six months, nine months, and ten years, respectively. That means two bonds covered the short end of the yield curve, which is not covered by any bond future. Despite this low default and duration risk, Dutch authorities apparently feared that the bonds might not be properly priced by market participants while the futures market is offline.

Was this fear justified? To find out, we study yield curve fitting errors, a popular measure for how well the bond market functions. Hu et al. (2013) e.g. argue that arbitrage forces usually keep the yield curve smooth. Hence, a low dispersion in bond yields along the yield curve is a sign that bond prices are in line with fundamental values. So were the prices of bond transactions that *did* occur during the Eurex outages 'fair'? We focus on German bonds to answer this question, as they constitute the benchmark risk-free yield curve for the euro area. We convert

[15] 'Decided to postpone today's [...] auctions [...], due to technical issues at Eurex' (DSTA press release).

transaction prices observed in the market into par yields and then fit a term structure model to these observed yields.[16] We do this separately for all transactions that occurred while Eurex was offline, and for all transactions that occurred during the same intraday window but in the previous or subsequent week. Figure 5 shows the results.

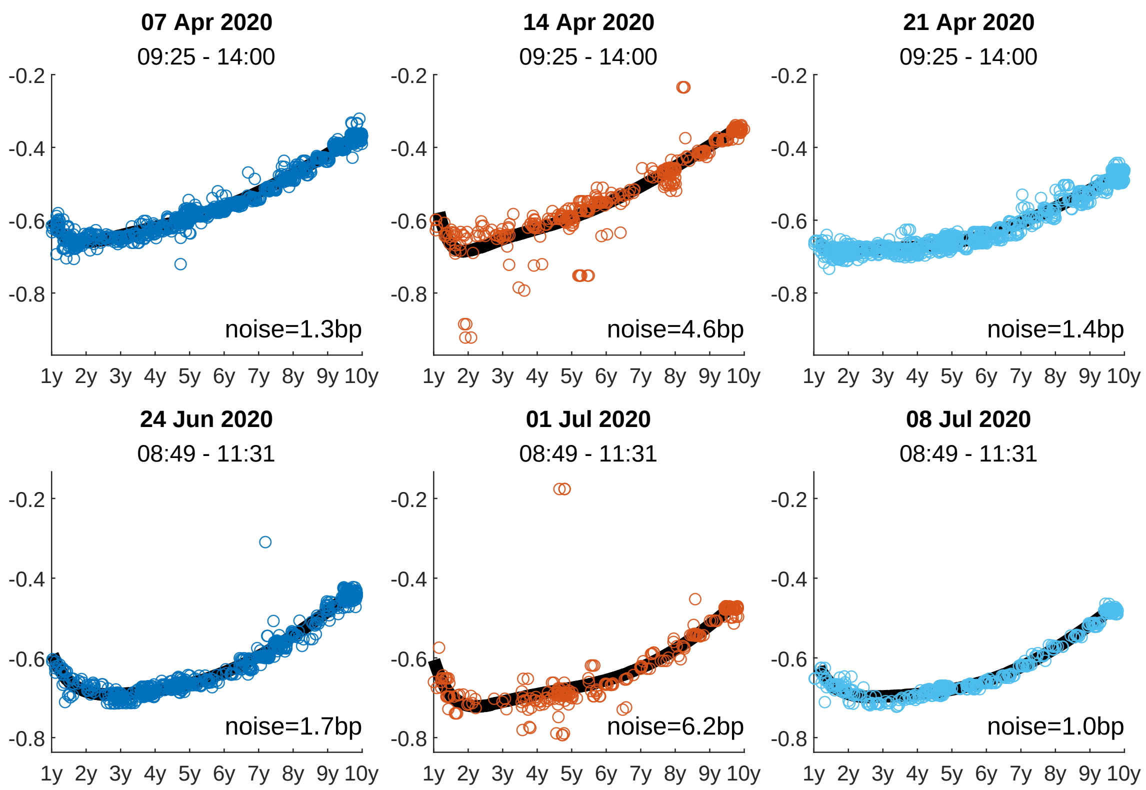

Figure 5: German Yields and Fitted Yield Curves. Each circle shows the implied yield of a transaction in German bonds during the intraday windows stated at the top of each panel. Red circles refer to the two Eurex outage days (middle column), dark and light blue circles refer to the same intraday window in the previous and subsequent week (left and right column, respectively). The vertical axis refers to the yield in percentage points, the horizontal axis to the remaining maturity in years. The black lines are fitted yield curves based on Svensson (1994). The value in the bottom right corner of each panel is the noise measure proposed by Hu et al. (2013), defined as the root mean squared pricing error (difference between actual and fitted yields).

The observed market yields usually lie on a smooth yield curve, but not when Eurex is offline. During the outages, many transactions deviate strongly from model-implied 'fair' yields. In fact, the dispersion in bond yields is so large that the exact method to compute 'fair' yields is secondary. We fit yield curves based on Svensson (1994), but we would obtain virtually the same increase in 'pricing errors' using the Nelson and Siegel (1987) or spline-based methods. During the outages, the noise measure proposed by Hu et al. (2013), defined as the root mean squared pricing error, is roughly three to six times higher than during the same intraday window one week before or after. Some market participants apparently struggle to price risk-free German sovereign bonds without bond futures as a guidepost. Section 4 will show who these investors are.

[16] For simplicity, we restrict this analysis to plain vanilla German government bonds with a remaining maturity of one to ten years, see Appendix A.5.

To put the Eurex outages into perspective, we repeat the above exercise for all trading days between 1 March 2020 and 8 July 2020. Figure 6 shows that the mispricing of German government bonds during the two Eurex outages was severe, comparable to or even higher than at the peak of the Covid-19 market turmoil in March 2020. For reference, the figure also shows the yield curve noise measure for US Treasuries published by Hu et al. (2013). Due to our use of intraday transaction prices, rather than end-of-day prices, our measure of noise is itself more noisy. This is because within our intraday windows, surprising macro news might hit the market, moving fair yields and hence mechanically increasing pricing errors. Nonetheless, the mispricing we compute for German bonds is remarkably close to US Treasuries. In both countries, the yield curve noise hovers around 1.5 basis points during normal times, but shoots up to more than 4 basis points during the Covid-19 market turmoil. On the two Eurex outage days, lastly, we observe a spike in mispricing only for German bonds.

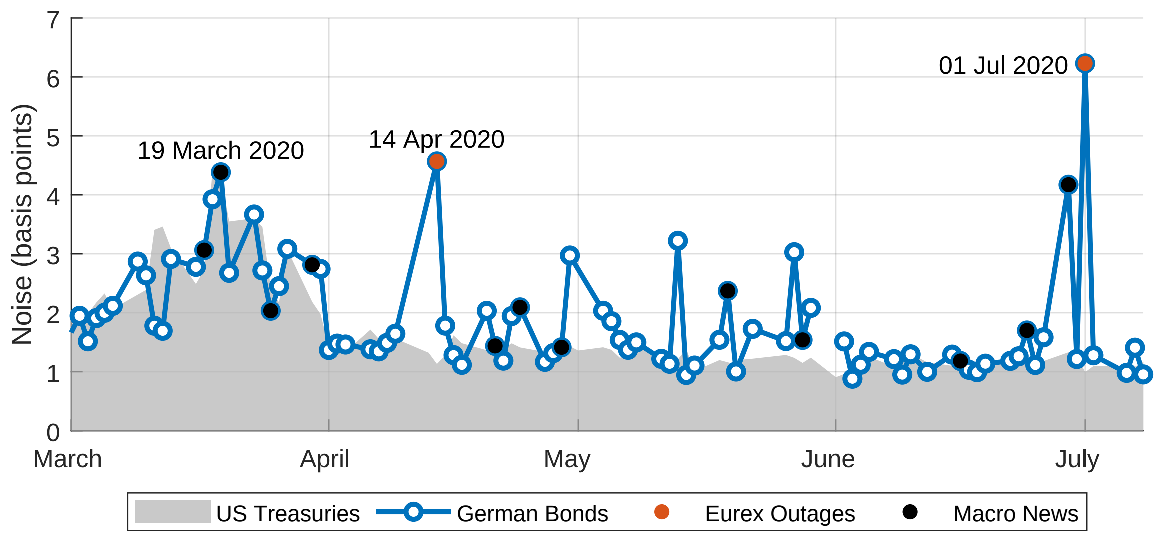

Figure 6: Yield Curve Noise during 2020. The grey area is the US Treasury noise measure published by Hu et al. (2013). It refers to the root mean squared pricing error, based on the cross-section of end-of-day bond prices from the CRSP database and using the Svensson (1994) method to fit yield curves. The blue line applies the same methodology to German government bonds, as in Figure 5. Before (after) 1 June 2020, the measure is based on all transactions between 9:25 a.m. and 2:00 p.m. (8:49 a.m. and 11:39 a.m.) each day, which corresponds to the intraday times of the first (second) Eurex outage. Red dots mark the Eurex outage windows. Black dots mark windows with major macroeconomic data releases (ifo survey, ZEW survey, German CPI, or US mortgage applications). 19 March 2020 indicates the peak of the Covid-19 market turmoil. The ECB announced its €750 billion Pandemic Emergency Purchase Programme shortly before midnight on 18 March.

One remaining possibility is that the pricing errors in German bonds were higher throughout the two outage days, for reasons other than the Eurex outages. Figure 7 zooms in on the two outage days to rule out this possibility. We again fit yield curves and compute root mean squared pricing errors, but this time for hourly windows from one hour before till four hours after the outages. These hourly windows allow a sharp identification, while simultaneously ensuring that we have sufficiently many observations along the yield curve for the Svensson (1994) methodology to work. The figure shows that the huge spike in pricing errors is indeed restricted to the Eurex outage periods. The noise measure jumps up immediately during the first hour of the outage and then quickly recedes, reverting back to normal once Eurex is back online.

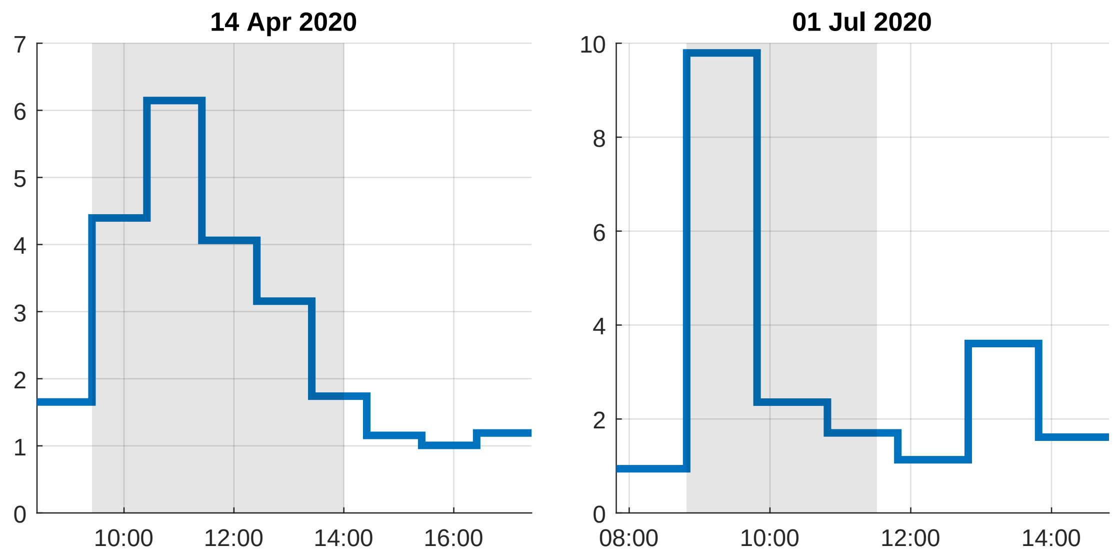

Figure 7: German Yield Curve Noise on Eurex Outage Days. This figure shows the noise measure proposed by Hu et al. (2013) on the two Eurex outage days, from one hour before the outage till four hours after the outage. For each one hour window, we fit a Svensson (1994) curve to the observed market yields and compute the root mean squared pricing errors. Grey areas mark the outage periods on Eurex.

At the macro-level, our results suggest that an efficient pricing of the euro area yield curve depends on an active futures market. Thanks to our granular transaction-level dataset, we now go one step further and study the price formation process at the micro-level.

4 Micro-Level Mechanisms of Futures Market Outages

This section traces the macro-level effects of outages back to the micro-level. We highlight the roles different investor types play on different trading venues in the price formation of the risk-free yield curve. As in the previous Section 3.3, we focus on German bonds here, since they constitute the benchmark curve for the euro area and since our non-anonymous transaction dataset has the best coverage for German bonds.

4.1 Trading Volumes across Venues and Investor Segments

First, we look at the effect of Eurex outages on trading volumes. Table 3 model (1) shows that trading volumes in German bonds drop most on the OTC market, particularly for bilateral OTC trades, slightly less on electronic platforms, and least on exchanges. In fact, while the trading decline on MTS's central limit order book is still significant, trading on regular stock exchanges does not drop at all. This last result is readily explained by retail investors trading as usual, probably unaware of the outage on Eurex. But recall that these bond transactions on regular exchanges account for a negligible overall market share, see Appendix A.5.

The venue-level results are closely aligned with Menkveld, Yueshen, and Zhu (2017)'s 'pecking order hypothesis'. According to this hypothesis, investors rank low-cost-low-immediacy venues (like the OTC segment) first and high-cost-high-immediacy venues (like exchanges) last. But when investors' trading needs become more urgent, they reverse this ranking. This is exactly what we find for cash bond trades during Eurex outages. However, in Menkveld et al. (2017)'s framework, a pure 'urgency shock' would *increase* aggregate trading volumes, implying that urgency alone cannot explain our venue-level results. Instead, the decline in total trading volume we find indicates a compositional effect: investors with a higher urgency to trade remain comparatively more active during Eurex outages.

	Trading Volume		Transaction Size	
	(1) Venue	(2) Segment	(3) Venue	(4) Segment
Outage × OTC bilateral	-5.13*** [1.06]		0.32 [0.44]	
Outage × OTC via IDB	-3.26*** [0.66]		-0.82*** [0.11]	
Outage × OTC via SI	-3.98*** [0.42]		-0.62** [0.16]	
Outage × electronic platforms	-2.95*** [0.35]		-0.76** [0.25]	
Outage × MTS	-2.55*** [0.39]		0.65 [0.95]	
Outage × regular exchange	-0.18 [0.63]		-0.28 [0.24]	
Outage × C2C		-2.04 [1.12]		-0.53** [0.18]
Outage × D2C		-2.69*** [0.32]		-0.81** [0.21]
Outage × D2D		-4.93*** [0.84]		0.18 [0.18]
FE Day	✓	✓	✓	✓
FE Time	✓	✓	✓	✓
FE Maturity Bucket	✓	✓		
FE ISIN			✓	✓
Observations	2160	1080	10629	11202
Adjusted R^2	0.445	0.377	0.319	0.278

Table 3: Effect of Eurex Outages on Cash Trading Volumes across Venues and Investor Segments. Models (1) and (2) refer to a balanced panel, where the dependent variable is the log of the transaction volume of German bonds in a given maturity bucket, executed on a given venue or by a given investor segment, measured in 30-minute intervals, analogous to Equation 1. We differentiate between client-to-client, dealer-to-client and dealer-to-dealer trades. Models (3) and (4) refer to the transaction-level, where the dependent variable is the log transaction volume.

To find out who these impatient investors are, we compare trading volumes across different investor segments. Table 3 model (2) shows that dealers reduce their trading activity the most. In particular, trading volumes drop most in the dealer-to-dealer segment, followed by the dealer-to-client segment, and least in the client-to-client segment. This suggests that dealers are comparatively more patient than clients.

Table 3 models (3) and (4) study the effect of Eurex outages on the size of the remaining transactions, i.e. the intensive margin. We observe some large discrepancies. While trading *volumes* drop most on the bilateral OTC market, for instance, the *size* of the remaining trades does not drop at all. The same is true for trades on the MTS interdealer platform, and in fact for dealer-to-dealer trades as a whole. This means that when trading among themselves, dealers rather forego trades entirely than decreasing the size of trades.

For dealer-to-client trades, in contrast, not only the aggregate volume falls but also the size of the remaining transactions, namely by exp(-.81)-1 $\approx$ 56%. For client-to-client trades, lastly, trade sizes decrease by roughly 41%. This aligns with the idea that clients have a comparatively higher urgency to trade and rather reduce the size of individual trades than not trading at all.

4.2 Mispricing across Bonds and Trades

Table 4 model (1) confirms what Figure 5 has shown visually: outages on Eurex cause a large and statistically significant increase in the mispricing of cash bond transactions.

By sequentially adding a variety of fixed effects, we check how much of the mispricing increase is driven by compositional effects. Table 4 model (2) shows that the mispricing spike is not due to different bonds being traded. Trading does not move to systematically less liquid and hence more mispriced bonds for instance. Model (3) shows that the outage dummy coefficient drops by about 15% when adding venue-level fixed effects, implying that more trades occur on venues with systematically higher mispricing during outages. When we control for investor-level fixed effects, the outage coefficient decreases by another 30%, see model (4). This means a sizable share of the observed spike in pricing errors is driven by different investors being active during the outage. Even controlling for all these compositional effects, however, the spike in mispricing remains economically large and highly significant.

	(1)	(2)	(3)	(4)
Outage	1.27***	1.25***	1.07***	0.73***
	[0.11]	[0.12]	[0.14]	[0.18]
Constant	0.98***	0.98***	0.99***	0.99***
	[0.07]	[0.08]	[0.08]	[0.07]
FE Minute	✓	✓	✓	✓
FE ISIN		✓	✓	✓
FE Venue			✓	✓
FE Buyer/seller ID				✓
Observations	3335	3335	3038	2387
Adjusted R^2	0.073	0.115	0.127	0.376

Table 4: Effect of Eurex Outages on Mispricing. Each column shows results of a different regression. Throughout, the dependent variable is the absolute pricing error in basis points, i.e. the difference between the observed and fitted yield based on Svensson (1994). The sample spans all trades shown in Figure 5, i.e. all trades in one to ten year German bonds during the Eurex outages and during the same intraday window in the previous and subsequent week. We sequentially add fixed effects: (1) for the time-of-day, using 15-minute buckets, (2) for the bond ISIN, (3) for the venue type the transaction is executed on, (4) for the buyer and seller ID.

To dig deeper, we now check for differential effects by adding interaction terms between the outage dummy and bond and trade characteristics. Table 5 reports the results. Model (1) looks at absolute pricing errors, as before. We see that pricing errors during Eurex outages differ dramatically depending on the transaction volume, but also depending on some bond characteristics. Small trades in short-term bonds become particularly mispriced. Conversely, large trades in long-term bonds exhibit a smaller increase in mispricing, as do trades in CTD bonds.

These mispricing results align with our earlier findings on trading volumes and transaction sizes. The fact that small trades become most mispriced supports the idea that clients, especially those with a high urgency to trade, rather trade in smaller size and at dislocated prices than not trade at all. Dealers, in contrast, help contain mispricing in the few larger, long-term bond trades that they do execute. The next section provides further evidence on this point.

Model (2) looks at net pricing errors, to check if particular bonds trade at a discount or a premium during outages. We find little evidence in that regard. The only notable exceptions are on-the-run and zero coupon bonds, which trade at excessively low yields (i.e high prices). We come back to this evidence in Section 4.7.

	(1) absolute PE	(2) net PE
Outage	2.75*** [0.41]	1.81 [1.15]
Outage × log(Volume)	-0.51*** [0.05]	0.11 [0.22]
Outage × CTD	-0.87** [0.25]	-0.60 [0.37]
Outage × OTR	-0.18 [0.34]	-0.96* [0.46]
Outage × Zero Coupon	-0.63 [0.50]	-0.96** [0.24]
Outage × Years since Issuance	-0.13** [0.04]	-0.14 [0.07]
Outage × Years to Maturity	-0.20*** [0.04]	-0.10 [0.14]
FE Minute	✓	✓
FE Venue	✓	✓
FE Buyer/seller ID	✓	✓
Observations	2387	2387
Adjusted R^2	0.410	0.354

Table 5: Explaining Pricing Errors with Bond and Trade Characteristics. Each column shows results of a different regression. The dependent variable is the absolute or net pricing error in basis points, i.e. the difference between the observed and fitted yield based on Svensson (1994). The sample spans all trades shown in Figure 5, i.e. all trades in one to ten year German bonds during the Eurex outages and during the same intraday window in the previous and subsequent week. The 'CTD' dummy equals one for bonds that are the cheapest-to-deliver in any bond future contract traded on Eurex. The 'OTR' dummy equals one for 'on-the-run' bonds, i.e. the most recently issued bond with approximately two, five or ten year original maturity. The 'zero coupon' dummy equals one for bonds that pay zero coupon. All regressions include time-of-day fixed effects at the 15-minute frequency.

4.3 Mispricing across Trading Venues and Investor Segments

Let us now study *where* and *which* investors misprice bonds during futures market outages. Table 6 column (1) shows that pricing errors spike on the bilateral OTC market, on electronic trading platforms, and on regular stock exchanges. OTC trades via interdealer brokers or systematic internalisers, in contrast, do not become more mispriced during the Eurex outages. The investor-segment-level results, shown in column (2), reveal that client-to-client trades become most mispriced during the outages, followed by dealer-to-client trades. The mispricing of dealer-to-dealer trades, in contrast, does not increase at all.

In column (3), we separate investors into those that are usually active on Eurex and those that

	(1) Venue	(2) Segment	(3) Eurex
Outage × OTC bilateral	1.97*** [0.40]		
Outage × OTC via IDB	0.14 [0.28]		
Outage × OTC via SI	0.17 [0.25]		
Outage × electronic platforms	0.91*** [0.17]		
Outage × regular exchange	4.46*** [0.97]		
Outage × C2C		3.34*** [0.20]	
Outage × D2C		0.72*** [0.13]	
Outage × D2D		0.35 [0.36]	
Outage × none active			2.88*** [0.32]
Outage × one active			1.33*** [0.17]
Outage × both active			0.49* [0.20]
FE Minute	✓	✓	✓
FE ISIN	✓	✓	✓
Observations	3038	3214	3070
Adjusted R^2	0.166	0.164	0.147

Table 6: Effect of Eurex Outages on Pricing Errors across Venues, Investor Segments, and depending on Investor's Eurex Activity. The dependent variable is the absolute transaction-level pricing error, see Table 5 for details. For brevity, the table shows results only for the outage dummy interaction terms. In column (1), the differential effect for MTS cannot be estimated, since there was not a single trade in 1-10y German bonds on MTS during the outages. In column (2), we differentiate between client-to-client, dealer-to-client and dealer-to-dealer trades. In column (3), we differentiate between trades in which both, only one, or none of the counterparties is usually active on Eurex, see Appendix A.6 for details. In Appendix D.2 we replicate this regression adding an interaction term between the outage dummy and transaction volume.

are not. Pricing errors spike most for trades in which none of the two counterparties is usually active on Eurex, slightly less if only one counterparty is, and least but still significantly if both use Eurex. This is evidence against the idea that the mispriced trades are solely attributable to 'mechanical' effects triggered by the outage, e.g. related to basis arbitrage trades or algorithms malfunctioning due to a lack of bond futures prices. Instead, these results reflect the fact that almost all dealers are active on Eurex while few clients are (see Appendix A.6).

To sum up, dealers largely withdraw from the cash market during Eurex outages but their remaining trades remain fairly priced, at least when trading with other dealers. This suggests that dealers are relatively well-informed and do not rely on the futures market to price Bunds on the cash market (in line with Hortaçsu and Kastl, 2012; Paiardini, 2015). The dealer-client dichotomy also explains why (i) trading volumes and market liquidity drop *more* but mispricing increases *less* at the long end of the yield curve, where dealers are comparatively more active, and why (ii) large trades become relatively less mispriced (in line with Pintér, Wang, and Zou, 2024), namely because these trades are disproportionately executed between dealers.

Diametrically opposed to these D2D trades, Eurex outages cause trading volumes to drop least and mispricing to spike most on the C2C segment. This suggests that clients are relatively less patient, less informed, and rely more on the futures market to price Bunds on the cash market. Dealer-to-client (D2C) trades fall between these extremes. The decline in trading volumes and the spike in mispricing are both significant but smaller in magnitude.

The next section takes a deeper look into the different investor types driving these effects.

4.4 Mispricing across Investor Types

So far, we have linked the mispricing to the different investor *segments*, namely the dealer-to-dealer, dealer-to-client, and client-to-client segment, which is a rather coarse distinction. Let us now differentiate the underlying investor *types*, i.e. banks, non-bank financial institutions (NBFI), investment funds, hedge funds, insurance companies and pensions funds (ICPF), non-financial corporations (NFC), the official sector (including central banks) and households (retail investors).

Table 7 column (1) shows that the spike in pricing errors during Eurex outages is driven by a broad range of investor types. The increase is most pronounced for households and hedge funds, but remains substantial and statistically significant for banks, particularly non-dealer banks, NBFIs, and investment funds. The three remaining investor types (ICPFs, NFCs and the official sector) executed very few transactions during the outages (see Appendix A.6), which may explain why the increase in mispricing is not statistically significant for these groups.

Given that so many different investor types contribute to the aggregate mispricing, a natural question is whether any specific investor type fared better than others during outages. Hence, we now examine the winners and losers behind the mispriced trades. To do so, we first look at markups. We follow Allen and Wittwer (2023a) and convert the yield of each transaction i into

$$\text{markup}_i = \begin{cases} y_i - \hat{y}_i & \text{for buys,} \\ \hat{y}_i - y_i & \text{for sells.} \end{cases} \tag{3}$$

Where y_i are actual transaction yields and $\hat{y}_i$ are fair-value yields from the fitted yield curve (see Figure 5). Positive markups mean the transaction is favorable for the investor.

Table 7 column (2) shows how the outage on Eurex affects markups across investor types. The largest effect is on trades by households, whose markups decrease by 4 basis points while Eurex is down, i.e. they buy Bunds at excessively low yields (high prices) and sell at excessively high yields (low prices). Markups also decrease significantly for investment funds and ICPFs. Hegde funds, in contrast, exhibit the biggest increase in markups.

The markup measure, however, does not measure profitability. It not only ignores the volume of each trade, but also the maturity of the traded bond, i.e. the duration over which the markup affects returns. Hence, we also calculate

$$\text{profit}_i = \text{markup}_i \times \text{volume}_i \times \text{maturity}_i \tag{4}$$

and use $sign(\text{profit}) \times log\left(abs(\text{profit})\right)$ as the dependent variable in our regressions. Table 7 column (3) shows that dealer banks' trades become significantly more profitable when the futures market is down, despite the non-significant increase in markups. This is because their markups are concentrated in long-term bonds and in larger ticket sizes. The opposite is true for households, which mitigates the negative effect of markups on their profits.[17] Similarly, the significant spike in markups for hedge funds and the drop in markups for investment funds turns insignificant once we take into account the traded volume and maturity.

	(1) mispricing	(2) markup	(3) profit
Outage × Bank Dealer	0.61*** [0.12]	0.26 [0.13]	2.33** [0.63]
Outage × Bank Non-Dealer	1.90*** [0.14]	0.65 [0.50]	-1.37* [0.66]
Outage × NBFI	1.24** [0.38]	0.48** [0.13]	0.95 [0.54]
Outage × Investment Fund	0.44** [0.14]	-0.67*** [0.09]	-2.93 [1.46]
Outage × Hedge Fund	2.62*** [0.31]	2.74*** [0.45]	1.56 [1.81]
Outage × ICPF	0.27 [0.41]	-0.51** [0.15]	-6.19 [3.22]
Outage × NFC	1.78 [1.64]	-1.28 [2.18]	-1.17 [2.56]
Outage × Official	0.20 [0.13]	-0.31 [0.27]	-3.11 [1.92]
Outage × Household	4.29*** [0.69]	-4.04*** [0.34]	-2.46* [1.16]
FE Minute	✓	✓	✓
FE ISIN	✓	✓	✓
Observations	6083	4701	4701
Adjusted R^2	0.165	0.054	-0.008

Table 7: Effect of Eurex Outages on Absolute Pricing Errors, Markups, and Profits across Investor Types. The dependent variable is the transaction-level pricing error, in basis points of yield, in absolute value (column 1), in net terms (column 2, see Equation 3), and volume- and duration-weighted (column 3, Equation 4). In columns (2)-(3), we drop trades between investors of the same type and the variables are calculated from the perspective of the investor type listed in the first column. Positive coefficients hence imply a favorable increase in markups or profits for that investor type. For brevity, the table shows results only for the outage dummy interaction terms.

In summary, some of the observed mispricing on the cash market is driven by dealers extracting higher markups from clients when the futures market is down, especially for large trades in long-term bonds. These findings align with the idea that dealers are better informed than clients, as they depend less on bond futures for pricing. However, the next section presents evidence for a complementary mechanism: while dealers partly raise markups opportunistically due to their informational advantage, they also do so reactively as Eurex outages reduce their intermediation capacity, raising the cost of their balance sheet space.

4.5 Outages as Shocks to Hedging Instruments

That dealers use bond futures as hedging instruments, in particular to hedge their temporary inventory risk that arises from intermediating trades on the cash market, has been shown by Naik and Yadav (2003) for UK Gilts and Fleming, Nguyen, and Rosenberg (2024) for US Treasuries. We begin this section by demonstrating that the same is true for German Bunds.

[17] In Appendix D.2, we confirm that these transaction-level results also hold in a balanced panel analysis, i.e. they are not driven by compositional effects. In particular, we aggregate the profit measure to a 30-minute frequency at the sector-level, imputing zeros for periods with no trades. Dealer banks' trading profits rise significantly, at the cost of investment funds, ICPFs and households. Appendix D.2 also splits up results into buys and sells. ICPFs and households incur most of their losses when selling bonds during the outage.

In particular, we run the following regression:

$$\Delta Duration_{it}^{f} = \alpha - \beta \times \Delta Duration_{it}^{c} \times Dealer_i + \epsilon_{it} \tag{5}$$

where $\Delta Duration^f$ is the duration-weighted net trading volume (buy minus sell) of investor i on day t in German government bond futures, based on EMIR data (Section 2.2). For each of the four futures, we multiply the number of traded contracts with the contract value and the modified duration and conversion factor of the underlying cheapest-to-deliver bond on day t. $\Delta Duration^c$ analogously is the duration-weighted net trading volume in German bonds on the cash market. $Dealer_i$ is a dummy variable equal to one if investor i is a dealer.

Table 8 model (1) shows a strong and highly significant negative relationship between the cash and bond future trading volumes for dealers. On average, dealers offset 8% of the duration risk arising from their cash market trades by taking opposite positions on the futures market on the same day. For clients, in contrast, we find a precisely estimated null effect, confirming that they do not use bond futures for hedging purposes. For many clients, this is obvious, because they are not active on the futures market at all (see Table A11 in Appendix A.6). But our results confirm that it is also true for the subset of clients that is active on both the cash and futures market.

In model (2), we drop some days where we expect the trading behavior on the cash and futures market to be dominated by exogenous factors, namely auction days, the last three business days at quarter ends, and days close to the expiration of bond futures (start of each quarter). As expected, the estimated coefficient for dealers increases, suggesting that they offset 16% of their daily cash exposures via bond futures, whereas the coefficient for clients remains unchanged. Model (3) confirms that these results hold when restricting the sample to days and investors with non-zero inventory changes in both markets.

	(1) all days	(2) excl. auctions, EoQ, fut.exp.	(3) excl. zeros
Client	0.10 [0.34]	0.04 [0.30]	0.09 [0.32]
Dealer	7.65*** [2.76]	16.10*** [3.34]	16.48*** [3.44]
FE Day	✓	✓	✓
FE LEI	✓	✓	✓
Observations	45296	36448	16014
Adjusted R^2	-0.001	0.009	-0.015

Table 8: Duration-weighted Net Trading Volumes in German Bunds on the Cash and Futures Market. This table shows regression results of Equation 5, predicting daily changes in the duration exposure on the futures market with those on the cash market, at the investor-level, distinguishing clients from dealers. In model (2), we drop roughly 50 trading days related to primary auctions, quarter ends, and days around the expiration of bond futures. In model (3), we further drop all observations with zero inventory change at the day-LEI level on either the futures or cash market. Coefficients are multiplied by 100 such that they refer to percentage effects.

The average hedging coefficient β of roughly 16% for the dealer sector masks substantial variation *across* dealers. To see this, we re-estimate Equation 5 only for the dealer sector and allow the β coefficient to vary across individual dealers. Table 9 shows the results. The β coefficients range from 0% to 99.2%, meaning that some dealers do not hedge their cash market trades at all while others hedge their entire exposure. To the best of our knowledge, we are the first to document the vast differences in hedging strategies across bond market dealers.[18] Given this large heterogeneity, we group dealers into three groups: a 'no hedging' group if the dealer hedges less than 5% of the daily cash market exposure via futures, an 'intense hedging' group if they hedge more than 25%, and a 'moderate hedging' group with the remaining dealers.

	min	p50	mean	max
no hedging (<5%)	0.0	0.1	0.9	3.4
moderate hedging	5.2	11.7	13.0	24.3
intense hedging (>25%)	29.5	40.6	51.2	99.2
All Dealers	0.0	11.7	17.2	99.2

Table 9: Dealer-Heterogeneity in Bond Futures Use for Hedging. This table refers to the cross-section of β coefficients when estimating Equation 5 at the dealer-level. The estimation sample is identical to Table 8 model (3), excluding clients. β measures the percent of daily cash duration exposure changes offset via bond futures. For the two dealers that are not active on the futures market at all (see Appendix A.6), we set $\beta = 0$. The final classification includes five dealers in the 'no hedging', five in the 'intense hedging', and 21 dealers in the 'moderate hedging' group.

Table 10 shows how differently these groups of dealers behave on the D2C segment during Eurex outages. The 'no hedging' group shows no obvious reaction. These dealers keep trading with their clients as usual, both in terms of volumes and prices. That means they neither increase their activity to compensate for the withdrawal of other dealers nor do they exploit the situation by increasing markups. Trading volumes drop significantly for the 'moderate hedging' group and even more for the 'intense hedging' group, reflecting their progressively greater reliance on the futures market. Regarding prices, we see that both groups cause mispricing but markups and profits only rise significantly for the 'moderate hedging' group.

One interpretation of these results is that for dealers in the 'intense hedging' group, intermediation capacity constraints become binding when Eurex goes down, forcing them to forego even highly profitable trades. Dealers in the 'moderate hedging' group, in contrast, retain some intermediation capacity, allowing them to trade when it is profitable.[19]

Overall, these results provide quasi-experimental evidence that dealers are important for market functionality (see e.g. Duffie et al., 2023). Outages on the futures market reduce dealers' capacity to intermediate bond trades on the cash market, as they are unable to hedge additional inventory risk. Consequently, clients either trade at unfavorable prices with dealers, or they have to trade directly with other clients, causing large mispricing.

[18] We thank Davide Tomio for suggesting this analysis. We adopt the approach from Hu, Kirilova, Muravyev, and Ryu (2024), who find similarly big differences in hedging strategies across market makers on the Korean stock options market. In Appendix D.2, we show that the hedging intensity is barely related to other dealer characteristics like connectedness, centrality and size.

[19] In Appendix D.2.3, we confirm that these results hold when adding dealer inventory as an additional explanatory variable. We also run the same type of regression for D2D trades and find that dealers in the 'intense hedging' group reduce their trading volumes and increase their markups the most.

	(1) volume	(2) mispricing	(3) markup	(4) profit
Outage × Dealer not hedging	0.55 [1.02]	0.32 [0.30]	-0.29 [0.61]	-0.50 [4.28]
Outage × Dealer moderately hedging	-2.34** [0.59]	0.81*** [0.13]	0.31** [0.11]	3.30* [1.40]
Outage × Dealer intensely hedging	-5.35** [1.71]	0.32* [0.14]	0.16 [0.35]	1.19 [2.42]
FE Minute	✓	✓	✓	✓
FE ISIN		✓	✓	✓
FE Client Sector		✓	✓	✓
Observations	162	1877	1877	1877
Adjusted R^2	0.364	0.069	0.030	0.032

Table 10: Effect of Eurex Outages on D2C Trades across Dealer Groups. The sample includes all D2C transactions during the two outage and four non-outage control windows. In model (1), we construct a balanced paned of trading volumes (in logs plus 1) at the 30-minute frequency, to avoid compositional effects. Models (2)-(4) are at the transaction-level. The dependent variables are calculated from the dealer perspective. Positive coefficients in (3) and (4) hence imply a favorable increase in markups or profits for a dealer group. For brevity, the table shows results only for the outage dummy interaction terms.

4.6 Outages as Shocks to the Network

The Bund cash market has the typical dealer-client and core-periphery network structure known from other OTC-traded assets (see e.g. Di Maggio et al., 2017; Li and Schürhoff, 2019; Bessembinder et al., 2020; Hendershott, Li, Livdan, and Schürhoff, 2020; Allen and Wittwer, 2023a). Is this network structure important to understand the dysfunction on the cash market we observe during Eurex outages? Or is the dysfunction mainly driven by the impaired intermediation capacity of dealers documented in the previous section? We use three well-established network measures to find out.

First, Kondor and Pintér (2022) measure clients' connections – the number of different dealers a client trades with – as a proxy for informational advantages. We expect better connected clients to fare better during outages. Second, Di Maggio et al. (2017) document in an aptly titled paper the value of trading relations in turbulent times. We follow their approach and measure the intensity of each client-dealer pair as the fraction of sales by client j to dealer k, normalized by j's total selling volume in 2020, and we compute the analogous measure for buys. We expect stronger relationships with a dealer to be beneficial for the client, i.e. associated with less mispricing and less trading losses. Third, Li and Schürhoff (2019) demonstrate the importance of a dealer's centrality, which we capture as the volume-weighted eigenvector centrality, again using the universe of Bund trades in 2020. They show that central dealers act as liquidity providers of last resort and charge larger markups for the immediacy they provide. Hence, we expect central dealers to increase markups more than peripheral dealers during outages.

In Table 11, we use all three measures to explain the dysfunction on the dealer-to-client segment, alongside a dummy variable that captures the hedging intensity of dealers (which we know is important from the previous section). As expected, better connected – and hence presumably more sophisticated – clients fare better during outages. They cause less mispricing, they pay less markup, and they incur less trading losses. Equally important is the dealer-client

	(1) mispricing	(2) markup	(3) profit
Outage	-0.70** [0.24]	-2.11*** [0.32]	-6.40 [8.90]
Outage × # Connections	-0.02* [0.01]	0.04*** [0.01]	0.32*** [0.06]
Outage × Relationship w/ Dealer	-1.38* [0.58]	0.50 [0.70]	4.82** [1.72]
Outage × ln(Dealer Centrality)	-0.25*** [0.04]	-0.22 [0.14]	0.14 [0.75]
Outage × Dealer moderately hedging	0.85*** [0.15]	0.14 [0.13]	-3.44 [4.33]
Outage × Dealer intensely hedging	0.88** [0.24]	0.36 [0.31]	-1.61 [5.03]
FE Minute	✓	✓	✓
FE ISIN	✓	✓	✓
FE Sector	✓	✓	✓
Observations	1662	1662	1662
Adjusted R^2	0.124	0.040	0.034

Table 11: Role of Dealer-Client Network Characteristics during Outages. The dependent variables are calculated from the client perspective. # Connections refers to the number of different dealers a client has traded with. Dealer Relationship measures the fraction of buying/selling volume of each client-dealer pair as a share of the total volume of each client. Dealer Centrality is the volume-weighted eigenvector centrality of the dealer involved in the transaction. The last two regressors are dummy variables equal to one if the dealer hedges between 5-25% or more than 25% of its cash market duration risk via bond futures (see Table 9). The sample includes all D2C transactions during the two outage and four non-outage control windows. We drop trades by households, since the various network measures cannot be computed, and trades on exchanges, as these occur anonymously in a CLOB. This leads to a slightly smaller sample compared to Table 10.

relationship. The stronger the relationship, the less trades become mispriced, and the less dealers extract profits from their clients. This explains why pricing errors do not spike on systematic internaliser platforms, where large dealer banks act as a central counterparty for trades initiated by their clients (Table 6).

The centrality of the dealer seems less important. Trades with more central dealers are less mispriced, but the effects on markups and profits are insignificant. This could indicate that during outages, more central dealers are better informed as they rely less on the futures market as a pricing signal, but they do not act as liquidity providers of last resort during outages and are therefore not compensated as such.

Importantly, these results hold even though we control for the differential effect of Eurex outages on dealer's intermediation capacity. Just like in Table 10, we find that D2C trades become more mispriced the more the dealer involved in the transaction relies on bond futures to hedge inventory risk. The differential effects on markups and profits, in contrast, turn insignificant in Table 11.

To conclude, the dysfunction observed on the D2C segment during Eurex outages is not entirely explicable by the reduced intermediation capacity of dealers. Instead, outages also exacerbate information asymmetries and increase the importance of client-dealer relationships.[20]

[20]In Appendix Section D.2, we run the same regression using a larger set of investor characteristics. We find that clients that are usually active on Eurex fare better during outages, probably because they are more likely to be aware of the Eurex outages, and adjust their trading on the cash market accordingly. Trades that are the first between a particular dealer-client pairs are also more profitable for the client. This is driven by trades on electronic trading platforms: during outages, clients are more likely to accept advantageous quotes by new dealers.

4.7 Ruling out Alternative Explanations

4.7.1 Outages Only Impair Intermediation, Not Price Formation

We claim that outages on the futures market cause dysfunction on the cash market via two channels. First, the lack of bond futures as hedging instruments impairs the intermediation capacity of dealers. Second, bond futures serve as benchmark prices, i.e. their unavailability impairs price formation. While these two channels are hard to disentangle empirically, our evidence suggests both channels play a significant role.[21]

Duffie et al. (2017) e.g. show that the *introduction* of a benchmark has positive externalities for the wider market. Benchmarks reduce the informational advantage of dealers relative to clients, and hence reduce dealers' profit margins. The outages we study provide quasi-experimental evidence of this effect in reverse: the *removal* of a benchmark increases dealers' profit margins (see Table 7).

In our view, the fact that Bunds become most mispriced during Eurex outages on the client-to-client market, where dealers are not directly involved, also points to an impaired price formation process (see Table 6). Of course, some C2C trades may occur only because dealers previously rejected a trading request by a client, something we cannot observe in the data, but this mechanism seems unlikely to explain the bulk of the mispricing in C2C trades.

A final piece of evidence comes from the swap market, which in principle provides an alternative to the futures market for price formation to occur (see e.g. Dalla Fontana, Holz auf der Heide, Pelizzon, and Scheicher, 2019). Figure 8 shows that interest rate swaps are severely mispriced during Eurex outages, just as we observed for Bunds on the cash market (see Figure 5).[22]

Why? An unsatisfactory explanation is that just like on the cash bond market, dealers on the swap market – which are mostly the same large banks– hedge their trades with bond futures. Hence, when the futures market suffers an outage, these dealers stop intermediating on the swap market, causing the illiquidity and mispricing we observe. But this explanation raises a deeper question: why are bond futures the dominant hedging instrument in the first place? In our view, a more satisfactory answer is that bond future prices are the most informative asset price on the fixed-income market. Hence, market participants use bond futures to price and provide liquidity in other assets, including cash bonds and interest rate swaps, in line with cross-asset learning models (Cespa and Foucault, 2014).

In Appendix D.2, we further confirm that the same network measures are *not* predictive on the D2D segment, in line with the idea that information asymmetries are much lower across dealers.

[21] An ideal test of the impaired price formation hypothesis would be to check if important fundamental news is properly incorporated into bond prices while Eurex is offline. Unfortunately, there were no such news. According to the extensive intraday news database of Kerssenfischer and Schmeling (2024), the most significant news during either outage was the Swedish central bank's announcement to extend its QE program on 1 July 2020 at 9:00 a.m., see Riksbank press release. However, this decision was largely anticipated and caused only minor market reactions, even in Sweden, see Riskbank staff memo.

[22] Appendix D.3 provides further evidence of a swap market breakdown. Indicative quotes become stale the moment bond futures become unavailable, particularly for longer-dated swaps. On Bloomberg, bid-ask spreads spike during outages, if quotes are available at all. Lastly, on one particular interdealer broker platform (for which we were able to obtain the full order book of executable quotes), Eurex outages cause a complete evaporation of liquidity, which is reversed within half an hour after Eurex goes back online.

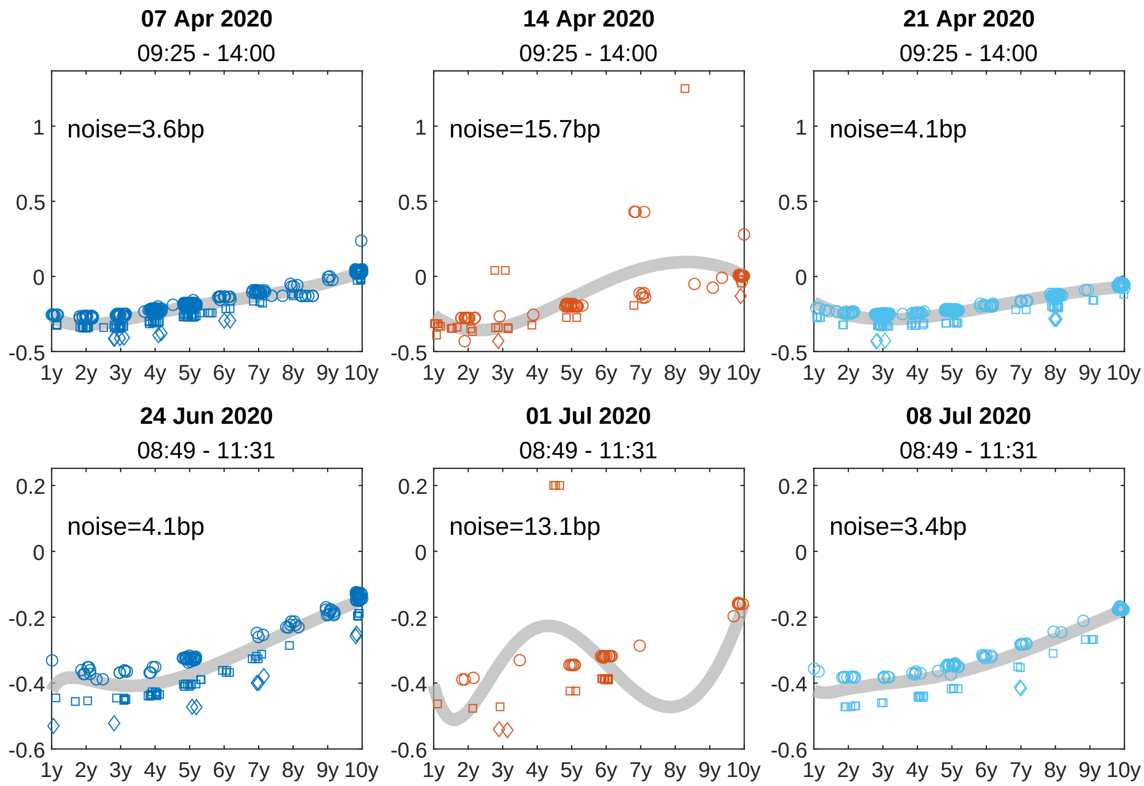

Figure 8: Euribor Swap Rates and Fitted Yield Curves. Each marker refers to an interest rate swap transaction during an outage (middle column) or the same intraday window in the previous and subsequent week (left and right column, respectively). The vertical axis refers to the fixed-leg interest rate (in percentage points), the horizontal axis to the contract horizon (in years). The floating rate is the Euro Interbank Offered Rate (Euribor) with a maturity of one, three, or six months, marked as diamonds, squares and circles, respectively. Grey lines are fitted yield curves based on Svensson (1994). The value in the top left corner of each panel is the noise measure proposed by Hu et al. (2013), defined as the root mean squared deviation of actual rates from the fitted curve. Based on EMIR data, see Section 2.2.

4.7.2 Market Panic, Flight to Safety, Dash for Cash

Is the dysfunction we observe on the cash bond market simply the result of futures market outages causing a market panic? To rule out this possibility, we first look at other asset classes. Figure 9 shows that stock prices do not crash and the USD/EUR exchange rate barely moves during the outage, at odds with a market-wide panic.

Next, we rule out the possibility that outages cause a 'flight to safety' or 'dash for cash'. In a 'flight to safety' event, Bunds of all maturities should appreciate in value, i.e. the entire yield curve should shift downwards, given that Bunds are deemed to have zero default risk (see e.g. Baele, Bekaert, Inghelbrecht, and Wei, 2020).[23] A 'dash for cash' scenario predicts the exact

[23]The only notable change in the yield curve during the outage is a drop in the 1-3 years to maturity spectrum. This is reminiscent of a 'short-term safety' shock (see e.g. Greenwood, Hanson, and Stein, 2015). The steepening of the yield curve could also be consistent with a 'risk-off' shock. Usually, such shocks are predicted to lower long-term yields more than short-term yields (see e.g. Cieslak and Povala, 2015; Cieslak and Pang, 2021). As Cieslak and Schrimpf (2019) explain, however, this prediction holds only if inflation is procyclical, i.e. inflation is low during recessions (when marginal utility is high). When inflation is countercyclical, 'risk-off' shocks lower short-term yields more than long-term yields, at least somewhat in line with our evidence.

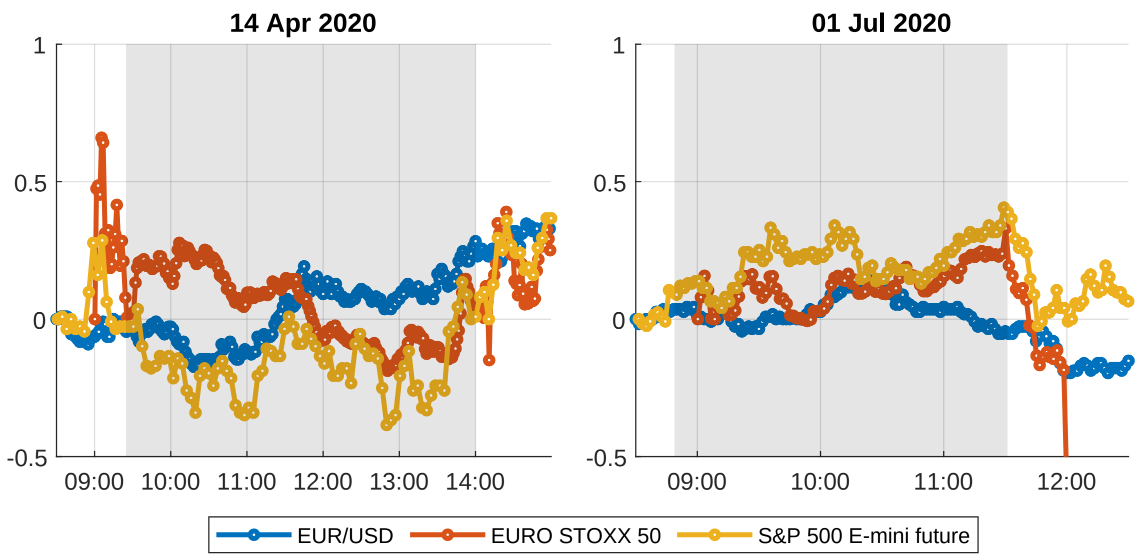

Figure 9: EUR/USD Exchange Rate and Stock Prices During Eurex Outages. All price changes are in percentage points since 08:30 a.m., the S&P 500 future refers to the front-end contract. Data is from Bloomberg. The grey area refers to the outage period on Eurex.

opposite: as investors try to sell Bunds in order to get cash, bond prices should fall and the yield curve should shift upward. Eisenbach and Phelan (2022) show in a model how this 'dash for cash' effect can outweigh the 'flight to safety' effect, rationalizing the temporary spike of Treasury yields in mid-March 2020.

While the dispersion of transaction yields *around* the curve spikes during outages, Figure 10 shows that the yield curve *itself* barely changes. This null effect is at odds with both a 'flight to safety' and 'dash for cash' explanation.[24]

4.7.3 Selling Pressure

Even if the Eurex outages caused no market-wide panic, they might have caused selling pressure for some subset of investors. Feldhütter (2012) proposes a measure of selling pressure in OTC markets based on the price differential between small and large trades. The idea is that during selling pressure episodes, willing sellers outnumber reluctant buyers, and large buyers can more easily 'shop around' among sellers, negotiating larger price discounts. Large trades should thus occur at prices below fair value while small trades occur above fair value.

Table 12 tests if this mechanism plays a role during Eurex outages. If so, we would expect a positive relationship between transaction volumes and net pricing errors, meaning large trades

[24] Our bond-level results also provide little evidence for either channel. In a 'dash for cash' scenario, investors would first sell the most liquid assets in their portfolio. Haddad, Moreira, and Muir (2021), among others, document these 'fire sales' during the Covid-19 crash in March 2020. If anything, we instead find that usually-liquid (OTR and CTD) bonds trade at a premium during outages, see column (2) in Table 5. This evidence is more in line with a less extreme 'flight to liquidity' scenario, in which investors might not reduce their aggregate bond holdings, but want to re-balance into more liquid bonds. O'Hara and Zhou (2021) e.g. study the US corporate bond market during the Covid-19 crisis and find, among other things, that trading volume shifts to liquid securities. We find, however, that trading volumes and liquidity drop more in usually-liquid bonds (see Appendix D.6).

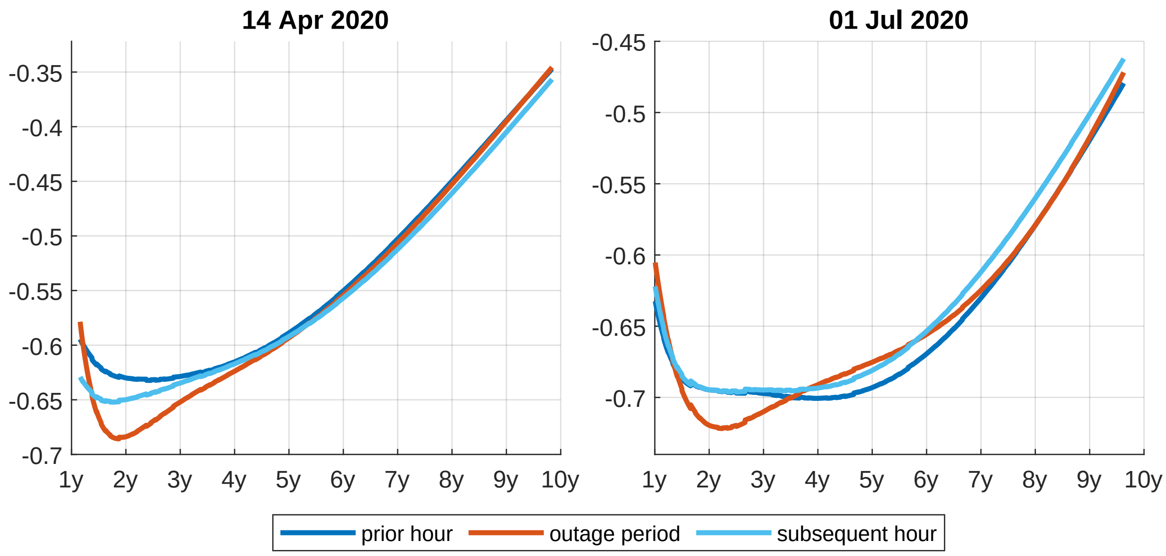

Figure 10: German Yield Curve before, during, and after Eurex Outages. This figure shows yield curves based on the Svensson (1994) method, using all transactions in German sovereign bonds with 1-10y maturity one hour before the outage, during the outage, and one hour after the outage. The fitted yield curves during the outages are identical to the ones shown in Figure 5

occur at excessively high yields (large price discounts). Analyzing all trades collectively, we find little evidence in this regard, see column (1). This changes, however, when we look at the different investor segments separately. For client-to-client and dealer-to-dealer trades, the predicted relationship between trade size and pricing errors is indeed present. The overall insignificant relationship is driven by the null effect for dealer-to-client trades, the largest segment on the cash bond market.

	(1)	(2)
Outage × log(Volume)	0.15 [0.18]	
Outage × C2C × log(Volume)		0.57* [0.26]
Outage × D2C × log(Volume)		-0.03 [0.17]
Outage × D2D × log(Volume)		0.25*** [0.06]
FE ISIN	✓	✓
FE Venue	✓	✓
FE LEI	✓	✓
Observations	2570	2570
Adjusted R^2	0.233	0.265

Table 12: Net Pricing Errors and Transaction Size. The dependent variable is the transaction-level pricing error, i.e. actual yield minus fair yield, in basis points. Positive values imply yields above fair value (prices below fair value). For brevity, the table shows results only for the outage dummy interaction terms.

In sum, selling pressure seems to be a rather minor channel via which outages on the futures market cause dysfunction on the cash market.

5 Evidence from Outages on Other Markets

The previous sections show that outages on the futures market have dramatic effects on the cash market for euro area sovereign bonds. This section demonstrates how unique these outage effects are. Section 5.1 documents a clear asymmetry: outages on cash market trading platforms reduce trading volumes, also on the futures market, but barely affect market functioning. Similarly, Section 5.2 checks for but does not find evidence for transatlantic spillovers: outages of the European futures exchange Eurex do not affect market functioning on CME, the main US futures exchange, and vice versa.

5.1 Cash Bond Market

When the centralized futures market suffers an outage, the decentralized cash market for EGBs is severely impaired. What about the other way around? An ideal experiment to answer this question would require a random incident that halts trading on the entire cash market, i.e. on all exchanges, electronic trading platforms, as well as the over-the-counter segment. Fortunately for the public at large, but unfortunately for us researchers, such a comprehensive and uniform shock has never occurred. Hence, the best we can do is to study outages on individual cash trading platforms. We found five such outages affecting four different platforms:[25] MTS, Bloomberg, the Frankfurt stock exchange (Frankfurter Wertpapier Börse), and Brokertec.

To study the effect of these cash venue outages on the aggregate cash and futures market, we run dummy regressions like below:

$$Y_{it} = \alpha + \beta \times D_t + \gamma \times FE + \epsilon_{it} \tag{6}$$

where D_t is a dummy variable equal to one during the outage. We include the outage period and the same intraday window during the preceding and subsequent week (as controls).

For the cash market, Y_{it} measures the transaction volume in € or the number of transactions (both in logs plus one), separately for German, French, Italian and Spanish government bonds, and t refers to a 5-minute frequency. For the futures market, Y_{it} also covers the trading volume (in number of contracts or the number of trades, both in logs plus one), separately for each of the eight bond futures traded on Eurex, and t refers to a minutely frequency. Since we have the entire history of transactions on Eurex, we also look at more direct measures of market functioning. In particular, Y_{it} also covers volatility (the sum of absolute log returns), an intraday Amihud (2002) measure (ratio of volatility over volume), and the Roll (1984) bid-ask spread estimate. For simplicity, these last three measures are normalized to mean zero and unit variance for each future.[26]

[25] Appendix B confirms all outages through newspaper reports, except the most recent one on MTS. We could not confirm this outage independently, but the episode we identified has the same characteristics as an earlier confirmed outage (no intraday transactions or quotes for any bond for a prolonged period during trading hours and in the absence of any major news).

[26] We focus on average effects here, see Appendix E for more granular country-level results. We do not attempt to link the differential effects across outages and countries to the different characteristics or market shares of each platform. We leave this to future research.

Table 13 contains results. The top panel shows that all cash venue outages reduce the aggregate trading activity on the cash market. This is at odds with the common claim that bond trading seamlessly moves to alternative platforms in case of individual outages, see the narrative evidence in Appendix F.1.1. So given that individual cash venue outages affect the aggregate cash market, do they also affect the futures market?

Yes, but mainly in terms of trading activity, not market functioning, as the lower panel in Table 13 shows. The trading volume on Eurex drops significantly during cash market outages, but not nearly as much as in the other direction: the pooled estimate is roughly one-tenth as large as the equivalent estimate in Table 1. More direct measures of market functioning show even less of an impact. Bond future prices do not become more volatile and the illiquidity measure of Amihud (2002) increases only during two of the five outages, as does the bid-ask spread estimate of Roll (1984). Pooling all cash venue outages together, the two measures imply that the liquidity on Eurex drops by only .05 and .09 standard deviations, respectively. These effects pale in comparison to the complete evaporation of liquidity on the cash market during Eurex outages (see Section 3.2).

Why do cash and futures market outages have so asymmetric effects? Recall that futures market outages cause dysfunction on the cash market because bond futures serve as a hedging instrument and a pricing signal (see Section 4). In contrast, Table 13 suggests that cash market outages only operate via the hedging channel. In particular, trading volumes drop on the futures market mainly because investors need to hedge less trades on the cash market. The liquidity on the futures market is barely affected, however, since cash trading venues are negligible for price discovery.

Let us now elaborate on the three most informative cash market outages below.

MTS Outage

We know from Section 3.2 that the MTS cash market platform is dependent on the futures market: trading and quotation activity stops when Eurex goes down. Is there a similar dependency of Eurex on MTS? January 12, 2010, provides a natural experiment to test this hypothesis. On this day, MTS suffered a roughly two and a half hour long outage at the beginning of the trading day: instead of 8:00 a.m., the first quotes for any bond appeared at 10:35 a.m in the order book. Table 13 suggests that this MTS outage barely affects the futures market. Similarly, the unconfirmed but suspected outage on MTS in 2019, when trading and quoting activity stopped entirely for almost an hour, reduces the trading activity on the futures market somewhat but has no significant impact on any of the market functioning proxies.

Since this latter outage occurred quite recently, Appendix E provides further evidence. Neither the country-level order book liquidity on the futures market, nor indicative bond quotes on Bloomberg show any obvious reaction to the MTS outage. That these null effects also hold for Italy is worth stressing. MTS is the dominant cash trading venue for Italian bonds but still, outages on MTS seem to have little macro-level market impact even for Italy.

Cash market	MTS 12 Jan 2010 8:00-10:35	Bloomberg 17 Apr 2015 9:20-10:10	FWB 27 May 2015 8:00-11:00	Brokertec 11 Jan 2019 19:43-21:35	MTS 26 Jul 2019 12:30-13:20	Pooled
Volume	-1.33***	-4.45***	-0.43*		-2.35*	-1.46***
	[0.11]	[0.13]	[0.10]		[0.69]	[0.44]
#Trades	-0.17***	-0.38	-0.08		-0.28***	-0.17***
	[0.00]	[0.17]	[0.08]		[0.01]	[0.05]
Futures market						
Volume	0.02	-0.25*	-0.59	-0.23***	-0.55**	-0.31*
	[0.03]	[0.06]	[0.50]	[0.01]	[0.12]	[0.17]
#Trades	0.03	-0.15**	-0.29	-0.16**	-0.43*	-0.17*
	[0.05]	[0.02]	[0.26]	[0.03]	[0.14]	[0.09]
Volatility	0.09	-0.02	-0.44	-0.04	-0.11	-0.20
	[0.10]	[0.03]	[0.41]	[0.02]	[0.09]	[0.19]
Amihud	0.02**	0.03***	0.09	-0.09	0.07	0.05*
	[0.00]	[0.00]	[0.05]	[0.15]	[0.02]	[0.03]
Roll	0.02	0.08*	0.15*	-0.13	0.05	0.09**
	[0.05]	[0.02]	[0.04]	[0.14]	[0.02]	[0.03]

Table 13: Effect of Cash Venue Outages. Each column refers to a different outage, each row to a different dependent variable. Each sample includes the outage period and the same intraday window on the preceding and subsequent week (as controls). The last column refers to a pooled regression of all outages. For the cash market, variables are at the country-level and five minute frequency and Volume refers to the transaction volume in €. For the futures market, variables are at the future-level and one minute frequency and Volume refers to the number of traded contracts. Volume and #Trades are in logs plus one, Volatility is the sum of absolute log returns, Amihud (2002) is the ratio Volatility/Volume, and Roll (1984) is a bid-ask spread estimate. The last three measures are normalized to mean zero and unit variance. Since these three measures are undefined when there are zero trades in a given period, estimates may suffer from selection bias. Replacing missing values with zeros renders all pooled estimates statistically insignificant. All regressions include fixed effects for the minute within a day and for each country or bond future.

Bloomberg Outage

On Friday, 17 April 2015, Bloomberg suffered an outage from 8:20 a.m. till at least 9:10 a.m. London time. Some newspaper reports suggest a longer duration, probably because Bloomberg terminals came back online gradually. In any case, traders worldwide were not able to access their terminals temporarily.

Table 13 shows that this cash venue outage has the biggest impact on the futures market for European government bonds. Trading activity in bond futures slows down and the illiquidity measures of Amihud (2002) and Roll (1984) increase significantly. The magnitude of these effects is small, however, corresponding to an increase of .03 and .08 standard deviations, respectively.

Appendix E provides further evidence for a limited impact of the Bloomberg outage.

Brokertec Outage

On 11 January 2019, another Friday, Brokertec, the dominant electronic trading platform for US Treasuries (see Fleming, Nguyen, and Ruela, 2024), suffered a roughly two-hour-long outage, from 1:43 till 3:35 p.m. US Eastern Time. Table 13 shows that this outage reduces trading activity in euro area bond futures, but does not affect actual market functioning.[27]

Since this outage occurred quite recently, we can again look at actual liquidity on the futures market, both in the euro area as well as the US. Figure 11 shows that the order book depth in German Bund futures seems unaffected by the outage on Brokertec. For US Treasury futures, liquidity slightly *improves* after the outage and falls back to normal once Brokertec goes back online (indicating latency arbitrage activity, see next section). The overall benign effects of the Brokertec outage suggest that one of our main findings – that price formation and liquidity provision is more of a one-way street from the futures to the cash market than previously thought – also applies to the US.

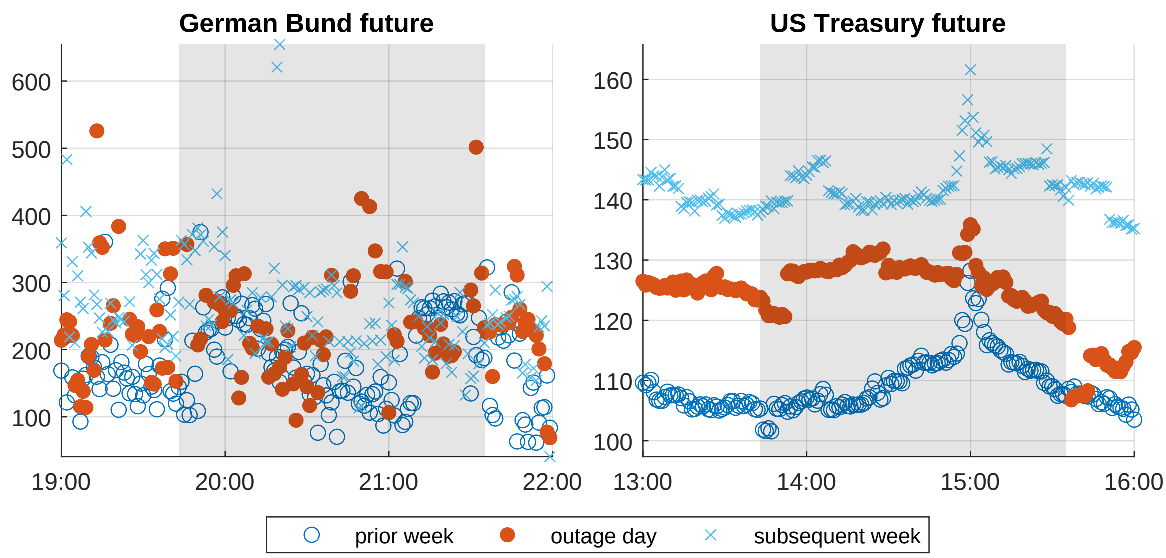

Figure 11: Order Book Depth of Bond Futures during Brokertec outage on 11 January 2019. This figure shows the number of quoted contracts in 10-year German Bund futures on Eurex (left panel; covering both sides of the first three levels of the order book; data comes from Bloomberg, since our Eurex order book data starts in April 2019) and 10-year US Treasury futures on CME (right panel; in thousands; covering both sides of the first 15 levels of the order book). The grey area refers to the outage period on the Brokertec cash trading platform. Red markers refer to the outage day, dark and light blue markers refer to the previous and subsequent week. Timestamps are in local time.

Overall, we conclude that outages on individual cash trading platforms affect the fixed-income market not nearly as much as outages on the centralized futures market. Next, we will investigate whether outages on the European and US futures market affect each other.

[27]The European *cash* market was unaffected by the Brokertec outage because it was effectively idle during this time of day (7:43-9:35 p.m. local time) and because Brokertec has a minor market share in EGBs.

5.2 US Futures Market

US and euro area bond yields are tightly linked (see e.g. Andersen et al., 2007; Faust, Rogers, Wang, and Wright, 2007). In fact, the sheer speed of the observed 'price spillovers' suggests that they are driven by algorithms that trade one asset depending on the price of the other.

What happens if one of these prices, due to an outage, becomes unavailable? Theoretically, there are two opposing effects. Liquidity in the remaining asset could *decrease*, because a useful pricing signal or hedging instrument is gone. This would be in line with Cespa and Foucault (2014)'s model, where liquidity providers use some particularly informative asset prices to provide liquidity in other assets.

Alternatively, liquidity could *increase*, if the outage leads to less latency arbitrage. This would be similar to Shkilko and Sokolov (2020), who document that heavy precipitation between Chicago and New York improves liquidity on the cash market for equities. They convincingly argue that some high-frequency trading firms pick off stale limit orders on the cash market in New York, exploiting their early access to futures price movements in Chicago as trading signals. When this early access is interrupted by heavy precipitation, the latency arbitrage trades stop and market liquidity improves. The same should apply in our setting, insofar as investors use US bond futures prices to trade German bond futures or vice versa.[28]

So do outages spill over across the Atlantic? Let us first look at the effect of Eurex outages. Figure 12 shows that the liquidity in US Treasury futures is barely affected. Using intraday order book data from the CME, we observe only a minor and short-lived drop in liquidity after the first Eurex outage. The lack of spillovers from Europe to the US might not be surprising, since a large literature has shown that asset price movements spill over much more from the US to Europe than the other way around, see e.g. Boehm and Kroner (2024). Hence, one might expect that latency arbitrage only works one way, namely from the US to Europe. We will now show, however, that outages of the US futures market also do not seem to affect the euro area futures market.

On 26 February 2019, the Chicago Mercantile Exchange (CME) suffered a roughly three-hour-long outage from 7:39 p.m. till 10:45 p.m. US Eastern Time affecting all markets, i.e. also US Treasury futures.[29] Figure 13 shows that this outage barely affects euro area bond futures. Neither the aggregate trading activity on Eurex, nor the order book liquidity of the 10-year Bund future is noticeably different during the CME outage.[30] In Appendix E, we show that this null effect is a robust finding and is not driven by the timing of the outage, which occurred very early in the morning in Europe, when trading is usually very quiet.

To sum up, outages on the US futures market do not affect the European futures market,

[28] A recent blog post by the Head of Quantitative Analytics at Eurex documents the growing use of short-wave data transmissions from the CME in Chicago to Eurex in Frankfurt. In bond futures, these latency arbitrage trades seem to occur almost exclusively around economic news events, however. See Shkilko and Sokolov (2020) and the Ars Technica article they cite for an overview of the high-frequency trading arms race, from the US futures market in Chicago to the US cash market in New York, onto London and finally Frankfurt.

[29] Appendix B confirms the outage through CME order book data and newspaper reports.

[30] Since the outage took place in late February, we compare the outage day with the previous and subsequent day, rather than week. This way we can compare the liquidity of the same futures contract (expiring in March 2019), avoiding complications due to the roll-over to the next-nearest contract that occurred in early March.

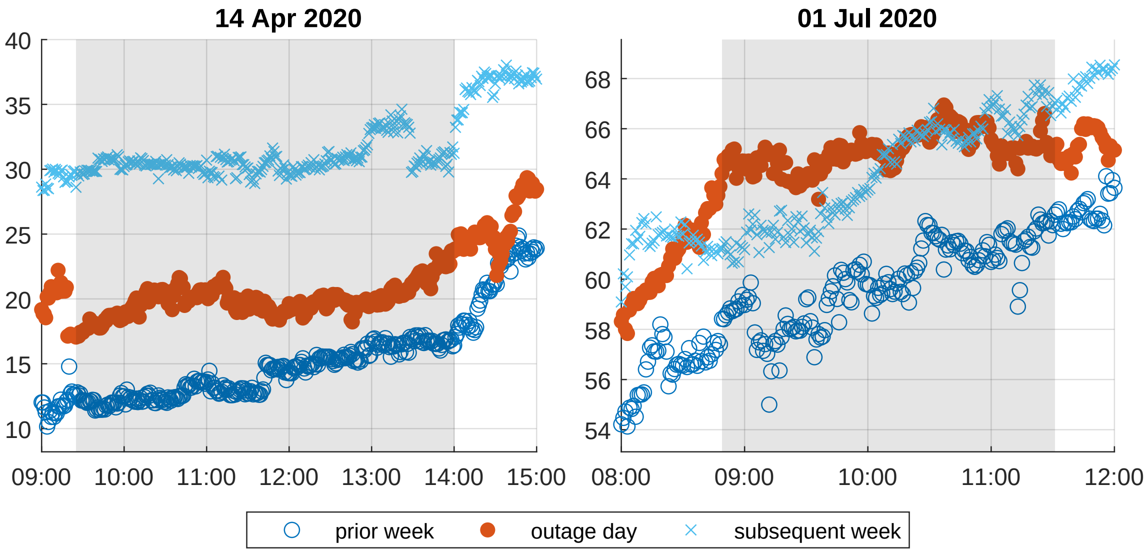

Figure 12: Order Book Depth of US Treasury Futures during Eurex outages. This figure shows the number of quoted contracts (in thousands) at the first 15 levels of both sides of the order book for 10-year Treasury futures. The grey area refers to the outage period on Eurex.

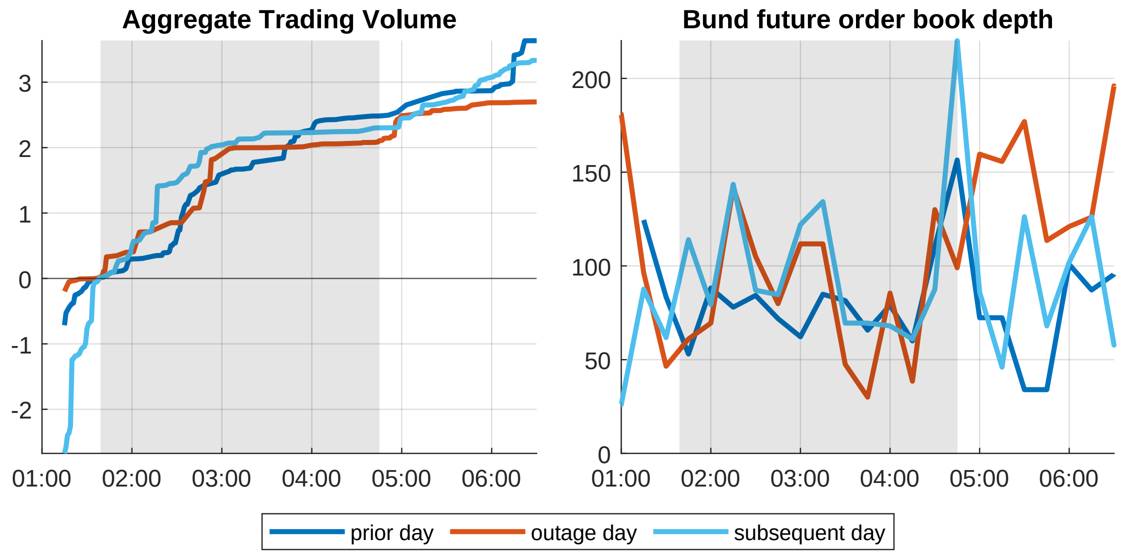

Figure 13: Eurex Activity during the CME Outage on 26 February 2019. The left panel shows the cumulative trading volume in all euro area bond futures on Eurex (in thousands of contracts, normalized to zero at the intraday time of the outage). The right panel shows the order book depth of 10-year German Bund futures (covering both sides of the first three levels of the order book; data comes from Bloomberg, since our Eurex order book data starts in April 2019). Red lines refer to the outage day, dark and light blue lines refer to the previous and subsequent day. In Central European Time, the outage occurred between 1:39 a.m. till 4:45 a.m. on 27 February 2019, marked by the grey area.

and vice versa. This lack of liquidity spillovers stands in stark contrast to the strong price spillovers documented in the literature, see Boehm and Kroner (2024) and references therein. This null result suggests that market participants provide bond liquidity purely 'domestically', not conditionally on a foreign risk-free yield curve.

6 Conclusion

The risk-free yield curve is a key building block to price assets. We show that the pricing of the yield curve itself depends vitally on bond futures. When the Eurex futures exchange suffers an outage, trading activity on the cash market for euro area government bonds declines, liquidity dries up, and the remaining transactions occur at prices far from fundamental values.

Thanks to our non-anonymous transaction-level dataset, we can pinpoint the micro-level mechanisms causing these macro-level effects. We show that dealers sharply reduce their cash market presence during Eurex outages. While interdealer trades remain fairly priced, the lack of bond futures reduces the capacity of dealers to intermediate client trades on the cash market. Hence, clients have to pay higher markups to their dealer or trade directly with other clients. These client-to-client trades become most mispriced during outages, suggesting that bond futures serve different purposes for different investors. Dealers use futures mostly to hedge inventory risk while clients use bond futures as pricing signals.

Lastly, we study outages on other markets and show that these have far less dramatic effects. Outages on individual cash trading platforms barely affect bond futures, suggesting that price formation and liquidity provision is more of a one-way street from the futures to the cash market than previously thought. We also find little evidence for transatlantic spillovers. Outages on Eurex have little impact on CME, the main US futures exchange, and vice versa. Market participants seem to provide liquidity purely ‘domestically’. This lack of liquidity spillovers stands in contrast to the strong asset price spillovers documented in the literature.

Our results have important implications for a number of ongoing policy debates, e.g. regarding the pros and cons of centralization. In December 2023, for instance, the U.S. Securities and Exchange Commission published a long-anticipated final rule that aims to increase central clearing and all-to-all trading on the Treasury market (see also Duffie, 2023). This would make the cash market, which is currently fragmented across multiple trading platforms, many of which lack central clearing, more similar to the futures market, which is fully centralized. We show that this centralization makes the futures market highly liquid and clearly dominant in terms of price discovery. The downside is that an outage of the futures market becomes a systemic risk. In contrast, the decentralized cash market is less liquid, provides little price discovery, heavily relies on dealers as financial intermediaries, but it is robust to an outage of any individual cash platform.

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Internet Appendix

for

Outages in Sovereign Bond Markets

by Mark Kerssenfischer and Caspar Helmus

(not for publication)

Appendix A provides details on our data, especially our cash transaction dataset.
Appendix B lists the outages we study and confirms them through newspaper reports.
Appendix C uses prior outages on Eurex as a robustness check of our main results.
Appendix D provides further evidence on the two most recent Eurex outages.
Appendix E contains further results regarding outages on other trading venues.
Appendix F presents narrative evidence, namely quotes from private market participants about their views on euro area bond market functioning.

Appendix A Data Details

This section contains background information on our data. Appendix A.1 provides an overview of our datasets and Appendix A.2 explains how to get access to the data. Appendix A.3 outlines the market structure on the European cash and futures market for bonds. Appendix A.4 describes the universe of cash bonds we study, Appendix A.5 provides details on our transaction-level data, and Appendix A.6 explains how we classify investors into different types and segments.

A.1 Overview Data Sources

Dataset / Source	Content	Anonymous	Sample period
Cash Market			
MiFID I ('Bafin')	transactions	no	2008-2017
MiFID II ('Mifir')	transactions	no	since 2018
MTS	transactions and order book updates	yes	since 2008
MTS BondVision, Tradeweb, BGC, TPICAP, GFI, Aurel	transactions	yes	six days in 2020 (two Eurex outage days and four control days)
Bloomberg, Refinitiv, TPICAP	indicative quotes	yes	
Futures Market			
EMIR	transactions	no	since 2008 (prior to 2018, data comes from the MiFID I dataset)
Eurex	transactions	yes	since 2002
Eurex (A7)	order book updates	yes	since April 2019 (data since January 2019 comes from Bloomberg)
CME (A7)	order book updates	yes	since February 2019

Table A1: Overview of Data Sources Used in This Paper.

Table A1 lists all datasets we use. We focus most of our analysis on the two most recent Eurex outages in 2020 for data availability and quality reasons. In particular, the MiFID I dataset captures less than half as much daily trading volume as the MiFID II dataset and covers particularly few trades by clients such as investment funds. MiFID II has better data coverage and much more granular information on trades, e.g. a flag identifying trades by retail investors. See Appendix A.5 for a detailed description. However, MiFID II data quality improved gradually over time and remains relatively poor for 2018 and 2019. Moreover, we obtained transaction-level data from various trading venues only for the six relevant days in 2020. For these reasons, we compute yield curve fitting errors and run venue- and investor-level regressions only for the outages in 2020.

A.2 Access and Availability

Access to the non-anonymous regulatory MiFID I, MiFID II and EMIR datasets can be requested via the Research Data and Service Centre (RDSC) at Bundesbank and is subject to strict requirements, see rules for visiting researchers at the RDSC.

The application process requires researchers to write a short proposal outlining the research question and its policy relevance. The data request is then evaluated by the RDSC and economists in the statistics department providing the data. Once the evaluation has been successfully completed, researchers need to sign a contract with the RDSC, before being granted secure on-site access to the data.

All other data is available directly from data vendors.

A.3 Future and Cash Market Structure

This section provides further details on the market structure for European government bonds briefly outlined in Section 2 of the main text.

Table A2 gives an overview of the available bond futures and their trading volumes in 2022. Because of their benchmark status in the euro area fixed income markets, futures on German government bonds dominate trading with roughly 80% of the total in 2022. Italian (10%), French (8%) and Spanish futures (<1%) are much less relevant. Importantly, the futures market is fully centralized on Eurex. For each future, three contracts with different expiration horizons can be traded, one for each of the three nearest months in the March, June, September and December cycle. We focus on the nearest-to-maturity contracts at any point in time. These account for over 90% of trading volume, as most investors 'roll over' to the next-nearest contract one or two days before expiration. That means for the Eurex outage (and control days) in April 2020, we use future contracts that expire in June 2020. For the July outage, we use contracts that expire in September 2020.

Table A3 gives a rough comparison of the relative size of the future and cash markets. For Germany, the trading volume on the futures market is roughly ten times as large as on the cash market. For France and Italy, the two markets are of comparable size. For Spain, where a future was introduced last, namely in October 2015, trading volumes in futures are only 1% of the cash market volume. Within the cash market, the trading volume in German and Italian bonds is similar, whereas the volume is only 75% as large for French and 30% as large for Spanish bonds.

Figure A1 visualizes EGB trading volumes, not only across but also within the futures and cash market. The figure highlights that trading volumes on the futures market are concentrated into a handful of bond futures whereas on the cash market, the trading volume is dispersed across hundreds of individual bonds, many with tiny trading volumes. For Germany, France and Italy, not even the most-traded cash bond comes close to any of the bond futures in terms of trading volume. For Spain, in contrast, the trading volume in the bond future is roughly equal to the median volume across cash bonds.

Table A4 gives a stylized overview of the different cash market venues for EGBs, differentiating between exchanges, electronic platforms, and the over-the-counter segment. We classify venues based on the employed trading protocol, which leads to some discrepancies with the MiFID II regulation. MTS, e.g., is regulated as a multilateral trading facility, whereas we classify it as an exchange, since MTS employs a central limit order book just like stock exchanges.[31]

[31] MiFID II Art. 4(1)(20)-(24) differentiates between regulated markets (exchanges in our terminology) and multilateral and organised trading facilities (MTF and OTF; mostly electronic platform in our terminology). Single-dealer platforms are called 'systematic internalisers' (SI) and are defined as 'an investment firm which, on an organised, frequent systematic and substantial basis, deals on own account when executing client orders outside a regulated market, an MTF or an OTF without operating a multilateral system'. We follow the MiFID

The market shares of different EGB trading venues are notoriously difficult to measure, due to the poor post-trade transparency and the lack of a consolidated tape. The last row in Table A4 provides a rough estimate based on public sources, which suggest that roughly half of the trading volume occurs OTC, with the remainder split 2:1 between electronic platforms and exchanges (mostly MTS).[32]

In fact, Figure A2 roughly confirms these aggregate market shares based on our transaction-level dataset, which we present in detail in Section A.5. The figure also documents substantial country-level differences. German bonds, e.g., are traded predominantly OTC or on electronic platforms and rarely on-exchange.[33] For Italian bonds, in contrast, on-exchange trading on MTS accounts for more than 40% of volume. Note, however, that the venue market shares for France, Italy and Spain should be interpreted with caution, since they rely solely on the anonymous *trade* – not *transaction* – reports mentioned in Section A.5. This is because proper identification of trade chains (affiliate trades) works best in German bonds and also the reason why we focus on German bonds in Section 3.3 and Section 4 in the main text when studying the venue- and investor-level market microstructure.

Name	Code	Country	Maturity (years)	Contracts (million)	%	Volume (billion €)	%
Bund	FGBL	DE	8.5-10.5	216	33%	32,835	37%
Bobl	FGBM	DE	4.5-5.5	158	24%	19,873	23%
Schatz	FGBS	DE	1.75-2.25	142	21%	15,543	18%
OAT	FOAT	FR	8.5-10.5	54	8%	7,745	9%
BTP	FBTP	IT	8.5-11	42	6%	5,390	6%
Short Term BTP	FBTS	IT	2-3.25	27	4%	2,977	3%
Buxl	FGBX	DE	24-35	22	3%	3,793	4%
Bono	FBON	ES	8.5-10.5	0	0%	21	0%
*Mid-Term BTP	FBTM	IT	4.5-6	0		0	
*Mid-Term OAT	FOAM	FR	4.5-5.5	0		0	
Sum				662		88,177	

Table A2: Euro Area Government Bond Futures on Eurex. Trading volumes refer to 2022 (source: Eurex). The maturity column refers to the remaining maturity a cash bond must have in order to be deliverable into the respective futures contract. *Since their trading volume is virtually zero, we exclude the FBTM and FOAM futures from our analysis.

II regulation and consider these trades a particular form of OTC trading. In practice, systematic internalisers are usually large banks and the 'SI' status comes with extra regulatory responsibilities, e.g. an obligation to report trades through an Approved Publication Arrangement (APA). A recent ESMA Consultation Paper provides a concise overview of European trading venues and the ESMA Register contains a list of regulated markets, MTFs, OTFs, SIs, and APAs. Lastly, a 2021 ICMA Directory catalogues cash trading venues including eligible participants and trading protocols.

[32] A 2021 European Commission Report about the proposed merger between the London Stock Exchange Group (owner of the MTS platform at that time) and Refinitiv (owner of the Tradeweb platform) provides a detailed overview of the European government bond market and the different trading platforms. The merger was approved only after the London Stock Exchange Group sold off its MTS platform to Euronext (see European Commission press release).

[33] de Roure et al. (2025) study dealer-to-dealer trades in German bonds (using the 'Bafin' dataset mentioned in Section 2.1) where they can identify both counterparties. In this subsample, they find that interdealer brokers account for roughly 80% of trading volume. Our data puts the IDB share at roughly 25% of the aggregate trading volume.

Country	Future Volume	Cash Volume	Sum	Ratio Future/Cash
Germany	72,044	7,404	79,448	9.7
France	7,745	5,435	13,180	1.4
Italy	8,367	7,197	15,564	1.2
Spain	21	2,002	2,023	.01
Sum	88,177	22,038	110,215	4.0

Table A3: Comparison of Euro Area Government Bond Trading Volumes on the Futures and Cash Market in 2022 in billion €. The bond future trading volumes correspond to the aggregate volume of all futures of a given country, see Table A2. The cash market trading volumes are based on the European Secondary Bond Market Data Report by the International Capital Market Association (ICMA). These numbers are roughly in line with data from the Government Bond Data Report from the Association for Financial Markets in Europe (AFME), whose numbers for Germany are based on a survey of the debt management agency among dealer banks. This survey puts the cash trading volume in German bonds in 2022 roughly 10% lower at 6,636 billion €, see Finanzagentur website.

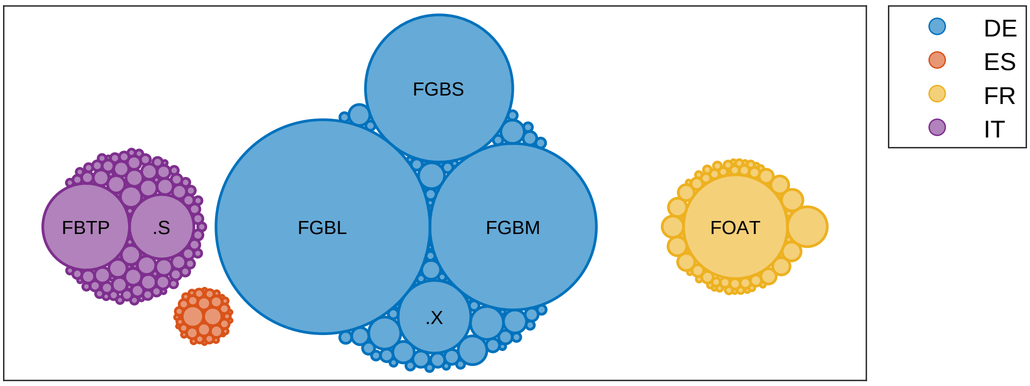


Figure A1: EGB Trading Volumes at the Instrument-Level. Each circle refers to an individual bond or bond future. Bond futures are labelled, e.g. 'FGBL' for the 10-year Bund future. The size of each circle is proportional to the trading volume in that instrument. In particular, the relative trading volume across countries and across the futures and cash market matches Table A3. Within the futures market, the relative volumes match Table A2. For the cash market, the number of bonds per country and the distribution of trading volumes across those bonds are based on our transaction dataset for a particular day (7 April 2020), see Section A.5. Since this dataset is restricted to plain vanilla bonds, see Section A.4, the above figure slightly understates the true number of bonds per country. Lastly, note that the Spanish bond future is not labelled due to its low trading volume (roughly equal to the median volume across Spanish cash bonds).

	On-Exchange	Electronic Platforms	Over-the-Counter
Trading Protocol	Central Limit Order Book	Request for Quote	Voice, Chat
Immediacy, Centralization, Pre-Trade Transparency	High	Moderate	Low
Post-Trade Transparency	High	Low	Low
Anonymity	High	Low	Low if bilateral, moderate if via broker
Examples	MTS, stock exchanges	Tradeweb, Bloomberg	interdealer brokers: TPICAP, BGC, ...
Market Share*	12.5%	37.5%	50%

Table A4: Stylized Differences between Cash Trading Venues for European Government Bonds. *The market shares are rough estimates based on public trading volume data from different sources covering different time periods. In particular, the above-mentioned 2022 ICMA report puts the OTC market share at roughly 50% (labelled 'systematic internaliser' trades, which are a major segment of the OTC market, see also Section A.5). To decompose the remaining "on-venue" volume into exchanges and electronic platforms, we use the 2019 EC Report cited in the main text. This report estimates that roughly 25% of "on-venue" volume occurs "on-exchange" (0-5% on regular stock exchanges and 15-30% on MTS, see Table 3 on p.168 of the report).

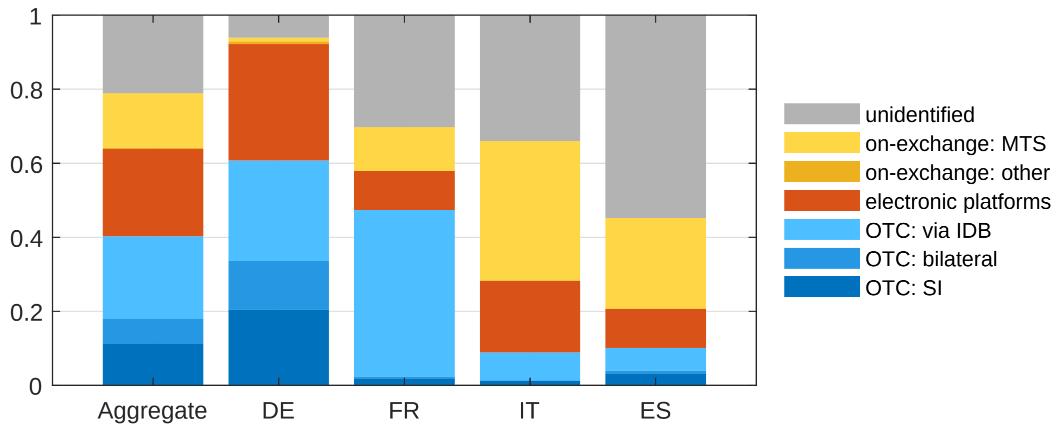


Figure A2: Market Shares of Cash Trading Venues. This figure breaks down the aggregate and country-level trading volume in EGBs into different cash trading venues. Results are based on our transaction dataset for all four non-outage days (i.e. April 7 and 21, June 30 and July 8, 2020), see Section A.5. 'IDB' refers to interdealer brokers, 'SI' refers to systematic internalisers and 'other exchanges' refer to regular stock exchanges.

A.4 Cash Bond Universe

To make life easier, we restrict our analysis to 'plain vanilla' European government bonds whenever we study the cash market. That means we ignore inflation-indexed bonds, bonds with variable coupon, 'strips', 'green' bonds, and any other exotic bonds. For each bond ISIN, we obtain a number of bond characteristics from Bloomberg, including the issuance and maturity date, the coupon rate, coupon frequency and day-count basis. Table A5 provides summary statistics regarding the time to maturity, time since issuance, original maturity, and the coupon rate of the bonds we study. Table A6 provides a breakdown of our bond universe by country and maturity bucket.

	min	p50	mean	max
Years to Maturity	0.0	2.9	6.3	46.9
Years since Issuance	0.0	2.5	4.7	28.4
Original Maturity in Years	0.2	10.0	11.0	50.4
Coupon Rate	0.0	0.9	1.7	9.0

Table A5: Bond Characteristics.

Maturity Bucket	DE	ES	FR	IT	Total
< 2.5 years	37	24	46	50	157
$2.5 - 5.5$ years	14	12	11	25	62
$5.5 - 10.5$ years	15	16	14	18	63
> 10.5 years	11	12	16	21	60
Total	77	64	87	114	342

Table A6: Number of Bonds by Country and Maturity Bucket.

We use maturity buckets of less than 2.5 years to maturity, 2.5 to 5.5 years, 5.5 to 10.5 years, and more than 10.5 years. These thresholds ensure that we have an 'on-the-run' (OTR) bond in each of the first three buckets and a cheapest-to-deliver bond in all buckets (if a corresponding future exists, see Table A2).

Table A7 shows the ISINs of the bonds that were cheapest-to-deliver into futures contracts at the time of the Eurex outages in 2020. Similarly, Table A8 shows the ISINs of on-the-run bonds, i.e. the most recently issued bond with approximately two, five or ten year original maturity. For France and Spain, we identify OTR bonds for the 1-year rather than the 2-year maturity, since the latter maturity is uncommon in these countries.

In Section D.6, we study a fixed set of bonds to avoid compositional effects. In particular, we drop bonds that were issued after 7 April 2020 or matured before 8 July 2020.

Maturity	Country	Future	April 2020	July 2020
2y	Germany	FGBS	DE0001104792	DE0001104800
	Italy	FBTS	IT0005367492	IT0005282527
5y	Germany	FGBM	DE0001102374	DE0001141810
10y	Germany	FGBL	DE0001102465	DE0001102473
	France	FOAT	FR0013407236	FR0013407236
	Italy	FBTP	IT0005365165	IT0005365165
	Spain	FBON	ES0000012E51	ES0000012E51
30y	Germany	FGBX	DE0001135481	DE0001102341

Table A7: Overview of Future Contracts and Cheapest-to-Deliver Bonds.

Country	Time	1y/2y	5y	10y
Germany	April 2020	DE0001104792#	DE0001141810	DE0001102499
	July 2020	DE0001104800#	DE0001141810#	DE0001102507
Italy	April 2020	IT0005388928	IT0005344335	IT0005403396
	July 2020	IT0005412348	IT0005408502	IT0005413171
France	April 2020	FR0125848699	FR0013157096	FR0013451507
	July 2020	FR0126001801	FR0013157096	FR0013516549
Spain	April 2020	ES0L02103056*	ES0000012F92	ES0000012F76
	July 2020	ES0L02106117	ES0000012F92	ES0000012F76

Table A8: Overview of On-the-Run Bonds. For Germany and Italy, we identify 2-year OTR bonds, for France and Spain we identify 1-year OTR bonds. #For Germany, some bonds were OTR and CTD bonds at the same time, see Table A7. *For Spain, the 1-year OTR bond changed between the first Eurex outage on 14 April 2020 and the subsequent control day on 21 April (namely to ES0L02104161 on 17 April 2020).

A.5 Cash Market Transaction Dataset

As explained in Section 2.1, we exploit multiple datasets to capture as many cash transactions in EGBs as possible. For the entire sample since 2008, we use data from the MiFID I/II datasets and from MTS. For the six most important days – the two Eurex outage days and the respective control days in 2020 – we exploit further sources, as explained below.

Data Sources

In a nutshell, we start with a non-anonymous regulatory dataset and add non-duplicate anonymous transactions sourced directly from trading venues.

To give more context, note that the MiFID II regulation differentiates between *trade* and *transaction* reporting. Trade reports are anonymous, need to be sent in near real-time, and must be made publicly available, e.g. via an Approved Publication Arrangement (APA).[34] These reports usually contain the intraday timestamp, ISIN, price and volume of a traded bond, with some exceptions.[35] Transaction reports, in contrast, contain additional information, most importantly about the counterparties involved in each trade.[36] These reports need to be sent on a $T + 1$ basis, either to the National Competent Authority (NCA) or ESMA, possibly via an Approved Reporting Mechanism (ARM).

What we refer to as 'MiFIR' or 'MiFID II' data refers to the *transaction* reports sent to Bafin, Germany's NCA. This data only covers trades in which a German security is traded or where at least one of the involved parties – the buyer/seller, the trading venue, or a central counterparty – is domiciled in Germany. We augment this data with non-duplicate *trade* reports we obtained directly from trading platforms (MTS, MTS Bondvision, Tradeweb) and interdealer brokers (TPICAP, BGC, GFI, Aurel).[37] See below for further details on how we define duplicates and clean the data.

[34] However, the regulation does allow to 'charge fees for the use and redistribution of historic data', see ESMA Q&A on MiFID II and MiFIR transparency topics. Hence, in practice, trade reports are only available for the current and previous business day, see e.g. Tradeweb website, Bloomberg website and Brokertec website. In June 2023, the European Commission has announced to improve this state of affairs by creating a '*consolidated tape [that] will bring together the prices and volumes of financial instruments, such as shares and bonds, from hundreds of execution venues across all Member states into a single stream of information, equally accessible for everybody*', see EC press release.

[35] Under MiFID II, transactions above specific 'large in scale' (LIS) or 'size specific to the instrument' (SSTI) thresholds or transactions in 'illiquid' bonds benefit from deferred publication. The thresholds vary across ISINs and are regularly updated by ESMA, as is the list of bonds deemed liquid. At the time of the two Eurex outages in 2020, the LIS threshold for sovereign bond transactions was €15 million, the SSTI threshold was €6.5 million (the latter only applies for trades where a party is dealing on own account) and ESMA deemed a total of 520 bonds liquid (see ESMA website). In some cases the deferral period can be indefinite, i.e. these transactions are never published individually. Instead, only a weekly aggregate volume is published at the ISIN-level. Lastly, MiFID II allows 'volume masking', i.e. some transactions can be reported without volumes. Regarding our dataset, these reporting exemptions apply only to the Tradeweb dataset, which covers only few trades above €6.5 million, none above €15 million, and roughly 5% of transactions omit the volume information. For details on the post-trade reporting requirements, see this AFME report.

[36] For the full list of reported fields, see EU regulation 2017/590 Annex 1 Table 2.

[37] For the sake of completeness, note that we unsuccessfully tried to obtain intraday transaction data from further data sources. Tradition, another large interdealer broker for European government bonds, see Tradition website, did not retain transaction data for the period we study. Similarly, Bloomberg provides the transaction data it collects under MiFID II only with a limited history. Lastly, various sources provide data on ISIN-level trading volumes, but only at a daily frequency, which is too coarse for our purposes (e.g. Clearstream and Euroclear, the two principal clearing houses in Europe, MarketAxess, a trading venue, and Markit, an independent data provider).

Final Sample

Table A9 panel (a) shows the final number of transactions we use from each data source. As expected, our MiFIR data has the best coverage for trades in German bonds. In theory, the dataset should cover all trades, and we are close to this ideal in practice. For instance, adding transactions from Tradeweb to the MiFIR dataset gives roughly 3% more observations for Germany, but almost doubles the number of observations for France and Spain. Similarly, adding transactions from MTS and MTS Bondvision is crucial for Italy, but rather negligible for Germany.

Table A9 panel (b) contains average daily trading volumes at the country-level. To put these numbers into perspective, we capture a volume of 24 billion Euro in German government bonds, which is slightly higher than the German debt management agency estimates based on a survey among dealer banks ($4,255/250 \approx 17$ billion Euro daily trading volume in 2020, see Finanzagentur website).

(a) Number Of Transactions

	DE	FR	IT	ES	Total
Mifir	16891	1821	13172	1950	33834
Tradeweb	550	1738	2365	1379	6032
MTS	36	431	5278	461	6206
BondVision	125	206	2711	218	3260
Interdealer Broker	601	660	516	103	1880
Total	18203	4856	24042	4111	51212

(b) Average Daily Trading Volume (in billion €)

	DE	FR	IT	ES	Total
in billion €	24.0	6.0	13.5	4.0	47.5
in % of total	50.5	12.6	28.5	8.4	100.0

Table A9: Number and Volume of Cash Transactions by Data Source and Country. All figures refer to transactions in 'plain vanilla' European government bonds, see Appendix A.4 for details. Panel (a) refers to the total number of transactions on all six days in our sample (the two Eurex outage days and the respective control days), whereas panel (b) refers to the average across the four control days.

MiFIR data cleaning procedure

From the raw MiFIR dataset, we first delete transactions i) with missing or implausible prices or quantities, ii) that occurred outside of trading hours (prior to 8.a.m. or after 7 p.m.), and iii) that occurred more than two days prior to the bond's issuance (so-called 'when-issued' transactions). We round prices to one decimal because we observed that multiple reports of the same transaction sometimes deviate slightly in prices. Since timestamps are vital for our deduplication procedure and the linkage of plausible trade chains, we correct those where a misreporting is highly likely. E.g. differences by precisely one or two hours in observations for equal bond, price, and quantity may be linked to erroneously reported timezones. We convert everything to CET. Timestamp deviations by up to two seconds are also accounted for when everything else points towards a trade chain.

Duplicates in bond, timestamp, price, and quantity are simply deleted for the macro-level analyses in Section 3. However, for our more granular analyses on sectoral or venue-level trading behavior in Section 4, we require a more thorough approach. For a probable trade chain with multiple different reported trade venues, we identify the ultimate trading venue by placing actual venues over systemic internalisers and OTC flags to identify the ultimate trading venue. Our final goal as regards trades' counterparties is to identify the ultimate buyers and sellers, i.e. those that ultimately exchange ownership in the bond. First we delete duplicates in timestamp, bond, buyer ID, seller ID, price and quantity but different submitting IDs. Trade chains are then identified by timestamp, bond, price and quantity. In the large majority of cases, netting over all involved buyers and sellers results in only two remaining counterparties of which one is a buyer and the other a seller with identical quantities. Only if this is not the case, we deploy a carefully designed algorithm. To give a basic example, when one buyer but two sellers remain after netting and both of these sellers show identical quantities, i.e. this is not a cumulative trade, we place the selling counterparty less likely to be intermediary first (e.g. an investment fund) and drop the other seller (e.g. a dealer bank). A set of these measures results in the identification of two (or in the case of cumulative trades three or more) ultimate counterparties for the bulk of identified trade chains. For the remainder, we drop the trade side that remains ambiguous. We also drop intragroup trades, i.e. trades between different LEIs belonging to the same investor, see Section A.6

Non-representative sample

One issue with our transaction dataset are the relative shares of the trading volume we capture across countries, reported in the last row in Table A9. German bonds account for 51% of volume in our dataset compared to a 'true' cash market share of only 34% in 2022 based on Table A3. The analogous figures are 13% vs. 25% for France, 29% vs. 33% for Italy, and 8% vs. 9% for Spain. That means even after augmenting the regulatory data with data from trading platforms, trades in German bonds are still overrepresented.

These data issues are not too concerning for our purposes, however, since we focus on the differential effect of outages. In particular, we compare outage days with 'control' days, usually the same day one week before and after the outage, and we compare the intraday periods just prior and just after the outage. In this setting, data issues such as duplicates and non-representative market shares should have little impact on the estimated treatment effect.

Additional Filters for Yield Curve Fitting

In Section 3.3, where we compute yield curve fitting errors for German government bonds, we apply some additional filters to the ones mentioned above. In particular, we exclude intragroup trades (see next section) and drop trades in bonds with less than one or more than ten years to maturity or that have implausible prices. For the latter filter, we convert each transaction price to an implied yield[38] and compute the difference to the daily maturity-matched yield from the Bundesbank's term structure model (see Bundesbank website). We drop a few transactions where the absolute yield difference is larger than 75 basis points, or larger than 25 basis points and the transaction price is exactly 100. These transaction prices most likely reflect reporting errors. These filters leave us with over 3,000 transactions during the six selected intraday windows. Table A10 provides some descriptive statistics on these transactions.

[38]We use Matlab's built-in *bndyield* function, taking into account the price of the bond, its maturity and issuance date, the coupon rate, coupon frequency, first and last coupon date, and assuming $T+2$ settlement.

	min	p50	mean	max
No Outage				
Volume (million Euro)	0.00	1.28	10.01	1292.00
Years to Maturity	1.00	5.36	5.77	9.86
Years since Issuance	0.11	2.23	3.26	26.47
Coupon Rate	0.00	0.00	0.53	6.50
Yield	-0.73	-0.62	-0.59	-0.31
Yield Curve Fitting Error	-12.23	-0.23	-0.18	27.94
Outage				
Volume (million Euro)	0.00	0.90	2.37	200.00
Years to Maturity	1.01	5.84	6.11	9.84
Years since Issuance	0.09	2.25	3.59	26.28
Coupon Rate	0.00	0.25	0.62	6.50
Yield	-0.92	-0.57	-0.56	-0.18
Yield Curve Fitting Error	-23.80	-0.12	-0.20	50.53

Table A10: Descriptive Transaction Statistics for Yield Curve Fitting Sample. These statistics refer to the over 3,000 transactions in German sovereign bonds with 1-10 year maturity shown in Figure 5 and underlying the regression results in Table 4.

A.6 Investor-Level Info

A key feature of our regulatory transaction data is that it contains a unique legal identifier (LEI) for at least one of the two counterparties involved in each cash transaction.[39] We can thus use Eurosystem supervisory lists and the Register of Institutions and Affiliates Database (RIAD database, see Perrella and Catz, 2020) to group LEIs into unique investors.[40] Then, we classify investors into the following categories: banks, non-bank financial institutions (NBFI), investment funds, hedge funds, insurance companies and pensions funds (ICPF), non-financial corporations (NFC), an official sector (including central banks) and households (retail investors).[41]

Table A11 gives an overview of the number of investors of each type and Table A12 gives an overview the number of transactions across investor segments and types.

	Eurex-Active	Eurex-Inactive	Total
Bank Dealer	29	2	31
Bank Non-Dealer	12	68	80
NBFI	6	39	45
Investment Fund	5	220	225
Hedge Fund	6	61	67
ICPF	1	55	56
NFC	0	20	20
Official	0	16	16
Household	0	1	1
Total	59	482	541

Table A11: Number of Investors by Type. Data refers to investors with Bund trades on the cash market on the six selected days in 2020. Investors are aggregated to group-level. The category 'household' comprises an unknown number of retail investors, as these are not uniquely identifiable via a LEI.

For banks, it is important to differentiate between (non)dealers. We identify dealers using the list of primary dealers participating in Bund auctions, see Finanzagentur website. In total, our sample covers cash market transactions by 31 different dealer banks. With this classification at hand, we categorize each transaction into one of three investor segments: client-to-client (C2C), dealer-to-client (D2C), and dealer-to-dealer (D2D).

We also separate investors into those that are usually active on the bond futures market and those that are not, see last column of Table A11. In particular, we exploit the European Market Infrastructure Regulation (EMIR) dataset, see Section 2.2. We deem any investor with more than 20 trades in any German bond future on the six selected days in 2020 (outage and control days) as 'active on Eurex'. This way we can differentiate between cash market trades in which both, only one, or none of the two counterparties are usually active on Eurex.

[39]This is in contrast to the Canadian transaction data used e.g. by Allen and Wittwer (2023a), which contains a LEI only for dealers, brokers, and the largest investors, whereas other investors remain anonymous. The US transaction data used e.g. by Duffie et al. (2023) only covers trades by registered broker-dealers, identified via Market Participant Identifier (MPID) codes. The UK transaction data used e.g. by Czech, Huang, Lou, and Wang (2021), lastly, contains a Business Identifier Code (BIC, issued by SWIFT) or a Firm Reference Number (FRN, issued by the UK's Financial Conduct Authority).

[40]The 31 dealers in our sample, e.g., comprise over 100 different LEIs (similar to Duffie et al., 2023).

[41]We start classifying investors using the Eurosystem lists of financial institutions (covering banks, investment funds and ICPFs, see ECB website) and use RIAD for the remaining investors. In some cases, we manually adjust the investor classification. Some of the largest global banks trade in EGBs via European subsidiaries, for instance, and RIAD identifies theses as NBFIs rather than banks, probably because they are no depository institutions in the euro area.

(a) Investor Segments

	No Outage	Outage	Total
C2C	865	257	1122
D2C	3121	638	3759
D2D	1032	170	1202
Total	5018	1065	6083

(b) Investor Types

	No Outage	Outage	Total
Bank Dealer	2595	489	3084
Bank Non-Dealer	539	175	714
NBFI	474	117	591
Investment Fund	489	99	588
Hedge Fund	256	64	320
ICPF	175	19	194
NFC	30	12	42
Official	323	25	348
Household	137	65	202
Total	5018	1065	6083

Table A12: Number of Cash Transactions by Investor Segment and Type. All figures refer to transactions in German sovereign bonds with 1-10 year maturity during the two Eurex outages in 2020 and the four non-outage control windows. With two sides to each trade, the totals sum to roughly twice the number of observations shown in Figure 5 and underlying the regression results in Table 4 (abstracting from unknown investor types due to anonymous transaction data).

For our trade report data, the investor classification is less straightforward, because this data is anonymous. However, the data source itself is informative about the venue type and investor segment and we use this information to the extent possible, see Table A13. For instance, we attribute transactions on MTS to the dealer-to-dealer segment, based on the fact that MTS is restricted to dealers. The classification is equally uncontroversial for data we obtained from interdealer brokers. The MTS Bondvision and the Tradeweb platform, in contrast, are open to both dealers and clients, and hence we leave the investor segment of these trades unclassified. However, besides transactions executed directly on its platforms, Tradeweb also publishes data on OTC trades (for which Tradeweb acted as an APA). Within these trades, systematic internaliser trades are explicitly flagged and we classify the remaining trades as bilateral OTC trades.

Data Source	Venue Type	Venue Subtype	Segment
MTS	On Exchange	MTS	D2D
TPICAP, BGC, GFI, Aurel	OTC	OTC via IDB	D2D
MTS Bondvision	Electronic Platforms		-
Tradeweb MTF*	Electronic Platforms		-
Tradeweb SI†	OTC	OTC via SI	-
Tradeweb other†	OTC	Bilateral OTC	-

Table A13: Venue and Investor Segment Classification for Anonymous Transaction Data. This table shows how we classify anonymous transactions, sourced directly from trading venues, into venues and investor segments. Empty cells mean we leave the segment unidentified. *Due to Brexit, Tradeweb runs two separate multilateral trading facilities (MTF) in the UK and the EU (MIC Codes 'TREU' for London and 'TWEM' for Amsterdam). †Tradeweb also offers an APA service, reporting trades from the OTC market, explicitly flagging trades by systematic internalisers (SI).

Appendix B Overview of Market Outages

This section provides an overview of the outages we study. Appendix B.1 lists all outages and affected assets, Appendix B.2 recounts newspaper reports for all Eurex outages in 2020 studied in Section 3 of the paper, and for the previous Eurex outages studied in Appendix C. Appendix B.3 does the same for the other outages studied in Section 5. Many articles are from the Factiva news archive, which is how we identified some of the outages in the first place.

B.1 Outage List

Table A14 contains a list of the market outages we study. Figure A3 shows the exact intraday times of each system-wide Eurex outage. We focus on outages since 2008 because we do not have cash market data prior to that. We have cross-verified all outages with news reports, see Section B.2. Figure A4 confirms the two partial outages on Eurex studied in Section C.2. The figure shows that only 5-year and 10-year German bond futures were unaffected by the outages on 26 May 2014 and 21 November 2016. On the first of these days, there were two separate outages. Figure A5 confirms the known outage of the MTS platform on 12 January 2010 and shows another suspected outage on 26 July 2019. Figure A6 confirms the most recent outage on CME.

Exchange/Platform	Affected fixed-income assets	Dates
Eurex	European Government Bond (EGB) futures	1 July 2020 14 April 2020 16 March 2018 13 December 2017 22 February 2016 20 July 2015 17 February 2015 26 August 2013 11 October 2011 23 December 2009 18 November 2009 4 February 2009
	all EGB futures except 5/10-year German Bund futures	21 November 2016 26 May 2014
MTS (unconfirmed) Brokertec Frankfurt stock exchange (FWB) Bloomberg MTS	cash bonds	26 July 2019 11 January 2019 27 May 2015 17 April 2015 12 January 2010
CME CBOT see Harding and Ma (2010)	US Treasury futures	26 February 2019 19 September 2007 23 August 2007 12 January 2007 11 January 2007 3 October 2006 4 August 2006

Table A14: Overview of Market Outages Studied in This Paper.

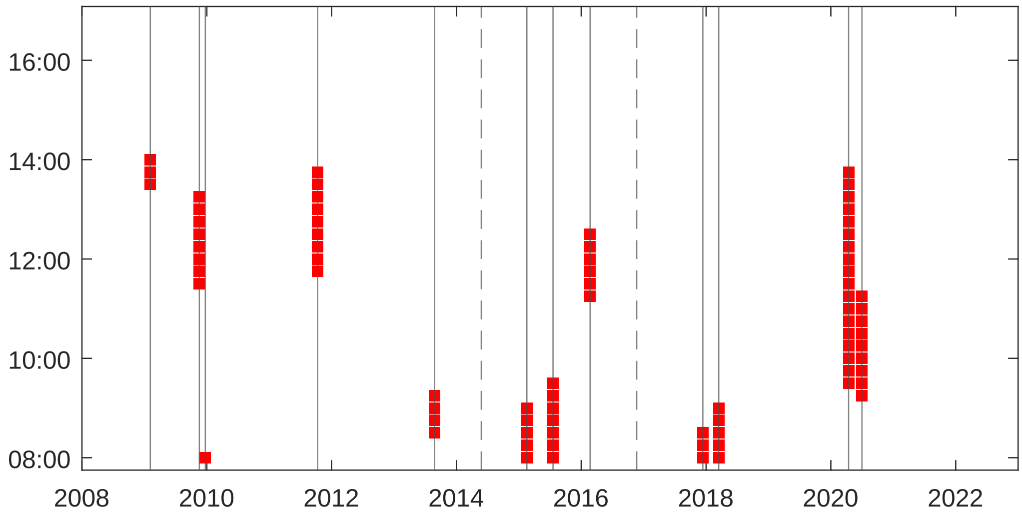


Figure A3: System-Wide Eurex Outages since 2008. For each trading day since 2008, red squares mark 15-minute intraday windows with no trading in the German 10-year bond future (FGBL), which line up perfectly with the twelve known outage days, marked by solid vertical lines. The two dashed lines mark days with partial outages, see Figure A4. The vertical axis ranges from 7:45 a.m. to 5:00 p.m. local time.

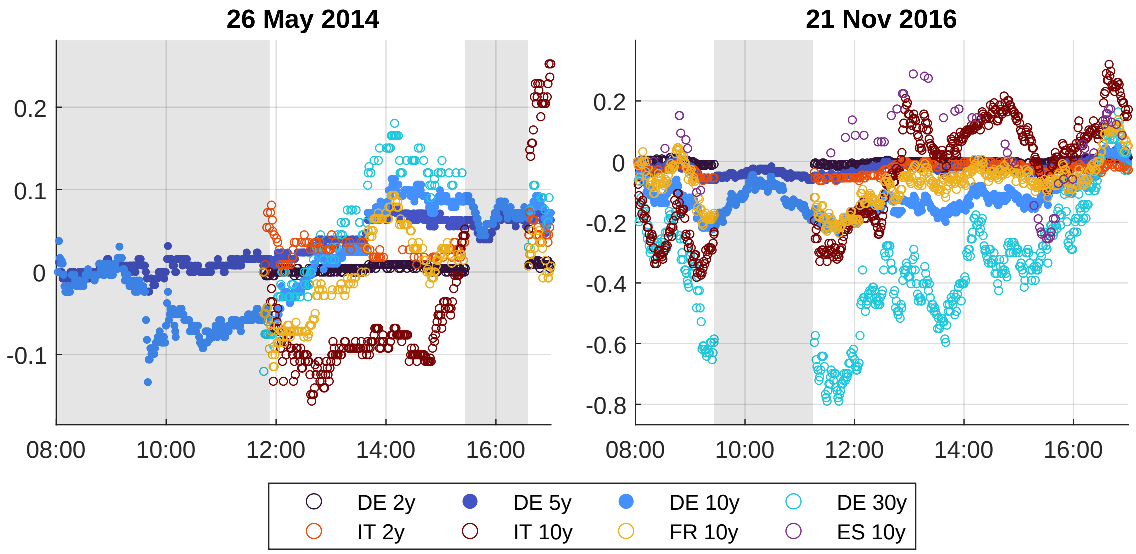
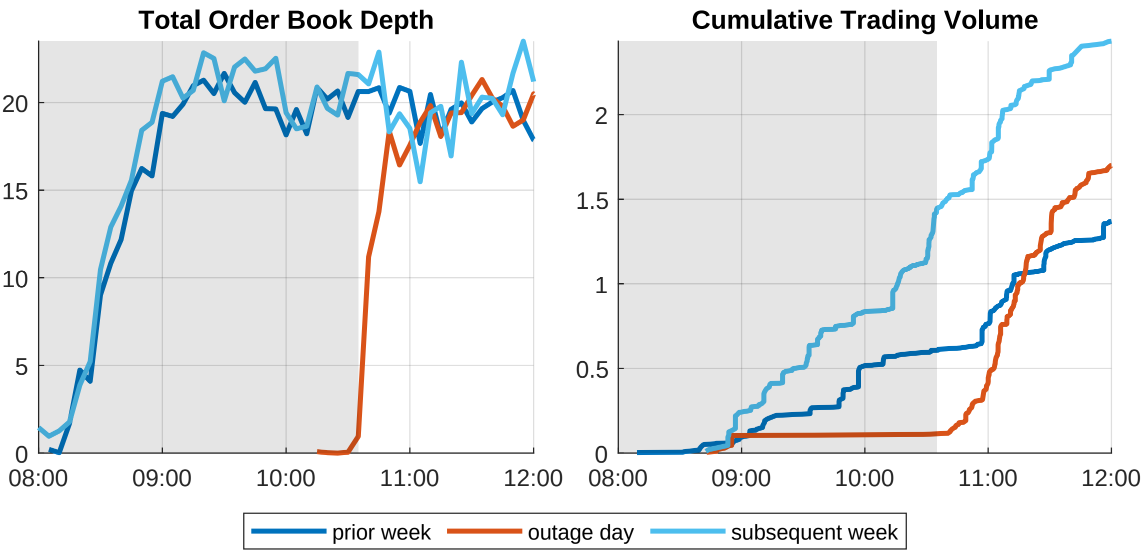


Figure A4: Partial Outages on Eurex. This figure shows intraday transaction prices of all euro area government bond futures (in percentage changes since 8:00 a.m., at minutely frequency). The grey areas mark the outage times that affected all futures except those for 5-year and 10-year German bonds. The Spanish 10-year future was introduced in October 2015, i.e. after the 2014 outage.

(a) Confirmed MTS Outage on 12 January 2010



(b) Suspected MTS Outage on 26 July 2019

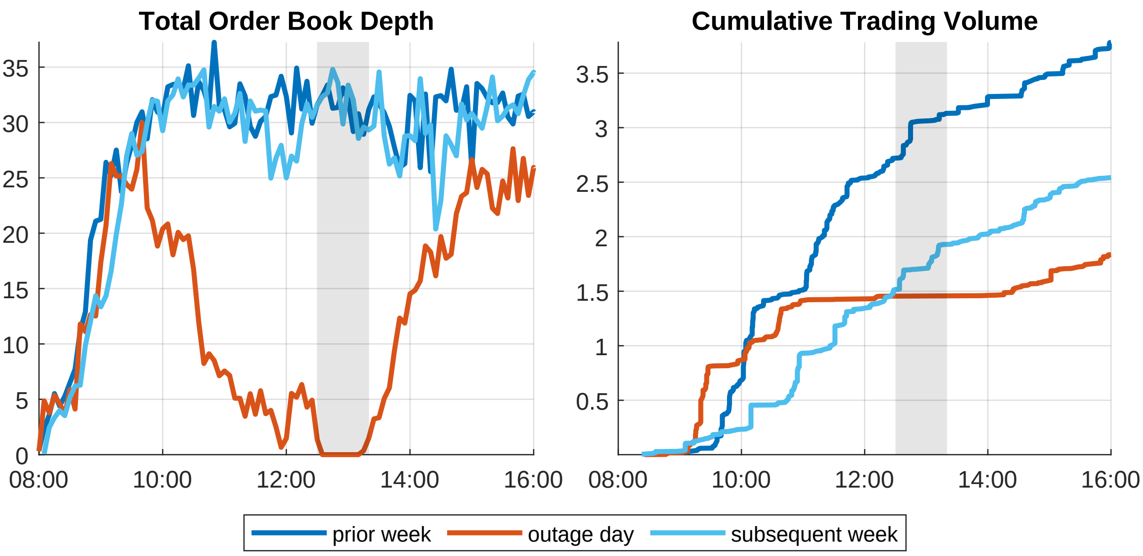


Figure A5: Outages on MTS. The left panels show the total quoted volume (in billion €), across all German, French, Italian and Spanish sovereign bonds and all market segments, in 5-minute intervals. The right panels show the total cumulative trading volume (in billion €). Red lines refer to the (suspected) outage day, dark and light blue lines refer to the previous and subsequent week. Grey areas mark the (suspected) outage times.

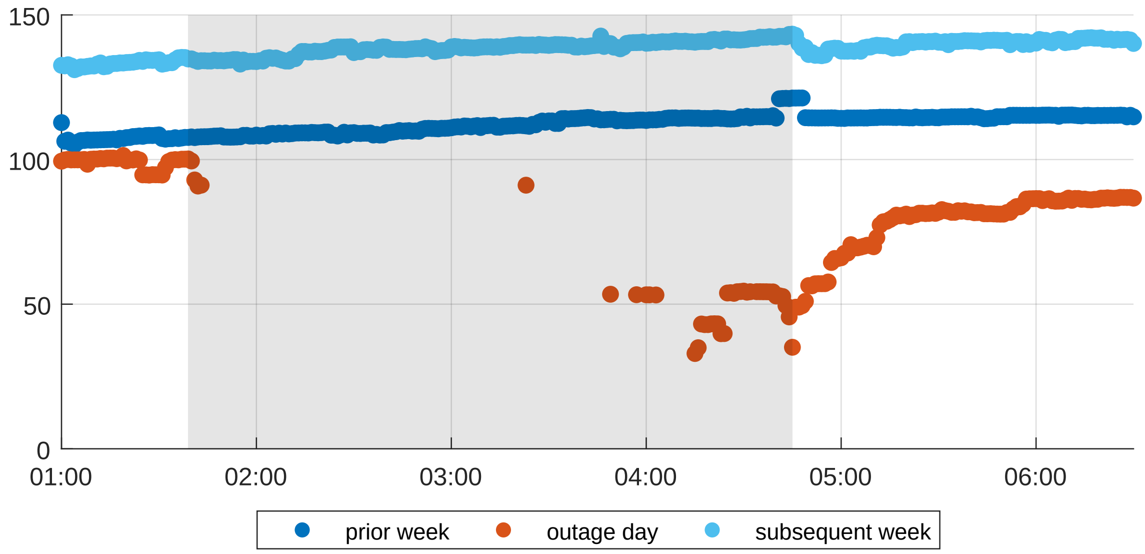


Figure A6: CME Outage on 26 February 2019. This figure shows the order book depth of 10-year US Treasury futures, i.e. the number of contracts (in thousands) quoted on both sides of the first 15 order book levels. The Red line refers to the outage day, dark and light blue lines refer to the previous and subsequent week. In Central European Time, the outage occurred between 1:39 a.m. till 4:45 a.m. on 27 February 2019, marked by the grey area.

B.2 News Reports on Eurex Outages

Table A15 provides a timeline of the two Eurex outages in 2020 and related news.

Table A15: Timeline of Eurex outages in 2020 and same-day news.

	14 April 2020
9:25	**outage start**
10:32 @Eurex	Due to technical problems, the Eurex T7 system is not available at the moment. We are investigating and will keep you informed.
11:47 DowJones	Trading on Deutsche Boerse AG's Xetra is currently suspended due to a technical fault, a spokesman for the German stock exchange operator said on Tuesday. The spokesman said to Dow Jones Newswires that he couldn't yet comment on when the trading would resume and communication related to trading resumption would be released on the Xetra Newsboard.
13:19 @Eurex	Trading will resume according to the following schedule: 13:15 CEST Pre-Trading Instrument State BOOK, 13:45 CEST Trading Instrument State OPENING AUCTION, 13:50 CEST Trading Instrument State CONTINUOUS.
14:00	**outage end**
17:51 Reuters	The outage was caused by a malfunction in the internal communication of the trading system, Deutsche Boerse said in a statement, adding that trading was operating smoothly again on Tuesday afternoon. A Deutsche Boerse spokesman said the outage was not due to a hacker attack.
	1 July 2020
8:49	**outage start**
9:39 Reuters	Frankfurt-based electronic trading system Xetra was experiencing a 'technical issue', affecting all securities traded on the platform, a Deutsche Boerse spokesman said on Wednesday. 'I just can confirm that there is a technical issue on Xetra... we're currently investigating the failure,' Patrick Kalbhenn, a spokesman for the German stock exchange, told Reuters.
10:11 @Eurex	Due to technical problems the trading system T7 is not currently available.
11:54 @Eurex	Update on the disruption: continuous trading on Eurex resumed at 1130.
11:31	**outage end**
17:25 Bloomberg	The disruption in the T7 system in April and today's failure had the same origin. They were due to faulty third-party software that is part of the trading system. We now understand the exact cause and have eliminated the issue. The system is now running stably and we expect it to remain so. External causes can be ruled out.

An ESMA report contains the following paragraphs about the Eurex outages in 2020: *'The first two incidents reported related to an issue with the Deutsche Börse T7 trading system. The first was reported on 14 April and trading was interrupted in the trading venue due to a software issue. This issue required the trading venue to stop and restart manually the system which was a heavy and time-consuming process. The second incident was reported on 1 July and due to a human error. Two failures of the trading venues' central network occurred which caused trading to be halted in Deutsche Börse. In both circumstances the incident affected a significant number of trading venues given that the T7 trading system is widely used across the EU.'*

What follows are newspaper reports for all previous outages on Eurex, in chronological order:

6 February 2004: Computer glitch caused Xetra failure

Deutsche Boerse AG said on Friday a computer failure led to a nearly hour-long outage on its Xetra electronic trading platform. The outage was the fourth on Xetra, which accounts for 90 percent of trade in German stocks, since the electronic trading platform was introduced six years ago. Pre-trading resumed at 1045 GMT after a 45-minute trading halt while full trading resumed at 1130 GMT, Deutsche Boerse said in a statement. The stock market operator said trade in some stocks had been delayed even longer with dealing halted from 0900 GMT, caused by a failure in a host database. Traders said the Xetra failure caused some concern. ‘It was a little bit hectic when it first began but luckily there was not that much important company news during the trading halt,’ said one trader.

19 November 2007: Rare glitch hits Frankfurt stock exchange
Trading in German stock exchange operator Deutsche Boerse's electronic order-matching system Xetra was interrupted early on Monday by technical problems, which traders and the bourse said were rare. The impact of the disruption of just over one hour was minor because early volume had been ‘very low,’ said one Frankfurt-based stock broker, who could not recall more than two or three short Xetra disruptions in the past two years. ‘Normally they (Deutsche Boerse) say the system is running nearly 100 percent,’ he said, adding from his own experience. ‘If it's down two times in one year, it's a lot.’ Xetra trading was halted around half an hour after the start at 0800 GMT and resumed at 0940 GMT. During the interruption, Deutsche Boerse said it was investigating ‘technical problems’ in the system, which handled 16 million transactions in October, up 74 percent year-on-year. A Deutsche Boerse spokesman said after the restart of trading that he did not yet have information about the exact nature of the problem.

4 February 2009: Derivatives exchange Eurex resumes trading
Derivatives exchange Eurex resumed trading on Wednesday after a one-hour shutdown that traders took with a shrug. Eurex said a technical glitch halted trading between 1218 GMT and 1315 GMT on what is the main market for Europe's most traded fixed income futures and stock index options and futures. Traders said such an event was rare. A Eurex spokesman said the last time something similar had occurred was in 2006. ‘(For us) there was no effect, no losses as a result of this Eurex downtime,’ said Sebastian Qureshi, head of German hedge fund manager Varengold, which specialises in managed futures strategies and trades also on Eurex.
‘One hour is too short, it's not really affecting our business,’ he said. ‘We just went out to get a coffee,’ a Frankfurt-based Eurex market-maker added.

18 November 2009: Eurex trade suspended until further notice
Trade on the Eurex derivatives exchange has been suspended since 1100 GMT due to technical problems, a Eurex spokesman said on Wednesday, adding it was not foreseeable when trade would resume. ‘We are working hard to solve the problem,’ the spokesman said. Eurex is jointly operated by Deutsche Boerse and SIX Swiss Exchange.

23 December 2009: Eurex Exchange says Wednesday opening delayed.

11 October 2011: Eurex trade suspended until further notice
Deutsche Boerse AG interrupted trading on its electronic derivatives platform Eurex on Tuesday to investigate technical problems. Trading on Eurex had been interrupted ‘to avoid any threat to the functioning of Exchange trading’, the stock exchange operator said in a statement. Earlier, Deutsche Boerse said it had been experiencing technical problems. ‘We are investigating and will keep you informed,’ Deutsche Boerse said in an e-mailed statement.

26 August 2013: Eurex Restarts Trading After Market Halt
German exchange operator Deutsche Boerse AG's (DB1.XE, DBOEF) Eurex Exchange arm reopened trading early Monday after a brief halt to certain trading earlier in the session. At roughly 0642 GMT, Eurex posted a note on its website saying that it had halted trading on its New Trading Architecture platform–a new electronic trading platform that was introduced by the firm in December–in order to avoid a threat to the functioning of exchange trading. The halted trading announcement came roughly 12 minutes after an earlier posting said there were technical problems at the exchange. Trading in all Eurex products was restarted at roughly 0720 GMT, according to the company's website.

26 May 2014 (partial outage): Btp and Oat futures, delayed opening due to technical problems
Italian, French bond futures trading delayed, Eurex recorded message citing technical problems at exchange

17 February 2015: Eurex Restarts Trading After Market Halt
There is no trading currently on any Eurex futures or option products due to technical issues, according to one London-based trader. According to one London-based trader, the earliest start of opening Auctions on Eurex will be 0915 CET or 0815 GMT, while netting will start as of 0920 CET or 0820 GMT. Adds these times 'not set in stone though.' Eurex spokesman not immediately available to comment.

20 July 2015: Eurex Restarts Trading After Market Halt
Europe's largest derivatives market, Eurex, suffered technical issues on Monday that delayed trading of all futures and options contracts and took two hours to fully resolve. The outage caused little disruption to broader cash equity and bond markets, however, unlike April's Bloomberg terminal outage, which delayed debt sales and exacerbated a spike in volatility. Traders said the outage had effectively choked off liquidity in the derivatives market, with only over-the-counter deals available. But receding fears over Greece and recent declines in volatility meant it had less impact than it might have. 'This type of outage is usually significant, but because of the broader environment things were much calmer,' said a London-based equity derivatives trader. 'It was a minor event in the end, but it could have been a major one had it hit a few weeks back.' Frankfurt-based Eurex said complete trading had resumed at 0810 GMT. Index futures trading usually begins around 0600 GMT. A bond trader based in Frankfurt said the mood was 'quite relaxed'. Another London-based trader said there had not been a big impact.

22 February 2016: Eurex says continuous trading to resume at 1150 GMT
Deutsche Boerse's Eurex says pre-trading to start at 1125 GMT, continuous trading from 1150 GMT.

21 November 2016 (partial outage):
≪For this outage, the only real-time confirmation we could find is on Twitter.≫

16 March 2018: Eurex hit by technical issues, bond and stock futures trading delayed
Many key European bond and stocks futures, including German Bund futures and DAX futures, did not open for trading on Friday as the Eurex trading system was hit by technical issues. German Bund futures, which allow investors to hedge against German government bonds, Italian BTP futures and French OAT futures were all down. Many stock futures were also down, in-

cluding were Eurostoxx futures and Dax futures 'There are some technical problems for the T7 system which has caused some delays. It's under investigation currently and we will have updates on our production newsboard. As of now I have no further details on when it will be resolved,' said a Eurex representative.
As a result, trading in government bonds is extremely thin, most likely because investors are unable to hedge their investments, DZ Bank strategist Daniel Lenz said.

B.3 News Reports on Other Outages

Bloomberg Outage on 17 April 2015

Yahoo: In the City of London [..] and financial centres around the globe traders and analysts were left gnashing their teeth as their Bloomberg computer terminals crashed on Friday morning, with fixed income markets suffering an especially large impact. Bloomberg [..] confirmed that its terminal system was unavailable worldwide, with the outage first cited at around 08:20 in London. [..] by 09:10 London time the company said that some customers had reported the terminal was back online.

The Globe and Mail: Bloomberg's trading terminals, which are used by most of the world's biggest financial firms, went down for two-and-a-half hours on Friday due to apparent technical problems.

UK Debt Management Office: Due to ongoing technical issues with the third party platform supplier [..] this morning's UK Treasury Bill tenders will be postponed.[42]

CME Outage on 26 February 2019

Financial Times: Technical problems froze derivatives trading on the CME's main platform for almost three hours from about 8pm New York time on Tuesday, disrupting a period in which thousands of futures linked to the S&P 500, US government bonds and West Texas Intermediate, the benchmark for US oil, would have typically traded.
All of its electronic futures and options markets were halted as of 7:07pm US central time and trading resumed at 9:45pm, according to a statement from CME.

Bloomberg: A technical error at CME Group Inc forced the world's biggest exchange operator to halt trading for about three hours, preventing the buying and selling of contracts tied to U.S. Treasuries, stock-futures and commodities.

CME Twitter account: Due to technical issues, all CME Globex markets have been halted.

Brokertec Outage on 11 January 2019

Reuters: BrokerTec, an interdealer broker of U.S. government debt, planned to reopen its U.S. market platform at 3:35 p.m. (2035 GMT) following an outage earlier Friday, a company spokeswoman said. 'All trading participants should be able to reconnect to the system,' the spokeswoman said in an email statement.

[42] The UK Debt Management Office runs its auctions on the Bloomberg Auction System (see Guide to DMO Primary Dealers). In this sense, the fact that the auction was postponed is no prima facie that UK officials necessarily feared an impaired price discovery process (as we argue for the cancelled auction of Dutch bonds during the Eurex outage on 14 April 2020).

Bloomberg: Treasuries Hit by One-Hour Outage on Biggest Electronic Platform. BrokerTec, the biggest electronic trading platform for Treasury securities, shut down for more than an hour on Friday because of a technical malfunction, an outage that several traders said caused a market-wide slowdown in one of the world's biggest assets.

Fed New York Treasury Market Practices Group meeting minutes: Members [..] noted that the timing and nature of this particular outage had a relatively limited impact given that [..] the outage occurred during a period of low trading activity.

Frankfurt stock exchange (FWB) Outage on 27 May 2015

Reuters: Deutsche Boerse said floor trading on the Frankfurt Stock Exchange on Wednesday would not resume before 11 Central European Time, or 0900 GMT. Trading on the Xetra electronic exchange remained intact.

Die Welt: On Wednesday a technical error brought the floor trading at the Frankfurt Stock Exchange to a halt all morning. Only around 1300 CET the trading began running smoothly again. Frankfurt Stock Exchange's electronic securities trading system Xetra, on which more than 90% of trade is handled, was not affected by the breakdown. Overnight there were problems in the data processing, a spokesman for stock exchange operator Deutsche Boerse said. Such a long breakdown is the absolute exception, according to the spokesman.

MTS Outage on 12 January 2010

Dow Jones: 'MTS Group can confirm that the cash market facility experienced an outage at the beginning of the trading day,' the company said in a statement. 'The issue was resolved and normal market conditions resumed. The outage caused no unverified transactions.' The problem resulted in users of MTS' system being unable to log in. It took place roughly between 0830 GMT and 0930 GMT after which the system was up a running again, Patrick Humphris, a spokesman for LSE, said.

Appendix C Previous Eurex Outages as Robustness Check

Section 3 in the main text suggests that market functioning for euro area sovereign bonds depends heavily on the futures market, but that evidence is based on just two Eurex outages in 2020. We put particular emphasis on these two most recent outages because we have the best data for this period, in particular regarding EGB transactions on the cash market, see Appendix A.5. The two Eurex outages in 2020 have not been without precedent, however. Hence, this section studies twelve previous outages on Eurex between 2009 and 2018 as a robustness check, see Section B.1.

Section C.1 confirms that these previous outages also cause trading volumes on the cash market to decline and liquidity on MTS to evaporate.

Section C.2 exploits the fact that two outages did not affect the entire Eurex exchange. Instead, trading continued in 5-year and 10-year German bond futures. We find that these partial outages reduce liquidity on the cash market roughly half as much as system-wide outages, in line with the benchmark status of German bond futures.

Section C.3, lastly, studies a particular trading day (25 May 2015) on which – as an exception – Eurex was closed while MTS remained open.

C.1 System-wide Outages

The two Eurex outages in 2020 have not been without precedent. At least ten other times since 2008, the Eurex platform already experienced similar outages, see Appendix B.1.[43]

Did these previous outages also cause trading on the cash market to decline? To find out, we run essentially the same regression as in Equation 1 for this older set of outages. The main difference is that we have to restrict this analysis to Germany, since the regulatory transaction-level dataset we use (the 'Bafin' dataset mentioned in Section 2.1) mainly captures trades in German bonds and we were not able to obtain intraday transaction data directly from trading platforms like we did for the 2020 outages. Thus, we regress the total trading volume in German bonds in a given maturity bucket and 30-minute time interval onto an outage dummy and fixed effects. The sample covers nine outage days plus the same day in the preceding and subsequent week, i.e. 27 days in total. Each day, we have 15 intraday observations (from 08:00 a.m. to 3:00 p.m.). Table A16 reports the results. In line with our previous finding, trading volumes on the cash market drop significantly when the futures market suffers an outage (model 1) and compared to short-term bonds, longer-term bonds are particularly affected (though there is no differential effect for bonds with more than 10.5 years to maturity).

How about MTS? Did Eurex outages always lead to an evaporation of liquidity on MTS, as we have shown for the two 2020 outages in Section 3.2? Yes, as shown in Table A17. We run the same regression as in Equation 2 for the older outages and get basically the same results. For most countries and maturity buckets, the entire liquidity on MTS evaporates, see model (1), and this dry-up is particularly pronounced for bonds with longer maturity, see model (2). The only major difference is in the country-level results, see model (3). In particular, the nine Eurex outages between 2008-2018 had equally dramatic effects on German, French and Spanish bonds. Only the liquidity Italian bonds was more robust. During the 2020 outages, also the liquidity in French and particularly Spanish bonds was more robust than in German bonds, cf. Table 2.

[43]In the following analysis, we omit the outage on 23 December 2009, when the start of futures trading was delayed from 8:00 a.m. to 8:20 a.m., because this outage is too short and too early in the day to observe any effect on the cash market.

	(1) Aggregate	(2) Maturities
Outage	-1.63*** [0.46]	-1.14 [1.11]
Outage × 2.5-5.5y		-1.57* [0.77]
Outage × 5.5-10.5y		-2.49** [1.21]
Outage × >10.5y		2.10 [2.06]
FE Day	✓	✓
FE Time	✓	✓
FE Maturity Bucket	✓	
Observations	1620	1620
Adjusted R^2	0.500	0.502

Table A16: Effect of Previous Eurex Outages on Cash Trading Volumes. Each column shows results of a different regression, as in Equation 1. For brevity, the table shows estimates only for the outage dummy and interaction terms. Throughout, the dependent variable is the log of the transaction volume of German bonds of a given maturity bucket in 30-minute intervals. In model (2), bonds with less than 2.5 years to maturity serve as the baseline.

	(1) Aggregate	(2) Maturities	(3) Countries
Outage	-10.73*** [0.93]	-4.08*** [1.11]	-13.23*** [0.61]
Outage × 2.5-5.5y		-8.33*** [1.09]	
Outage × 5.5-10.5y		-8.90*** [1.28]	
Outage × >10.5y		-9.36*** [1.30]	
Outage × ES			2.07 [1.43]
Outage × FR			0.62 [0.47]
Outage × IT			7.29*** [1.01]
FE Day	✓	✓	✓
FE Time	✓	✓	✓
FE Country	✓	✓	
FE Maturity Bucket	✓		✓
Observations	47088	47088	47088
Adjusted R^2	0.601	0.631	0.617

Table A17: Effect of Previous Eurex Outages on MTS Order Book Depth. Each column shows results of a different regression, see Equation 2. Throughout, the dependent variable is the log of the quoted bid and ask volume of bonds of a given country and/or maturity bucket, at 5-minute snapshots. All explanatory variables are dummies, either for the maturity bucket (bonds with less than 2.5 years to maturity serve as the baseline) or for different countries (Germany serves as the baseline).

C.2 Partial Outages

Besides the system-wide outages discussed so far, there have been two outages on Eurex that affected all futures except those on 5-year and 10-year German bonds, see Appendix B.1. These events can shed additional light on the interaction between MTS and Eurex. Since two German bond futures were still available, we would expect that these partial Eurex outages i) lead to a smaller drop in the overall liquidity on MTS, ii) particularly for 5-10 year bonds and iii) particularly for German bonds.

To test these predictions, we repeat the dummy regressions from Equation 2 for this new type of outage. In particular, we regress the order book depth of all bonds of a given country and maturity bucket onto an outage dummy that equals one during the partial Eurex outages. We again include six days (the two outage days plus the preceding and subsequent week), this time using 109 intraday observations per day to cover all outage times (5-minute snapshots from 08:00 a.m. to 5:00 p.m.). All regressions control for day and time-of-day fixed effects. We can then compare the estimated effects with those from the system-wide Eurex outages studied in Table 2. Table A18 shows the results.

	Maturity Buckets		Countries	
	(1) System-Wide	(2) Partial	(3) System-Wide	(4) Partial
Outage	-4.95*** [0.21]	-2.89* [1.18]	-18.03*** [0.43]	-7.12*** [0.60]
Outage × 2.5-5.5y	-8.50*** [0.32]	-3.20 [1.88]		
Outage × 5.5-10.5y	-7.73*** [0.61]	-3.82* [1.52]		
Outage × >10.5y	-7.40*** [0.72]	-4.80*** [0.48]		
Outage × ES			8.57** [2.46]	2.53* [1.19]
Outage × FR			3.87*** [0.07]	-1.16 [0.75]
Outage × IT			16.24*** [0.91]	3.76*** [0.47]
FE Day	✓	✓	✓	✓
FE Time	✓	✓	✓	✓
FE Country	✓	✓		
FE Maturity Bucket			✓	✓
Observations	8736	10464	8736	10464
Adjusted R^2	0.558	0.614	0.644	0.616

Table A18: Comparison of the Effect of Partial and System-Wide Eurex Outages on MTS Order Book Depth. The 'system-wide' effects refer to columns (2) and (3) from Table 2 and are based on the two Eurex outages in 2020. The 'partial' outages estimate the same regressions for the two Eurex outages on 26 May 2014 and 21 November 2016, which affected all bond futures on Eurex except those for 5-year and 10-year German bonds. See Equation 2 and Table 2 for details.

Prediction i) is clearly confirmed by the data: partial outages reduce the liquidity on MTS only roughly half as much as system-wide outages. Prediction ii) on the maturity-specific effect is also confirmed. While the liquidity of 2.5-10.5 year bonds drops significantly more than shorter-term bonds during system-wide outages, this differential effect is barely significant during partial outages. Both of these results are in line with the benchmark status of German bond futures.

Prediction iii), that other countries should be more affected by the partial Eurex outages than Germany, however, is not true. In fact, we see that the liquidity drops similarly for French bonds, slightly *less* for Spanish bonds and much less for Italian bonds. Recall that this is despite the fact that two German bond futures were still available for trading on Eurex while all French, Italian and Spanish futures were unavailable.

C.3 Non-Trading Days

One last piece of evidence on the interaction between Eurex and MTS comes from different non-trading days between the two platforms. While MTS usually has the same holiday schedule as Eurex, 25 May 2015 was an exception. On that day, Eurex was closed while MTS remained open.[44] Figure A7 shows that MTS was basically inactive that day. There were very few quotes for any bonds and barely any transactions. Of course, this non-trading day does not constitute a true shock, since it was not exogenous and since it could be well anticipated by market participants. But in a sense, this makes our point stronger: even when market participants have enough time to prepare, they are not willing to trade or quote EGBs without an active futures market.

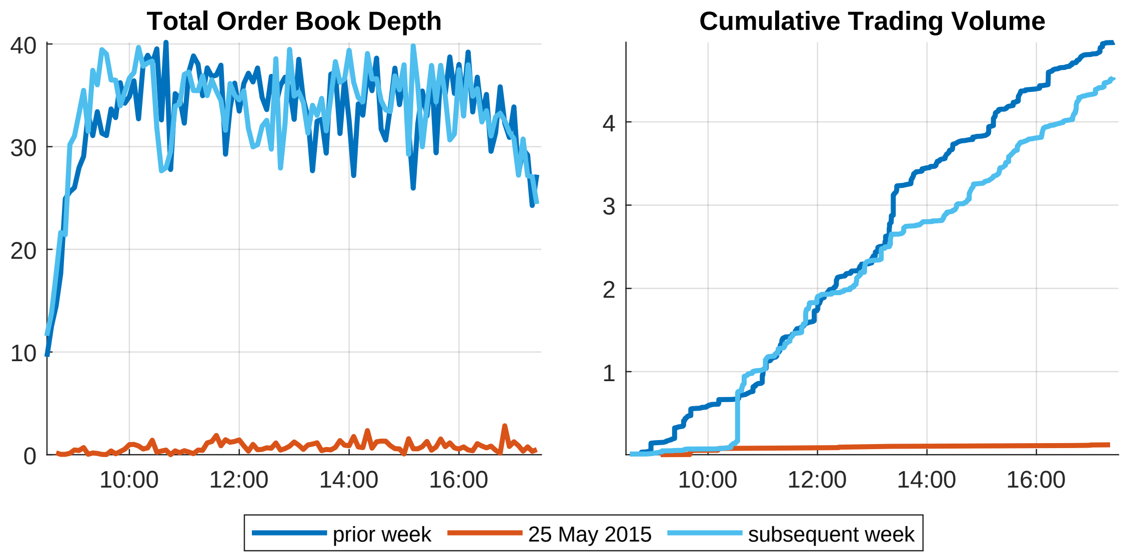


Figure A7: MTS Inactivity on Eurex Holiday. The left panel shows the total order book depth on MTS (in billion €), across all German, French, Italian and Spanish bonds and all market segments, in 5-minute snapshots. The right panel shows the total cumulative trading volume, in billion €. Red lines refer to 25 May 2015 (when Eurex was closed due to a holiday), dark and light blue lines refer to the previous and subsequent week.

[44] Our results suggest an obvious explanation for why the two trading calendars coincide: since MTS is dependent on Eurex, it adopts their trading calendar. Regarding the 25 May 2015 exception, see MTS trading calendar 2015 and Eurex press release. The latter explains that 'Eurex [...] decided, as an exception, not to offer any trading [...] on 25 May 2015. On that day there will be national public holidays in the U.S. ('Memorial Day'), Great Britain ('Late May bank holiday'), Germany, Austria and Switzerland ('Whit Monday'), as well as in South Korea ('Buddha's Birthday'). Therefore, essential markets are not available.'

Appendix D Further Evidence on Eurex Outages

This section provides further evidence on the two Eurex outages in 2020 studied in Section 3 of the main text.

Appendix D.1 confirms that trading volumes on the EGB cash market catch-up after the outages on the futures market are over.

Appendix D.2 provides further micro-level evidence on the trading behavior of different investor types during Eurex outages.

Appendix D.3 shows that long-maturity interest rate swaps are severely affected by outages on Eurex. Short-term swaps, in contrast, continue to provide a reliable indicator of 'fair' short-term rates during the outages.

Appendix D.4 documents that the liquidity dry-up on MTS was widespread and affected virtually all bonds.

Appendix D.5 shows that the separately run local market segments on MTS were somewhat less affected by the outages on Eurex, potentially due to the 'market making obligations' that are enforced on these segments.

Appendix D.6 contains ISIN-level regression results for the effect of Eurex outages on trading volumes and order book liquidity of cash bonds.

Appendix D.7 provides robustness checks regarding the effect of Eurex outages on indicative EGB quotes on the cash market.

D.1 Catch-up in Cash Trading Volumes after Eurex Outages

As mentioned in Section 3.1 of the main text, Table A19 documents a catch-up in trading activity on the EGB cash market after outages on the futures market. Trading volumes are significantly higher roughly two hours after Eurex goes back online.

	(1) All Countries	(2) Germany
Outage Window	-1.46** [0.41]	-1.14* [0.51]
+[0,30) min	-0.38 [0.37]	0.06 [0.74]
+[30,60) min	0.30 [0.51]	0.83 [0.76]
+[60,90) min	-0.00 [0.26]	0.73 [0.81]
+[90,120) min	0.21 [0.37]	0.87** [0.24]
+[120,150) min	0.81*** [0.20]	1.99** [0.54]
FE Day	✓	✓
FE Time	✓	✓
FE Country	✓	
Observations	360	90
Adjusted R^2	0.457	0.483

Table A19: Catch-up in Cash Trading Volumes after Eurex Outages. The dependent variable is the log of the transaction volume in German, French, Italian and Spanish bonds in 30-minute intervals, analogous to Equation 1.

D.2 Micro-Level Evidence

The following sections expands on the results presented in Section 4.3-4.6 of the main text.

D.2.1 Reduced-trade-size-channel

Recall that (i) outages cause a significant decrease in transaction sizes (see Table 3) and (ii) smaller transactions become particularly mispriced during outages (see Table 5). Does this reduced-trade-size-channel drive the mispricing across venues and segments shown in Table 6? To find out, Table A20 replicates the table adding an interaction term between outages and transaction volumes. By controlling for trade sizes, we are effectively blocking part of the causal effect of outages on mispricing.

Nonetheless, model (1) shows that bilateral OTC trades remain significantly more mispriced. In contrast, the estimated coefficients for electronic platforms and regular stock exchanges are cut in half and lose statistical significance. Model (2) shows that the differential effects across investor segments are also partly driven by the transaction size effect. The marginal increase in pricing errors of client-to-client trades is only half as large when controlling for the across-the-board higher mispricing of small trades. In model (3), lastly, including the outage-volume interaction term produces a rather uniform increase in pricing errors, regardless of how many counterparties are usually active on Eurex.

	(1) Venue	(2) Segment	(3) Eurex
Outage × OTC bilateral	1.36*** [0.17]		
Outage × OTC via IDB	0.27 [0.27]		
Outage × OTC via SI	0.29 [0.22]		
Outage × electronic platforms	0.50* [0.24]		
Outage × regular exchange	2.06 [1.37]		
Outage × log(Volume)	-0.59*** [0.07]	-0.67*** [0.01]	-0.74*** [0.03]
Outage × C2C		1.56*** [0.21]	
Outage × D2C		0.38* [0.16]	
Outage × D2D		0.64 [0.40]	
Outage × none active			0.69*** [0.10]
Outage × one active			0.72*** [0.13]
Outage × both active			0.61** [0.18]
FE Minute	✓	✓	✓
FE ISIN	✓	✓	✓
Observations	3016	3214	3070
Adjusted R^2	0.210	0.228	0.225

Table A20: Effect of Eurex Outages on Pricing Errors across Venues, Investor Segments, and depending on Investor's Eurex Activity. This table replicates Table 6 from the main text, adding an interaction term between the outage dummy and transaction volumes.

D.2.2 Investor Type Results

Table A21 reproduces Table 7 from the main test, but differentiating buys from sells. ICPFs and households incur most of their losses when selling bonds during the outage. Dealers, in contrast, both buy and sell profitably. Due to the approximate halving of the sample size, however, many coefficients lose their statistical significance.

Table A22 reproduces some transaction-level results in a balanced panel analysis, to ensure that they are not driven by compositional effects. In particular, we aggregate the trading volume and our profit measure to a 30-minute frequency at the investor-sector-level, imputing zeros for

	mispricing		markup		profit	
	(1) Buy	(2) Sell	(3) Buy	(4) Sell	(5) Buy	(6) Sell
Outage × Bank Dealer	0.37	0.80***	0.05	0.24	2.30	2.50
	[0.24]	[0.19]	[0.62]	[0.28]	[2.92]	[3.20]
Outage × Bank Non-Dealer	2.64***	1.19*	1.07*	-0.09	-0.32	-3.27
	[0.57]	[0.51]	[0.44]	[0.52]	[2.97]	[4.10]
Outage × NBFI	1.96*	0.62**	0.54	0.48	1.30	0.56
	[0.97]	[0.24]	[0.57]	[0.89]	[5.10]	[4.67]
Outage × Investment Fund	0.61***	0.22	-0.58	-0.71**	-3.17	-3.77**
	[0.11]	[0.29]	[0.38]	[0.23]	[2.17]	[1.23]
Outage × Hedge Fund	0.40	5.08***	0.28	5.78***	2.05	1.88*
	[0.79]	[0.22]	[0.35]	[0.24]	[2.97]	[0.88]
Outage × ICPF	0.30	0.27	-0.34	0.13	-2.01	-6.57*
	[0.37]	[0.57]	[0.42]	[0.39]	[2.19]	[3.17]
Outage × NFC	2.30	0.76	-1.58	3.04***	-6.08	13.83***
	[2.05]	[0.67]	[2.56]	[0.46]	[4.15]	[2.61]
Outage × Official	0.01	0.57	0.11	-0.65**	-3.09	-3.83
	[0.16]	[0.44]	[0.52]	[0.20]	[3.38]	[2.80]
Outage × Household	4.18*	4.85***	-2.62**	-5.40***	-1.07	-4.92**
	[1.66]	[0.85]	[0.99]	[0.94]	[1.45]	[1.72]
FE Minute	✓	✓	✓	✓	✓	✓
FE ISIN	✓	✓	✓	✓	✓	✓
Observations	3036	3047	2345	2356	2345	2356
Adjusted R^2	0.154	0.186	0.155	0.240	0.238	0.256

Table A21: Effect of Eurex Outages on Absolute and Net Pricing Errors of Buys and Sells across Investor Types. This table reproduces Table 7, but differentiating buys from sells.

periods with no trades. Column (1) shows that almost all investor types, except households, reduce their trading volumes. In columns (2) and (3), we use different transformations of our profit measure as the dependent variable. We see that dealer banks' trading profits rise significantly, at the cost of investment funds, ICPFs and households.

Table A23 breaks down the trading volume reactions into buys and sells. We see a differential effect only for investment funds, who reduce their buying but not their selling activity, and for ICPFs, who do the exact opposite. Dealers and other banks, in contrast, reduce their buying and selling volumes equally.

	Volume	Profit	
	(1) log(x+1)	(2) sign(x)*log(abs(x)+1)	(3) asinh(x)
Outage × Bank Dealer	-2.12*** [0.20]	6.87** [2.08]	7.37** [2.23]
Outage × Bank Non-Dealer	-1.92*** [0.22]	-6.54** [1.74]	-7.15** [1.88]
Outage × NBFI	-2.19*** [0.33]	0.67 [1.21]	0.72 [1.30]
Outage × Investment Fund	-1.72*** [0.41]	-4.80 [3.58]	-5.19 [3.87]
Outage × Hedge Fund	-3.25*** [0.80]	-3.53 [2.46]	-3.74 [2.64]
Outage × ICPF	-3.36 [1.83]	-3.10** [0.77]	-3.39*** [0.84]
Outage × NFC	-3.07 [3.54]	0.26 [0.48]	0.39 [0.55]
Outage × Official	-10.41*** [1.37]	-1.23 [1.85]	-1.20 [1.99]
Outage × Household	-0.11 [0.61]	-1.74*** [0.27]	-1.84*** [0.32]
Outage × unknown	-3.49*** [0.25]	-0.06 [0.75]	-0.02 [0.82]
FE Minute	✓	✓	✓
Observations	420	420	420
Adjusted R^2	0.536	0.048	0.050

Table A22: Effect of Eurex Outages on Total Trading Volumes and 'Profits' across Investor Types. Trading profits or losses are defined as the 'mispriced trading volume' (difference between transaction price from fair price in percent, multiplied by transaction volume), at a 30-minute frequency. This leads to $10 \times 42 = 420$ observations (10 investor sectors and 42 time periods, 14 during outages and 28 during non-outages). Since the profit measure can be non-positive, and since we are interested in the relative change in profits during outages, we convert profits into 'log of absolute values plus one' in column (2) and use the inverse hyperbolic sine transformation in column (3). Positive coefficients imply that outages cause trading 'profits', negative values imply 'losses'. For brevity, the table shows results only for the outage dummy interaction terms.

	(1) Buy	(2) Sell	(3) Difference
Outage × Bank Dealer	-2.11*** [0.20]	-2.07*** [0.20]	-0.04 [0.11]
Outage × Bank Non-Dealer	-2.16*** [0.28]	-1.78*** [0.11]	-0.39 [0.34]
Outage × NBFI	-2.08*** [0.30]	-0.39 [1.06]	-1.69 [1.02]
Outage × Investment Fund	-6.08* [2.51]	-0.50 [0.39]	-5.57* [2.36]
Outage × Hedge Fund	-4.89*** [0.43]	-6.01*** [1.37]	1.13 [1.75]
Outage × ICPF	-1.40 [2.09]	-5.18** [1.32]	3.77* [1.55]
Outage × NFC	-1.47 [3.40]	-1.82 [1.80]	0.36 [1.74]
Outage × Official	-6.89** [1.99]	-12.00*** [1.31]	5.11 [2.73]
Outage × Household	-1.25 [0.89]	0.05 [1.46]	-1.31 [2.21]
Outage × unknown	-3.35*** [0.23]	-4.05*** [0.32]	0.70 [0.55]
FE Minute	✓	✓	✓
Observations	420	420	420
Adjusted R^2	0.466	0.577	0.041

Table A23: Effect of Eurex Outages on Trading Volumes across Investor Types. The dependent variable is the log of the trading volume plus one at a 30-minute frequency. For brevity, the table shows results only for the outage dummy interaction terms.

D.2.3 Dealer Hedging Behavior

Table A24 shows that the different hedging strategies across bond market dealers are barely correlated with other important characteristics. Neither the connectedness, the centrality, nor the size of the dealer reliably predicts how much of its cash market duration risk she offsets on the futures market. In a kitchen sink regression, the only statistically significant relationship is that more connected dealers use bond futures slightly more to hedge their inventory risk.

	(1)	(2)	(3)	(4)	(5)
# Connections	0.40				3.68**
	[1.11]				[1.70]
ln(Centrality)		-2.87			13.23
		[2.34]			[19.56]
ln(Yearly # Trades)			-1.84		2.75
			[2.55]		[5.73]
ln(Yearly Trading Volume)				-2.95	-23.65
				[2.23]	[18.78]
Observations	31	31	31	31	31
Adjusted R^2	-0.030	0.016	-0.016	0.024	0.129

Table A24: Relation between Dealers' Hedging Intensity and other Characteristics. The dependent variable is the dealer-level β coefficient from Equation 5, which measures how much of the cash market duration risk the dealer offsets via bond futures. See Table 9 for details. # Connections refers to the number of different dealers each dealer has traded with and Centrality is the volume-weighted eigenvector centrality, based on all trades in 2020. As a proxy for size, we use the number of trades and total trading volume of each dealer in 2020. See Section 4.6 for details.

Table A25 replicates Table 10 from the main text for dealer-to-dealer transactions. Dealers in the 'intense hedging' group reduce their trading volumes and increase their markups the most.

Table A26 lastly, confirms that the results from Table 10 are virtually unchanged when we include dealer inventory as an additional explanatory variable. For each dealer, we compute the net trading volume in 1-10y German Bunds from the start of the prior trading day until the intraday time of the respective outage.[45] Since the inventory can be positive or negative, we use its inverse hyperbolic sine as a regressor. The results show that dealers with larger inventories caused more mispricing and traded less profitably.

D.2.4 Network Results

Table A27 replicates Table 11 using additional explanatory variables. We find that during outages, trades are more beneficial for the client if it is the first trade with that particular dealer. This appears to contradict the value of established dealer-client relationships, but it is driven by a selection effect: during outages, clients are more likely to accept advantageous quotes by new dealers on electronic trading platforms (in line with Table A29 below). Another important characteristic is whether a client is active on the futures market at all. Trades by these clients are much more profitable (less unprofitable). This suggests that Eurex activity can serve as another proxy for informational advantages. In our particular application, clients that are usually active on Eurex are much more likely to be aware of the Eurex outages, and adjust their trading on the cash market accordingly.

[45]Since the first outage on 14 April 2020 occurred on the Tuesday following the Easter holidays, we compute the net trading volume from the prior Thursday till 9:25 a.m. on Tuesday. For all other outage and control days, the previous day was a trading day.

	(1) volume	(2) mispricing	(3) markup	(4) profit
Outage × Dealer not hedging	-3.34 [2.63]	0.59* [0.24]	0.03 [0.09]	-0.58 [0.63]
Outage × Dealer moderately hedging	-0.37 [0.59]	0.41 [0.21]	-0.10 [0.06]	-0.70 [0.71]
Outage × Dealer intensely hedging	-7.23* [2.82]	0.25 [0.19]	0.78*** [0.12]	5.74 [3.71]
FE Minute	✓	✓	✓	✓
FE ISIN		✓	✓	✓
FE Client Sector		✓	✓	✓
Observations	162	1202	1202	1202
Adjusted R^2	0.390	0.177	-0.084	-0.086

Table A25: Effect of Eurex Outages on D2D Trades across Dealer Groups. See Table 10 for details.

	(1) mispricing	(2) markup	(3) profit
Outage × Dealer not hedging	0.32 [0.27]	-0.29 [0.60]	-0.51 [4.39]
Outage × Dealer moderately hedging	0.84*** [0.16]	0.31** [0.10]	3.20* [1.32]
Outage × Dealer intensely hedging	0.32 [0.21]	0.21 [0.35]	1.49 [2.65]
Outage × asinh(Inventory)	0.02*** [0.00]	-0.01 [0.01]	-0.10* [0.04]
FE Minute	✓	✓	✓
FE ISIN	✓	✓	✓
FE Client Sector	✓	✓	✓
Observations	1877	1877	1877
Adjusted R^2	0.074	0.032	0.037

Table A26: Effect of Eurex Outages on D2C Trades across Dealer Groups. This table replicates Table 10 from the main text, adding dealer inventory as an additional explanatory variable.

Table A28 employs network proxies to explain the trading behavior on the dealer-to-dealer and client-to-client segments during Eurex outages. None of the network characteristics are predictive on the D2D segment, in line with the idea that information asymmetries are much lower across dealers, and in line with the fact that D2D trades do not become significantly more mispriced during outages. For C2C trades, lastly, we find that more central investors trade more profitably during the outage. Somewhat puzzlingly, however, better connected clients, i.e. those with more dealer connections, trade significantly *less* profitably.

	(1) mispricing	(2) markup	(3) profit
Outage	-0.42 [0.24]	-1.60*** [0.17]	-4.12 [8.88]
Outage × # Connections	-0.04 [0.02]	0.00 [0.02]	0.19** [0.05]
Outage × Relationship w/ Dealer	-1.47* [0.63]	0.35 [0.74]	4.21* [1.88]
Outage × ln(Dealer Centrality)	-0.26*** [0.06]	-0.18 [0.19]	0.75 [0.61]
Outage × Dealer moderately hedging	0.79** [0.20]	0.08 [0.13]	-3.22 [4.70]
Outage × Dealer intensely hedging	0.70* [0.28]	0.19 [0.34]	-1.51 [5.20]
Outage × New Relationship	-0.02 [0.20]	0.17 [0.32]	4.16** [1.31]
Outage × Eurex-Active	0.64 [0.43]	1.02 [0.59]	4.92** [1.79]
FE Minute	✓	✓	✓
FE ISIN	✓	✓	✓
FE Sector	✓	✓	✓
Observations	1662	1662	1662
Adjusted R^2	0.129	0.046	0.039

Table A27: Role of Dealer-Client Network Characteristics during Outages. # Connections refers to the number of different dealers a client has traded with. Dealer Relationship measures the fraction of buying/selling volume of each client-dealer pair as a share of the total volume of each client. Dealer Centrality is the volume-weighted eigenvector centrality of the dealer involved in the transaction. The dependent variables are calculated from the client perspective. The sample includes all D2C transactions during the two outage and four non-outage control windows. We drop trades by households, since the various network measures cannot be computed, and trades on MTS and regular exchanges, as these occur anonymously in a CLOB.

D.2.5 New Trade Pairs

As mentioned in Section 4.6 of the main text, Table A29 shows that outages on Eurex cause a significant increase in new buyer-seller pairs. The likelihood that a given trade is the first between that particular investor pair rises by 2 and 8 percentage points in the C2C and D2C segment, respectively. These number might appear small, but when compared to the low baseline probabilities, they imply a 60% and 160% increase in new trade pair formations, respectively. Intuitively, column (2) shows that these new trade pairs are formed entirely on electronic trading platforms, not on the OTC market. The 10% increase corresponds to more than a doubling in the likelihood that a given trade on an electronic trading platform is the first between that pair of investors. That there is no comparable increase in new trade pairs on the OTC market is unsurprising, given the higher search frictions and the rather short duration of the outages.

(a) D2D Trades

	(1) mispricing	(2) markup	(3) profit
Outage × # Connections	-0.01 [0.02]	0.07 [0.04]	0.69 [0.45]
Outage × Dealer Relationship	-0.20 [1.23]	-2.96 [2.59]	2.18 [1.41]
Outage × ln(Centrality)	0.07 [0.14]	0.09 [0.20]	-1.28 [0.82]
FE Minute	✓	✓	✓
FE ISIN	✓	✓	✓
Observations	1014	1014	1014
Adjusted R^2	0.161	-0.098	-0.104

(b) C2C Trades

	(1) mispricing	(2) markup	(3) profit
Outage × # Connections	0.04 [0.06]	-0.23* [0.09]	-0.32*** [0.06]
Outage × ln(Centrality)	-0.45* [0.18]	0.15 [0.28]	0.51** [0.13]
Outage × Eurex-Active	-0.18 [3.16]	9.33* [4.55]	11.12 [5.70]
FE Minute	✓	✓	✓
FE ISIN	✓	✓	✓
FE Sector	✓	✓	✓
Observations	959	959	959
Adjusted R^2	0.358	0.186	-0.022

Table A28: Role of Network Characteristics for C2C and D2D Trades during Outages. # Connections refers to the number of different dealers an investor has traded with. Centrality is the volume-weighted eigenvector centrality of the investor. In panel (a), Dealer Relationship measures the fraction of buying/selling volume of that particular dealer pair as a share of the total volume of each dealer. In panel (b), Eurex Active is a dummy equal to one if the client has traded Bund futures on Eurex in 2020. The samples include all transactions during the two outage and four non-outage control windows. On the D2D segment, we drop trades on MTS and regular exchanges, as these occur anonymously in a CLOB. On the C2C segment, we drop trades by households, since the various network measures cannot be computed.

	(1) Venue	(2) Segment
Outage × C2C	0.02* [0.01]	
Outage × D2C	0.08** [0.03]	
Outage × OTC bilateral		0.06 [0.03]
Outage × OTC via SI		0.03 [0.02]
Outage × electronic platforms		0.10*** [0.02]
FE Minute	✓	✓
FE ISIN	✓	✓
Observations	2469	2231
Adjusted R^2	0.027	0.031

Table A29: Effect of Eurex Outages on the Formation of New Buyer-Seller Pairs. The dependent variable equals one if a trade is the first between a given investor pair and is zero otherwise (using all Bund trades in 2020). For brevity, the table shows results only for the outage dummy interaction terms. The sample covers all Bund trades, except D2D trades (due to the lack of new buyer-seller pairs) and trades on regular exchanges, as these occur anonymously in a CLOB.

D.3 Effect on Swap Market

Interest rate swaps are a key segment of the fixed-income market. These swaps exchange fixed-rate interest payments for floating-rate interest payments over a specified period.[46] How does the swap market react to Eurex outages?

Figure A8 shows that quotes on €STR interest rate swaps become stale the moment bond futures become unavailable, particularly at longer maturities.[47]

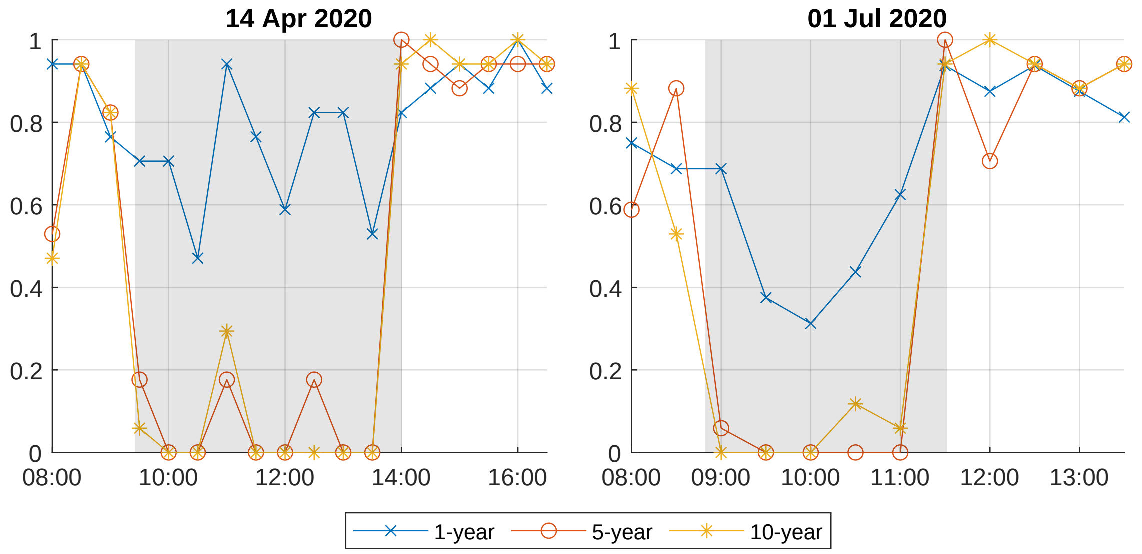


Figure A8: Quote Update Frequency for €STR Swap Rates on Bloomberg. We approximate the number of new quotes as the number of tick-by-tick price changes. To show all series on a single scale, we aggregate the number of quote updates in 30-minute windows and normalize them to a 0-1 range for each maturity. All series refer to overnight index swaps of different maturity based on the euro short-term rate (€STR)

Figure A9 confirms that bid-ask spreads for longer-dated swaps spike during outages, if quotes are available at all.

Lastly, we confirm these results with executable quotes from an interdealer broker. In particular, Compagnie Financière Tradition, a listed company on the Swiss stock exchange, runs the Trad-X platform. This platform is based on a central limit order book, i.e. immediately executable quotes, in contrast to the indicative quotes on Bloomberg. According to their own statements, Trad-X is the market-leading platform for interest rate derivatives and is used by market participants from over 29 countries. For ease of exposition, we focus on the most liquid instrument on Trad-X, namely 10-year/6-month Euro Interbank Offered Rate (Euribor) swaps, which exchange 10-year fixed-rate interest payments for six-month floating-rate interest payments. Figure A10 shows that the Eurex outage led to a complete evaporation of the order book for these swaps. The number of available order book levels declined and spreads widened immediately. After Eurex went back online, the order book recovered within half an hour.

[46]See Dalla Fontana et al. (2019) and Boudiaf, Frieden, and Scheicher (2024) for a detailed anatomy of the euro area interest rate swap market.

[47]Recall that the €STR is closely linked to the ECB's policy rates, and that the ECB provided extensive forward guidance at the time. Between April and July 2020, the €STR rate fluctuated between -.53 and -.56 percent.

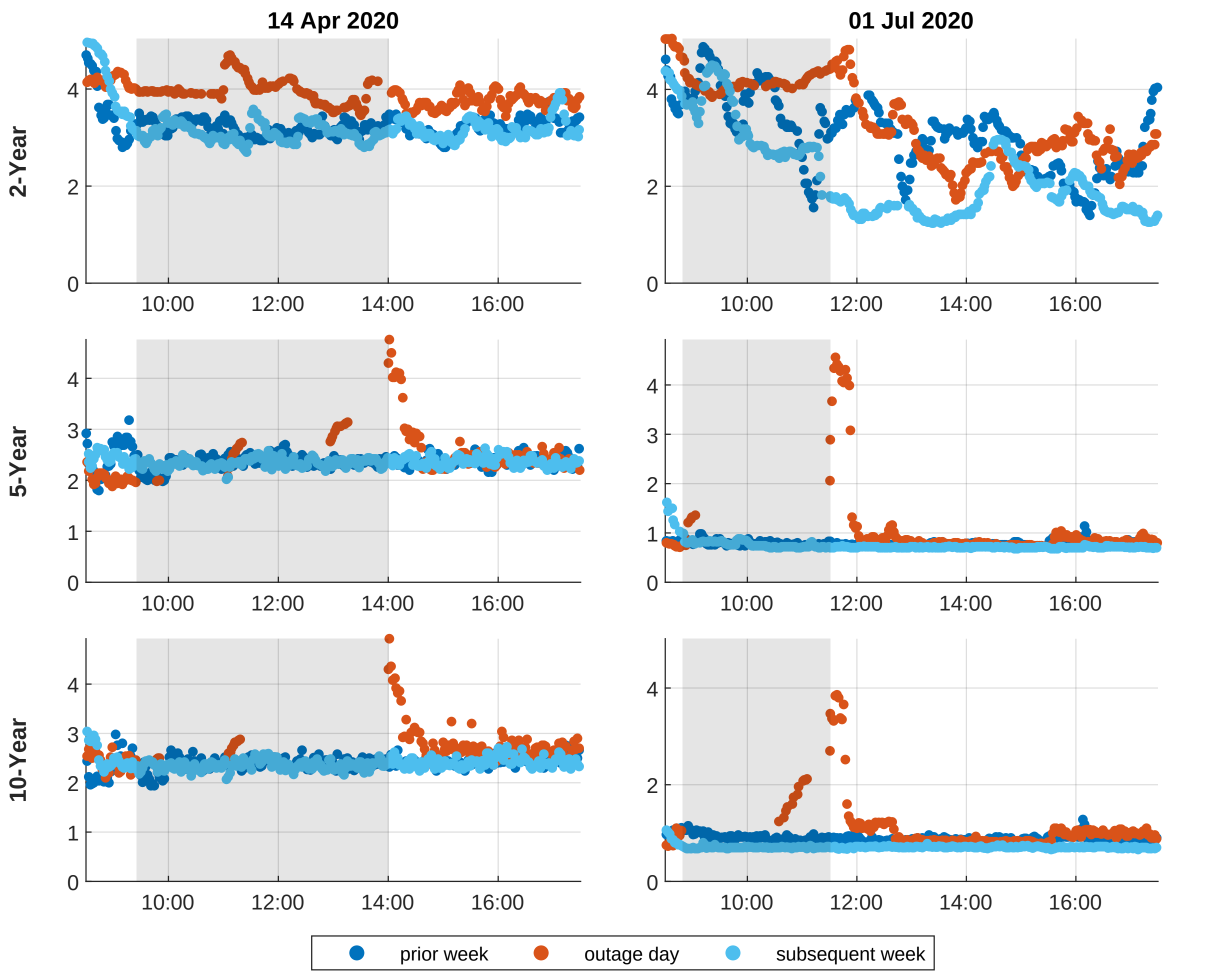


Figure A9: Bid-Ask Spread of €STR Swap Rates on Bloomberg. This figure shows the bid-ask spread (in basis points) for overnight index swaps of different tenors based on the euro short-term rate (€STR). Red lines refer to outage days, dark and light blue lines refer to the previous and subsequent week.

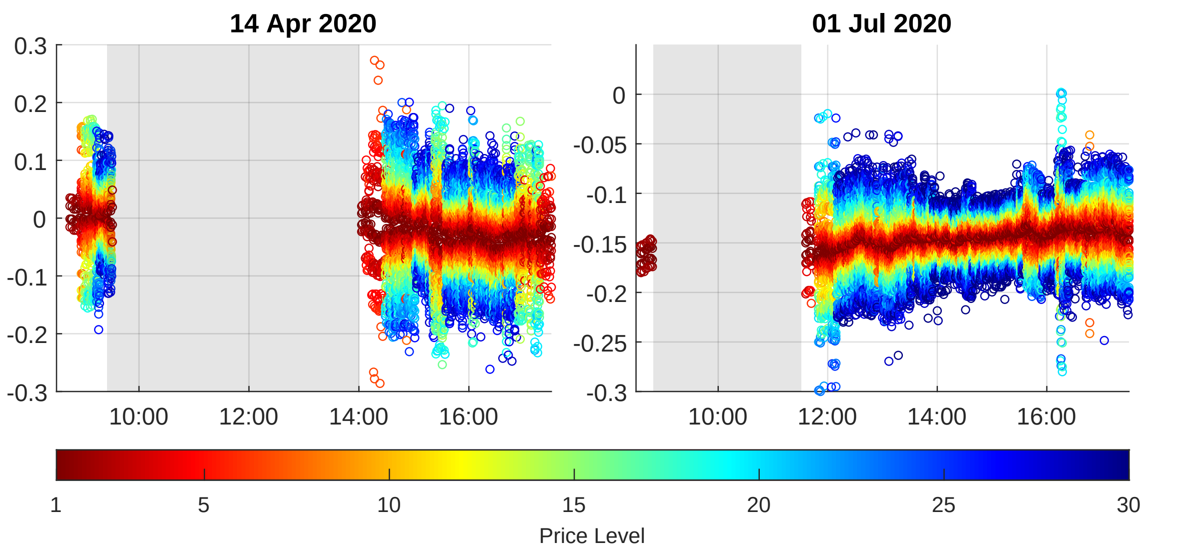


Figure A10: Bid and Ask Quotes for 10y/6m Euribor Swaps on Trad-X. The figure shows bid and ask quotes across different order book levels.

D.4 MTS Liquidity

This section provides robustness checks for the results in Section 3.2.1 in the main text.

Recall that Figure 3 in the main text shows that liquidity in the cheapest-to-deliver bonds underlying 10-year bond future contracts evaporates on MTS when Eurex goes down. Figure A11 replicates this figure at the country-level.

The above results are based on MTS's euro area wide 'EBM' platform (for 'European Bond Market'). In parallel, MTS also runs local bond market platforms (labelled 'GEM' for Germany, 'FRF' for France, 'MTS' for Italy, and 'ESP' for Spain). Figure A12 confirms that liquidity also evaporates on these local market segments.

Next, we confirm that our results are not confined to 10-year CTD bonds either. Our results hold for the entire universe of bonds. Figure A13 documents a sharp decline in liquidity across countries.

In fact, Figure A14 shows that the liquidity evaporates also for other euro area countries, which do not have an own futures market. Figure A15, lastly, looks at non-euro countries whose bonds are traded on MTS. Except for Denmark, whose currency is pegged to the Euro, market liquidity seems unaffected by the outage on Eurex. In a sense, these results serve as a placebo test: the breakdown of MTS was indeed caused by the outage on Eurex, there was no simultaneous independent incident on MTS.

Another insightful exercise is to connect our order book data with the transaction data on MTS. When we focus on 10-year deliverable bonds for instance, i.e. bonds that were deliverable into the 10-year bond future, we only observe a single trade during each outage. Figure A16 zooms in on these two trades. We see that in both cases, quotes were quite stable at first, but then a single trade caused massive quote adjustments. In the case of the French bond on the first outage, spreads widened massively before quotes disappeared entirely. This is consistent with some stale quotes getting 'picked off'.

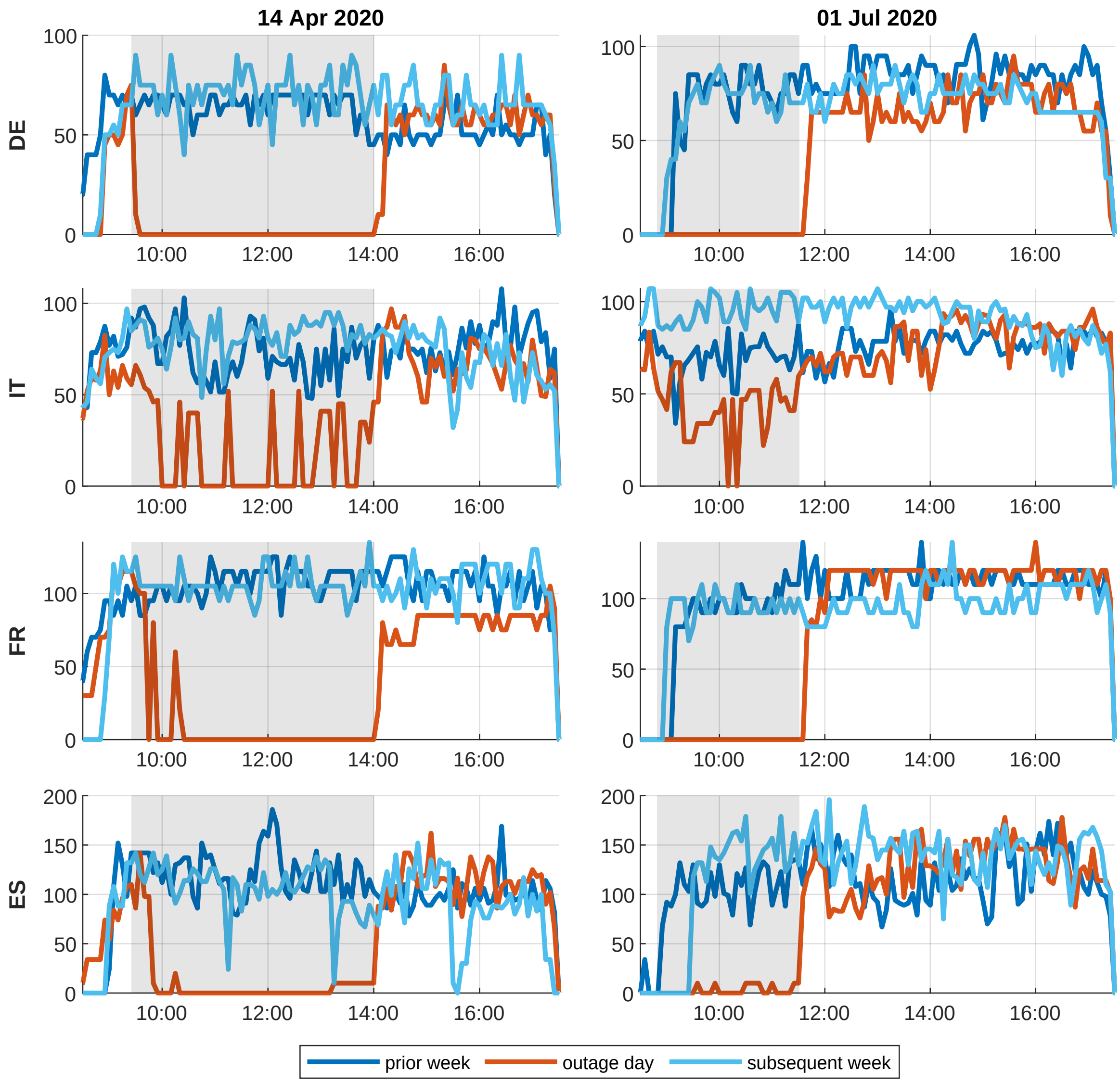


Figure A11: Order Book Depth on MTS. This figure shows the total quoted volume for 10-year CTD bonds (in million €) across all three levels and both sides of the order book, at 5-minute snapshots.

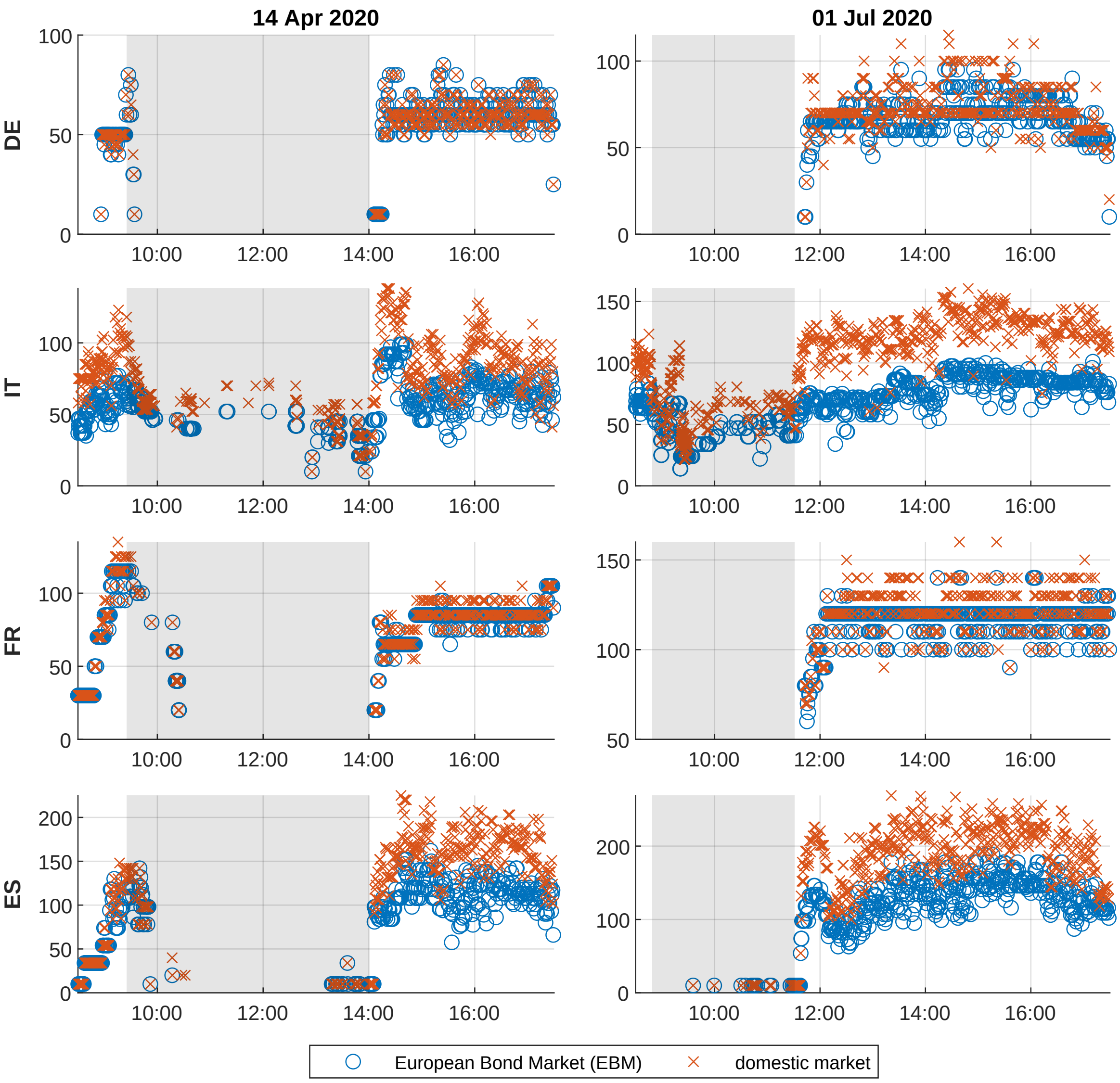


Figure A12: Order Book Depth of CTD bond on different MTS market segments. This figure shows the total quoted volume (in million €) across all three levels and both sides of the order book, for the cheapest-to-deliver bond underlying the 10-year future. Blue circles refer to the 'European Bond Market' segment (as in the main text), red crosses refers to the domestic market segment.

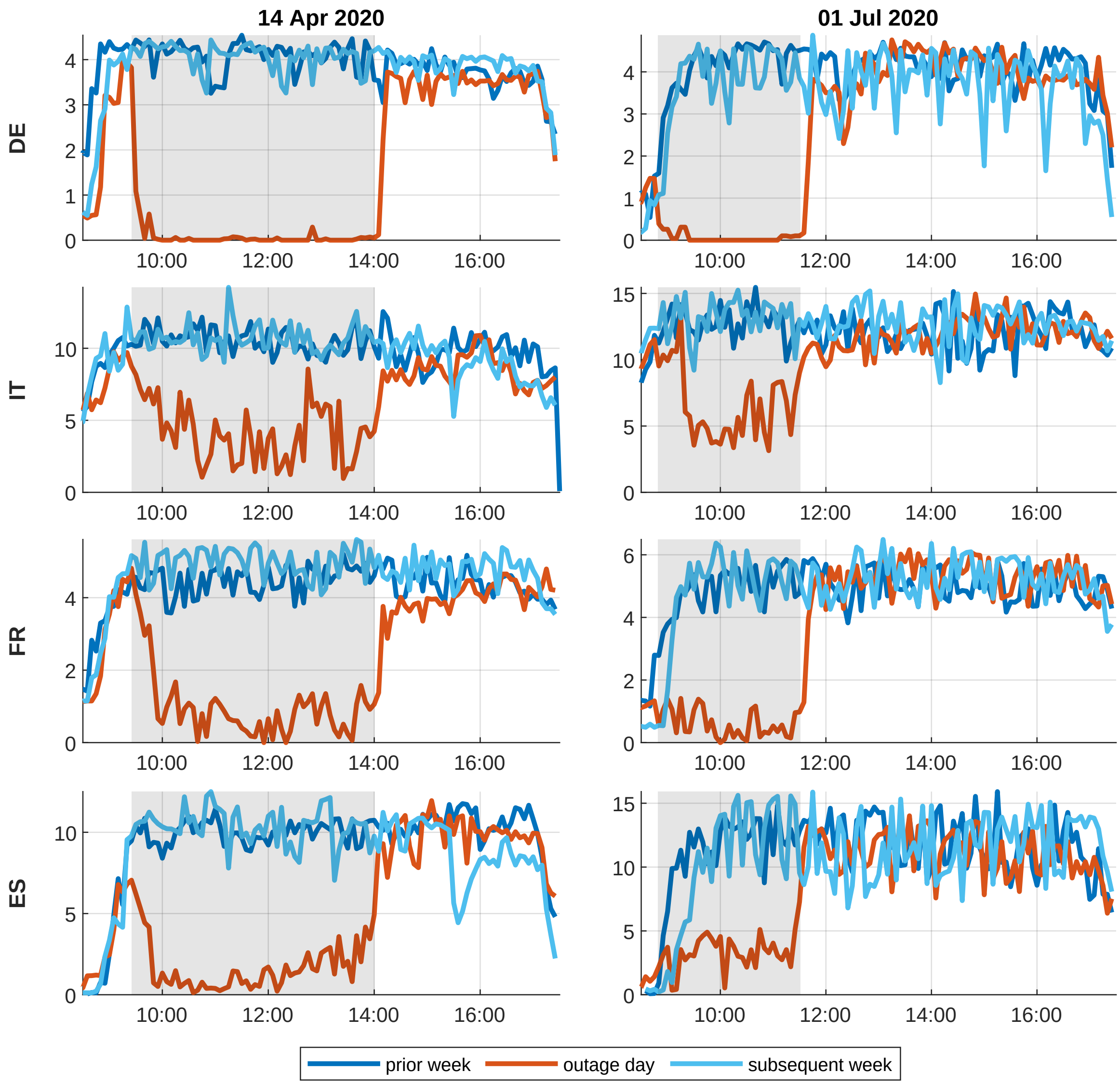


Figure A13: Total Order Book Depth on MTS across Countries. This figure shows the total quoted volume (in billion €) for German, French, Italian and Spanish bonds across all three levels and both sides of the order book, at 5-minute snapshots.

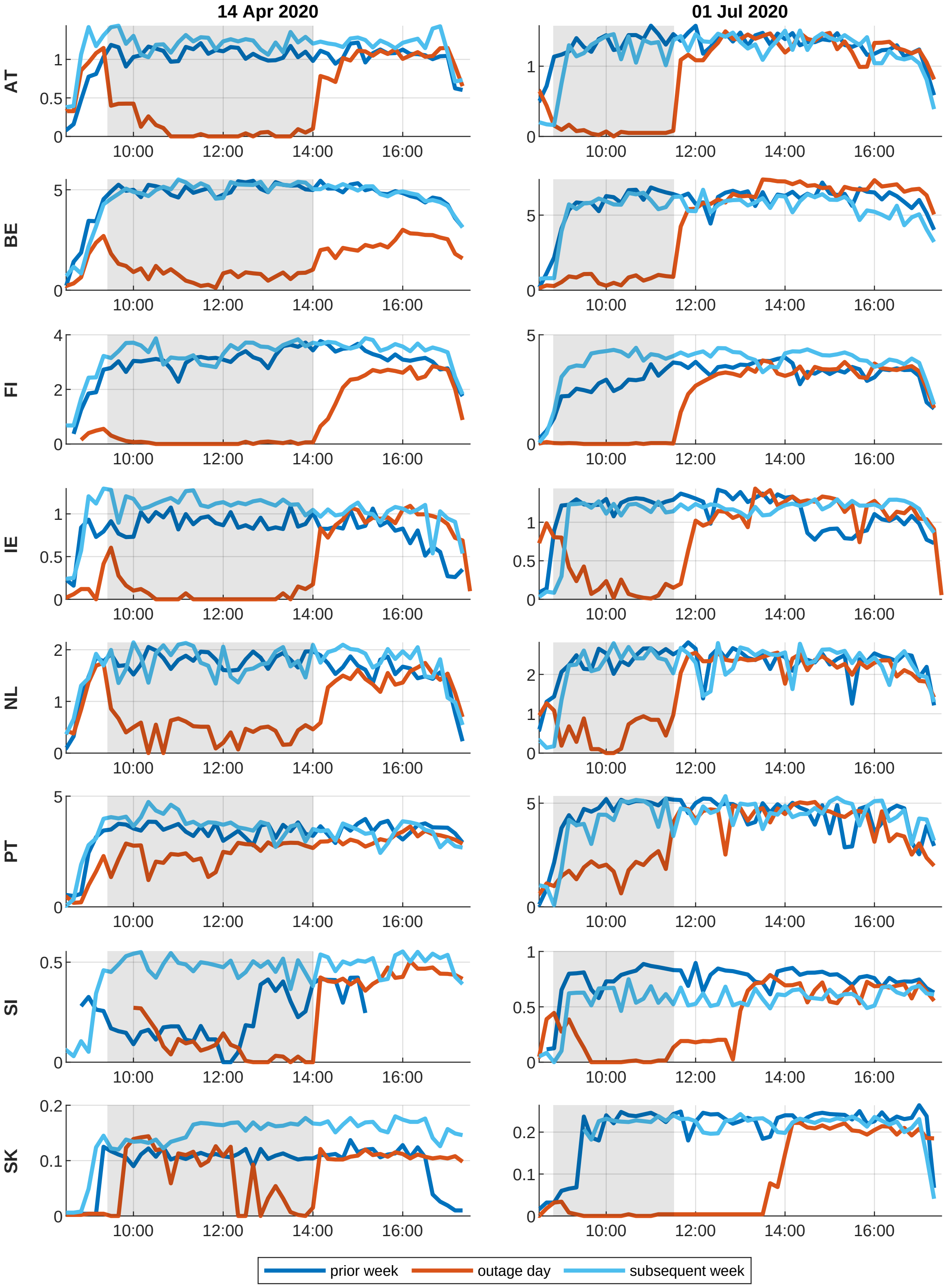


Figure A14: Total Order Book Depth on MTS for Other Euro Area Countries. This figure shows the total quoted volume (in billion €), across all three levels and both sides of the order book, at 10-minute snapshots, for other euro area member states whose bonds are traded on MTS.

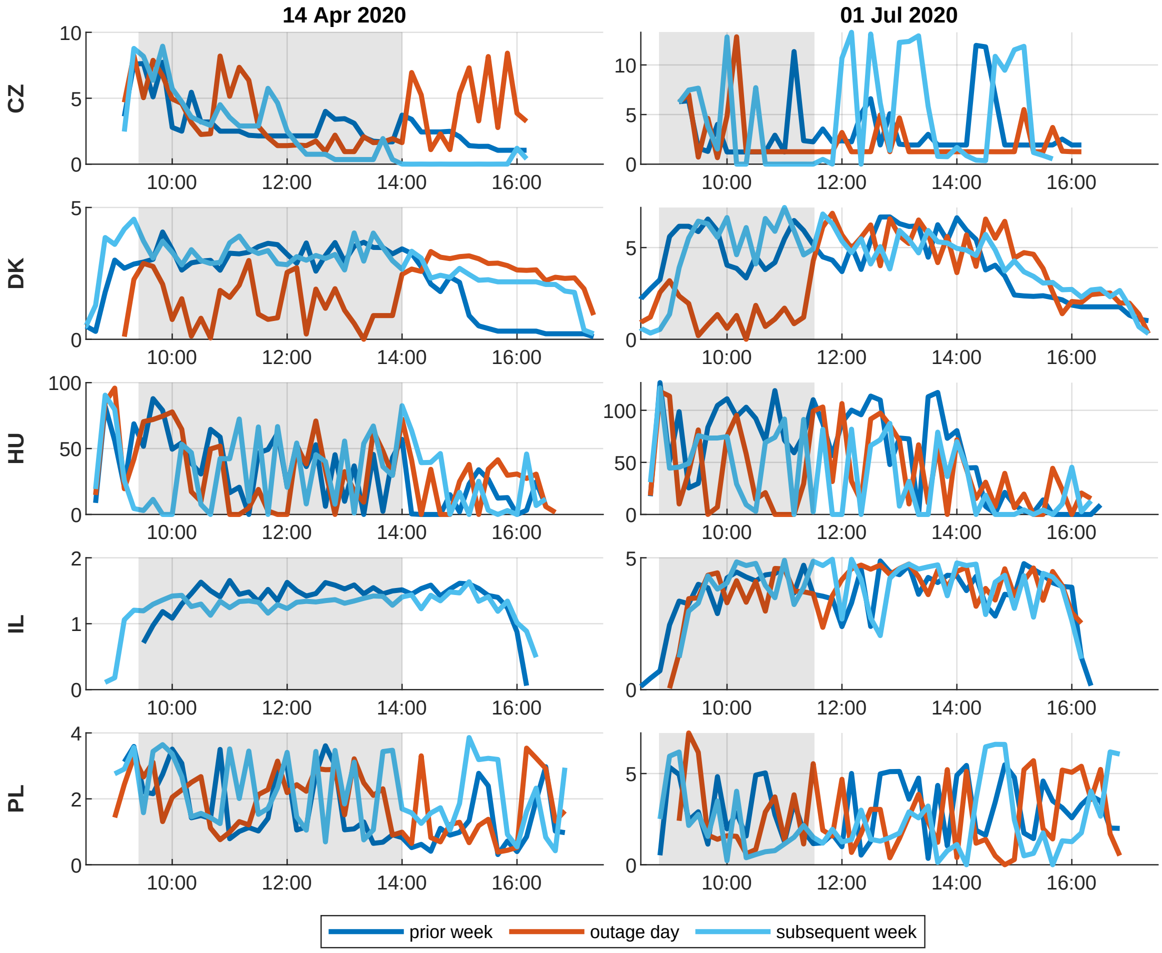


Figure A15: Total Order Book Depth on MTS for Non-Euro Area Countries. This figure shows the total quoted volume (in billion of local currency), across all three levels and both sides of the order book, at 10-minute snapshots, for non-euro countries (CZ for Czech Republic, DK for Denmark, HU for Hungary, IL for Israel, PL for Poland). The lack of liquidity on 14 April 2020 for Israeli bonds was due to a public holiday, not the outage on Eurex.

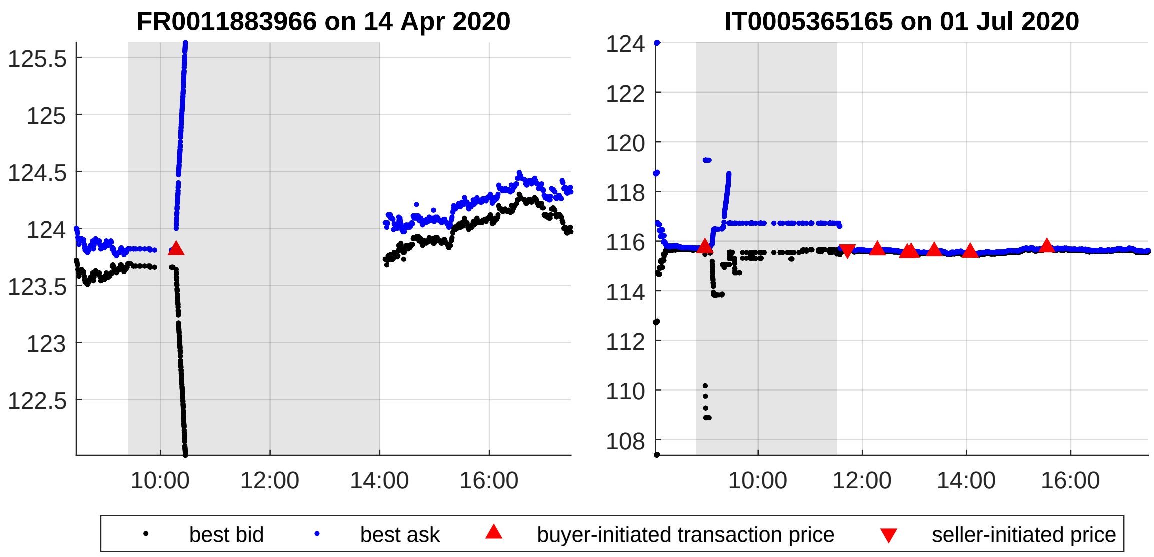


Figure A16: Quotes and Transactions Prices on MTS during Eurex Outage. This figure shows the only two trades in 10-year bonds that were deliverable into a 10-year futures contract.

D.5 MTS Quoting Obligations

A peculiarity on MTS are so-called 'market making commitments'. While MTS's euro area wide 'EBM' market has no such commitments, MTS also runs local bond markets, see previous section. On these local markets, each local issuer, i.e. usually the debt management office, can set obligations and requirements for their own country. For instance, market makers might have to provide bid and ask quotes for specific bonds, sometimes at pre-defined maximum spreads and minimum volumes and for a specified duration, e.g. at least five hours a day or 50% of trading time. See Cheung, Rindi, and De Jong (2005) for a detailed overview of the microstructure of the MTS trading platforms and the MTS website for current rules.

Do these quoting obligations matter? Figure A17 compares the order book depth on the EBM and local markets for each country. We can clearly see liquidity drops on both segments for all countries, but it is hard to eyeball whether the relative decline differed across countries.

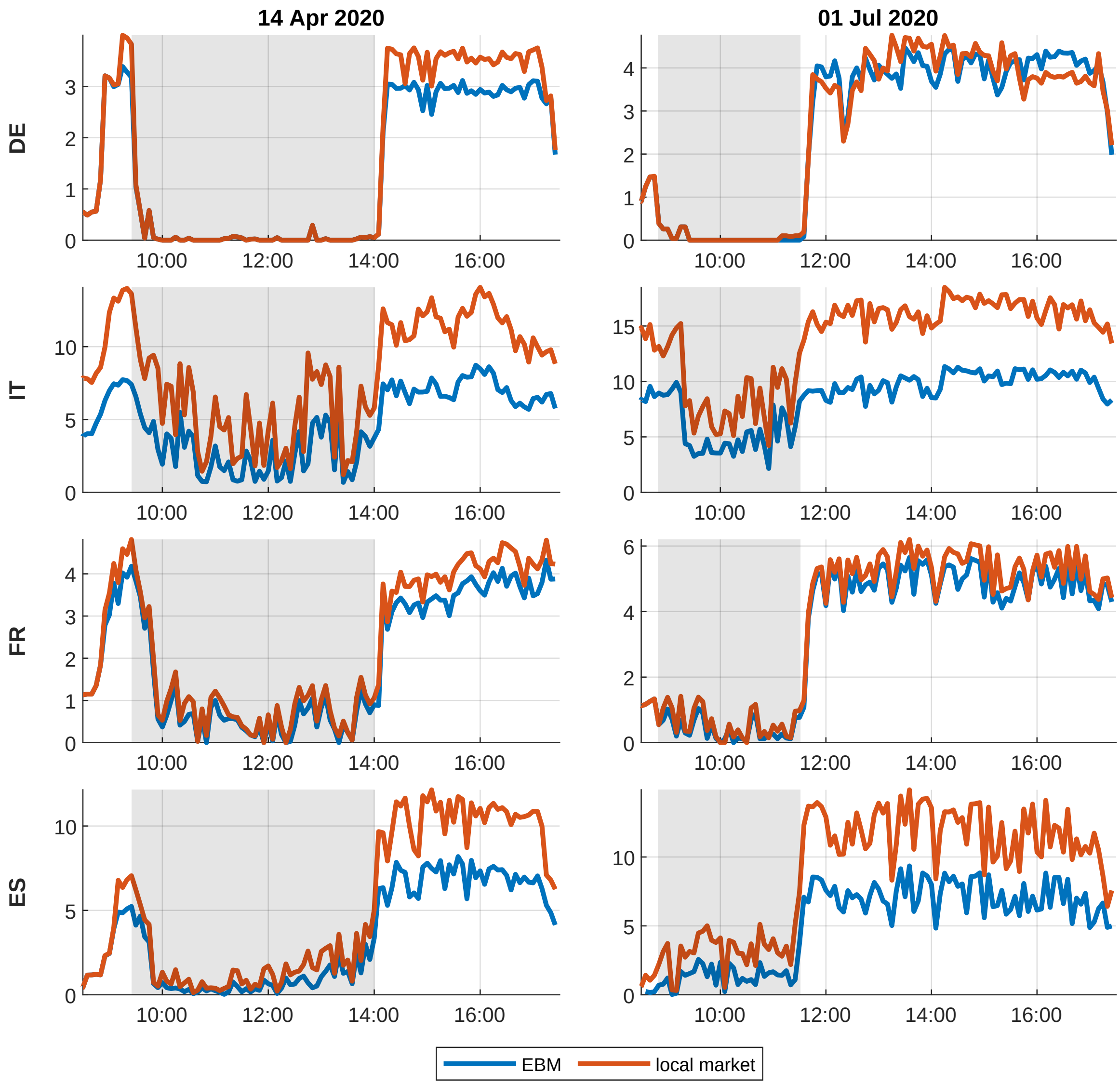


Figure A17: Order Book Depth across different Market Segments on MTS. This figure shows the total quoted volume (in million €) across all three levels and both sides of the order book, at 5-minute snapshots, for all bonds of a given country. Blue lines refer to the 'European Bond Market' segment (as in the main text), red lines refers to the respective domestic market segment.

Hence, Table A30 reports results from another dummy regression, this time run separately for each country, namely:

$$log(1 + OBdepth_{smt}) = \alpha + \beta_1 \times D_t + \beta_2 \times D_t \times local + \gamma \times FE + \epsilon_t \quad \text{(A1)}$$

where $OBdepth_{smt}$ is the order book depth (in €) of all bonds in maturity bucket m at time t, measured at 5-minute snapshots, quoted on market segment s. D_t is a dummy that equals one during the Eurex outages and *local* is a dummy variable that equals one for MTS's local market segment and is zero for the EBM segment. We include six days (the two outage days plus the preceding and subsequent week) and 91 intraday observations per day (5-minute snapshots from 08:30 a.m. to 4:00 p.m.).

	(1) DE	(2) ES	(3) FR	(4) IT
Outage	-17.68*** [0.67]	-10.42** [2.71]	-14.18*** [0.56]	-1.36*** [0.14]
local	0.21** [0.08]	0.55*** [0.05]	0.18* [0.07]	0.48*** [0.01]
Outage × local	0.11 [0.24]	0.47*** [0.09]	-0.03 [0.08]	0.18*** [0.02]
FE Day	✓	✓	✓	✓
FE Time	✓	✓	✓	✓
FE Maturity Bucket	✓	✓	✓	✓
Observations	4368	4368	4368	4368
Adjusted R^2	0.805	0.538	0.647	0.567

Table A30: Differential Effect of Eurex Outages on MTS Market Segments. Each column shows results of a separate regression run at the country-level, see Equation A1. Throughout, the dependent variable is the log of the order book depth of all bonds in four different maturity buckets, for the country mentioned in the column header. We differentiate between the EBM and local market segment.

We see that the order book depth is higher on the local market for all countries, especially so for Italy and Spain. And precisely for these two countries, we see a differential effect during the Eurex outage. The liquidity of Italian and Spanish bonds drops markedly less on the local market segment compared to the EBM market. This is in line with the stricter quoting obligations on the local Italian and Spanish market compared to the German and French market.

Note that these results are analogous to Clark-Joseph, Ye, and Zi (2017), who show that even mild quoting obligations significantly improve liquidity on US stock exchanges.

D.6 Bond-Level Regression Results

D.6.1 Cash Trading Volume

In Section 3.1 in the main text we run dummy regressions at the country/maturity-bucket level. In particular, Table 1 shows that trading volumes drop more for long-term than short-term bonds but similarly for German, French, Italian and Spanish bonds. Here, we go one step further and estimate the following dummy regression at the bond-level:

$$log(1 + Volume_{it}) = \alpha + \beta \times D_t \times BondCharacteristics + \gamma \times FE + \epsilon_{it} \tag{A2}$$

where $Volume_{it}$ is the transaction volume (in €) of a particular bond i at time t (measured in one hour intervals), D_t is again the outage dummy and FE captures fixed effects. What we are interested in is β, i.e. the interaction term between the outage dummy and bond characteristics, which include dummies for CTD bonds (cheapest-to-deliver in any bond future contract), OTR bonds (recently issued 'on-the-run' bonds) and zero coupon bonds. It also includes the remaining time to maturity and the time since issuance for each bond. To avoid compositional effects, we study a fixed set of bonds throughout and use the logarithm of the trading volume plus one as the dependent variable.[48]

	(1)	(2)
Outage	-3.16** [0.89]	-3.65** [1.02]
CTD		2.73*** [0.33]
OTR		1.15** [0.32]
Zero Coupon		-1.36*** [0.13]
log(Years to Maturity)		0.88*** [0.09]
log(Years since Issuance)		-1.15*** [0.08]
Outage × CTD		-1.30* [0.64]
Outage × OTR		-1.46** [0.46]
Outage × Zero Coupon		0.69* [0.34]
Outage × log(Years to Maturity)		0.06 [0.18]
Outage × log(Years since Issuance)		0.31 [0.34]
FE Day	✓	✓
FE Time	✓	✓
FE ISIN	✓	
FE Country		✓
Observations	10752	10752
Adjusted R^2	0.284	0.231

Table A31: Effect of Eurex Outages on Cash Trading Volume at Bond-Level. Each column shows results of a different regression, see Equation A2. Throughout, the dependent variable is the log of the hourly transaction volume in a given bond ISIN.

Table A31 reports the results. Trading volumes drop dramatically when Eurex is offline, see model (1). Model (2) shows that during normal times, CTD bonds are traded more frequently, as are bonds with longer maturity. Older seasoned bonds, by contrast, are traded less frequently. During the Eurex outage, we see a differential effect for OTR bonds, where trading volumes fall particularly sharply and for zero coupon bonds, where trading volumes are comparatively

[48] Appendix A.4 provides details about the selected bonds. We use relatively wide hourly windows for the bond-level regressions to reduce periods with zero trading volume in a given bond.

robust.

D.6.2 MTS Order Book Depth

Similarly, Section 3.2 in the main text contains regression results at the country/maturity-bucket level. In particular, Table 2 shows that the liquidity on MTS drops more for long-term than short-term bonds and more for German, French and Spanish than for Italian bonds. Here, we move to the most granular level and estimate the same type of regression at the individual bond-level:

$$log(1 + OBdepth_{it}) = \alpha + \beta \times D_t \times BondCharacteristics + \gamma \times FE + \epsilon_{it} \tag{A3}$$

where $OBdepth_{it}$ is the order book depth of bond i at time t, measured at 5-minute snapshots, D_t is the outage dummy and FE captures fixed effects. We are interested in β, the interaction term between the outage dummy and bond characteristics. To avoid compositional effects, we again study a fixed set of bonds and use the logarithm of one plus the quoted volumes of bonds as the dependent variable. In particular, we study all 255 bonds that were quoted on MTS out of all the 259 bonds mentioned in Appendix A.4.

Table A32 contains the results. The quoted volume goes to zero for most bonds when Eurex goes offline, see model (1). Model (2) shows that CTD, OTR and zero-coupon bonds are particularly affected. As we have already seen, the longer the remaining maturity of a bond, the more its liquidity drops during Eurex outages. The same is true for the age of a bond, i.e. older bonds are more affected by the outage.

	(1)	(2)
Outage	-10.97*** [0.53]	-6.09*** [1.11]
CTD		0.65** [0.21]
OTR		2.34*** [0.35]
Zero Coupon		0.35 [0.37]
log(Years to Maturity)		1.00*** [0.17]
log(Years since Issuance)		0.68*** [0.11]
Outage × CTD		-1.59*** [0.07]
Outage × OTR		-2.12** [0.79]
Outage × Zero Coupon		-3.33*** [0.58]
Outage × log(Years to Maturity)		-1.90*** [0.25]
Outage × log(Years since Issuance)		-1.49*** [0.23]
FE Day	✓	✓
FE Time	✓	✓
FE ISIN	✓	
FE Country		✓
Observations	139230	139230
Adjusted R^2	0.514	0.446

Table A32: Effect of Eurex Outages on Order Book Depth on MTS at Bond-Level. Each column shows results of a different regression, see Equation A3. Throughout, the dependent variable is the log of the quoted bid and ask volume in a given bond ISIN, at 5-minute snapshots.

D.7 Indicative Quotes

This section reproduces the results presented in Section 3.2.2 of the main text at the country-level. Recall that Figure 4 shows across three different data sources that indicative quotes for EGB cash bonds become stale during the Eurex outage.

Figure A18 confirms that the result holds for Germany, Italy, France, and Spain: the number of quote updates drops dramatically during Eurex outages. Figure A19 plots the bid yield of 10-year bonds quoted for each country. Yields stay virtually constant while Eurex is offline. By all appearances, these prices are stale.

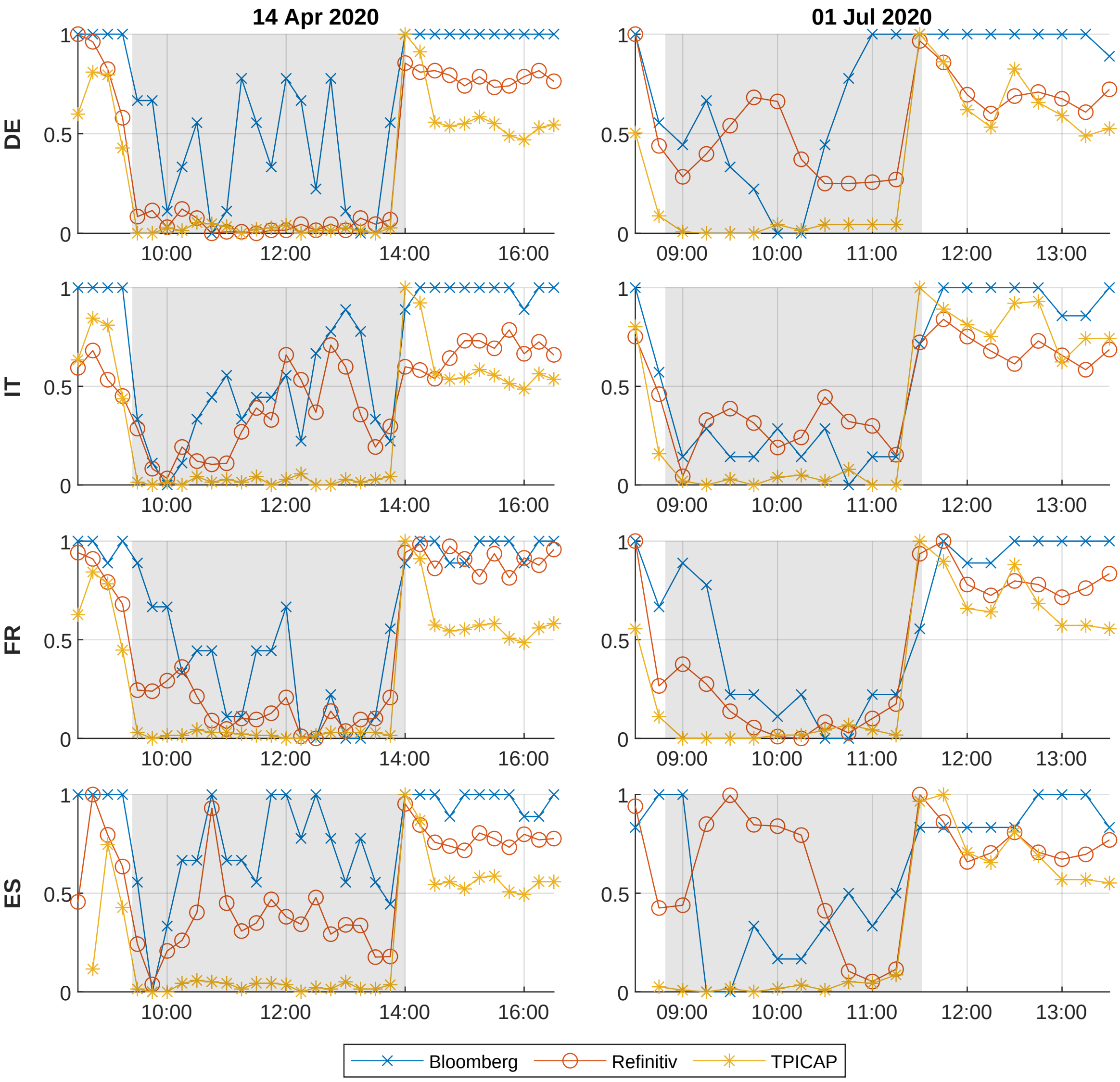


Figure A18: Quote Update Frequency for 10-Year Government Bonds on Different Platforms. Bloomberg and TPICAP data refer to quote updates in the cheapest-to-deliver bond, Refinitiv data to the on-the-run bond. For Bloomberg, we approximate the number of new quotes as the number of tick-by-tick price changes. To show all series on a single scale, we sum the number of quotes updates in 15-minute windows and normalize them to a 0-1 range for each data provider.

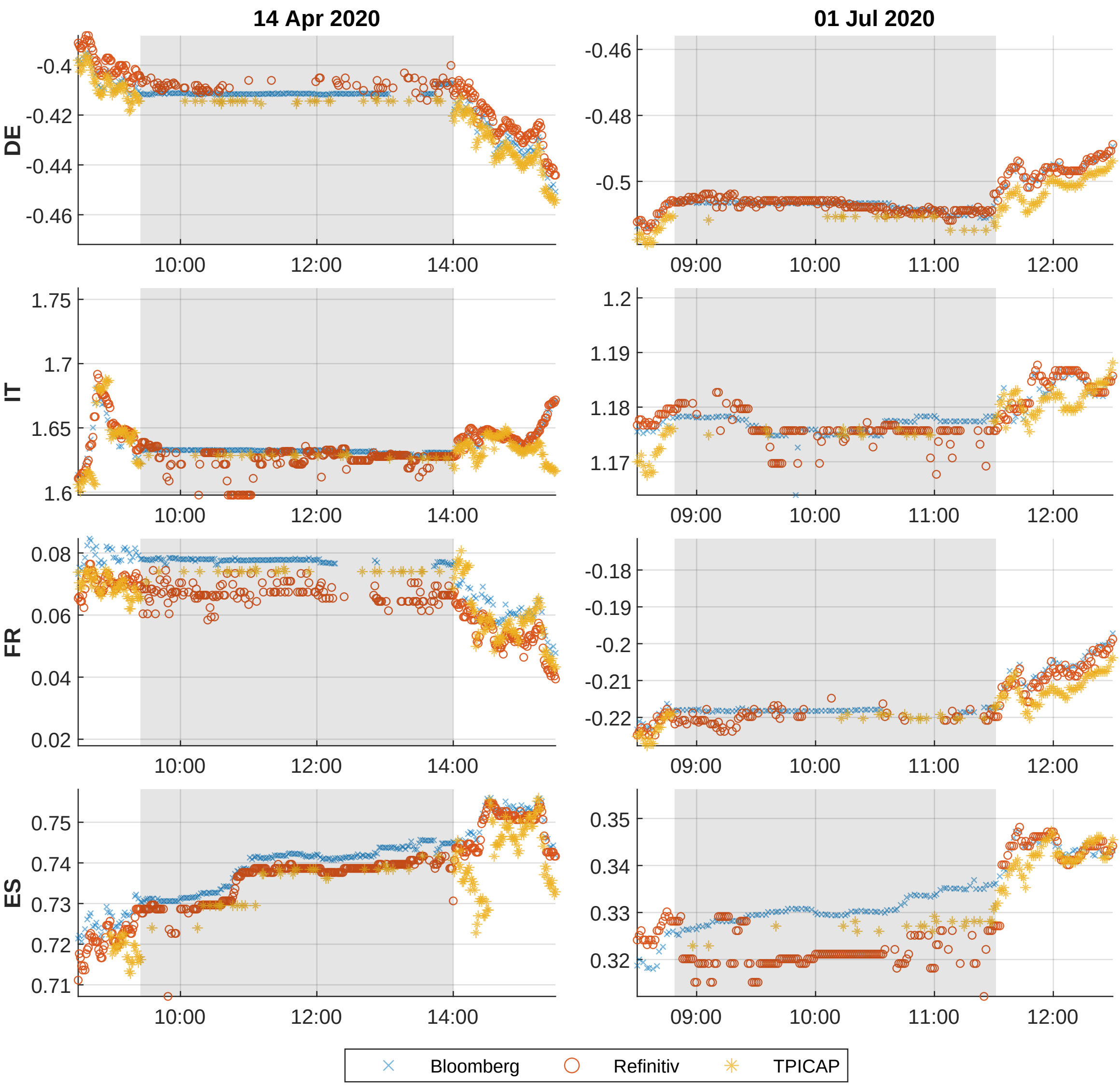


Figure A19: Quoted Bid Yield of 10-Year Government Bonds on Different Platforms. Bloomberg and TPICAP data refer to the cheapest-to-deliver bond, at minutely snapshots. Refinitiv data refers to the on-the-run ('benchmark') bond, at minutely snapshots and as the median value across all available 'pricing contributors'. To show all series on a single scale, we apply a level adjustment to the Refinitiv yield, such that the daily median yield matches the daily median yield of Bloomberg and TPICAP.

Appendix E Further Evidence from Outages on Other Markets

This section provides further evidence on the outages studied in Section 5 of the main text. Recall that Table 13 shows how cash venue outages affect various metrics of market functioning, like trading volumes and return volatility. The results refer to average effects across all four euro area countries we study (for the cash market) or all eight bond futures (for the futures market).

Table A33 instead looks at the effect on aggregate and country-level cash trading volumes. At the aggregate level, only the trading volume decline during the Bloomberg outage is statistically significant. Looking at individual countries, we observe the largest effects for German and French bonds.

Similarly, Table A34 looks at country-level trading volumes on Eurex. We see that the drop in trading volumes is entirely driven by German bond futures. In fact, the reduction in Italian, French and Spanish bond future trading volume is insignificant.

Table A35 zooms in on the most liquid instrument on Eurex, namely 10-year German bond futures. In line with the average effects across all futures, trading activity tends to decline during cash venue outages but most other measures of market functioning are unaffected.

	MTS 12 Jan 2010 8:00-10:35	Bloomberg 17 Apr 2015 9:20-10:10	FWB 27 May 2015 8:00-11:00	MTS 26 Jul 2019 12:30-13:20	Pooled
All Bonds	-0.47	-2.09**	-0.39	-1.05	-0.70**
	[0.27]	[0.24]	[0.44]	[0.62]	[0.25]
Obs.	96	33	111	33	273
DE Bonds	-0.35	-9.13***	0.49	-0.58	-1.10
	[0.90]	[0.67]	[1.30]	[0.30]	[1.09]
IT Bonds	-2.34	-0.64	1.39	-0.97	-0.45
	[1.04]	[0.73]	[1.15]	[0.64]	[0.94]
FR Bonds	-2.00	-8.31*	-1.72	-3.42	-2.82***
	[0.95]	[2.52]	[1.12]	[1.31]	[0.86]
ES Bonds	-0.63	0.30	-1.88	-4.45**	-1.49**
	[0.29]	[1.74]	[1.46]	[0.98]	[0.67]

Table A33: Effect of Cash Venue Outages on Cash Market Trading Volumes. Each column refers to a different outage and regression. Each sample includes the outage period and the same intraday window on the preceding and subsequent week (as controls), at a 5-minute frequency. We omit the Brokertec outage because the EGB cash market was effectively idle during this time of day (7:43-9:35 p.m. local time). The last column refers to a pooled regression of all outages. The number of observations is equal across columns. The dependent variable differs across rows and refers to the log of the transaction volume in € plus one, in all EGBs (first row) or all bonds of the stated country. All regressions include time-fixed effects. For brevity, the table shows results only for the outage dummy.

Sections E.1-E.2 below provide further evidence on MTS and Bloomberg outages. To put the size of these outages in perspective, note that the 2019 European Commission Report estimates that each platform has a 20-30% market share in electronic EGB trading, compared to 0-5% for Brokertec and FWB (see Table 3 on p.168 of the report). Section E.3, lastly, confirms the null

	MTS 12 Jan 2010 8:00-10:35	Bloomberg 17 Apr 2015 9:20-10:10	FWB 27 May 2015 8:00-11:00	Brokertec 11 Jan 2019 19:43-21:35	MTS 26 Jul 2019 12:30-13:20	Pooled
All Futures	0.13	-0.31	-0.77	-1.16**	-0.41	-0.52*
	[0.05]	[0.15]	[0.62]	[0.12]	[0.24]	[0.26]
Obs.	465	153	540	339	153	1650
DE Futures	0.13	-0.56*	-0.81	-1.16**	-0.49	-0.57**
	[0.05]	[0.15]	[0.62]	[0.12]	[0.29]	[0.26]
IT Futures	0.13	0.83**	-0.56		-0.41	-0.11
	[0.07]	[0.09]	[0.70]		[0.34]	[0.24]
FR Futures		-0.94	-0.74		-0.46	-0.37*
		[0.33]	[0.54]		[0.50]	[0.21]
ES Futures					-0.11	-0.01
					[0.12]	[0.01]

Table A34: Effect of Cash Venue Outages on Bond Future Trading Volumes. Each column refers to a different outage and regression. Each sample includes the outage period and the same intraday window on the preceding and subsequent week (as controls), at a minutely frequency. The last column refers to a pooled regression of all outages. The number of observations is equal across columns and corresponds to three times the duration of the outage in minutes. The dependent variable differs across rows and refers to the log of the number of traded contracts plus one, in all bond futures (first row) or all future of the stated country. Empty cells mean there were no futures available at the time or the trading volume was zero during the outage and control windows. All regressions include time-fixed effects. For brevity, the table shows results only for the outage dummy.

effect of CME outages on Eurex using six older outages as a robustness check.

E.1 MTS Outage

While we did not find any newspaper reports about an outage on 26 July 2019, we noticed a prolonged and unexplained period without any activity on MTS using our intraday dataset of transactions and order book updates. Trading and quoting activity on MTS was lower than usual from about 10:00 that day, before breaking down entirely from 12:30 till 13:20. There were no quotes and no transactions in any bond (see Figure A5). MTS representatives could not provide an explanation for the incident, but the similarity with the confirmed outage from 2010 is striking in our view. We use this suspected outage as a robustness check.

Since this event took place quite recently, we can zoom in on the futures market using granular order book data. In particular, Figure A20 confirms that there is no discernible drop in market liquidity for the 10-year bond future for any country when MTS is inactive. Similarly, indicative quotes on Bloomberg do not show any obvious reaction to the suspected MTS outage, see Figure A21.

	MTS 12 Jan 2010 8:00-10:35	Bloomberg 17 Apr 2015 9:20-10:10	FWB 27 May 2015 8:00-11:00	Brokertec 11 Jan 2019 19:43-21:35	MTS 26 Jul 2019 12:30-13:20	Pooled
Volume	0.42***	-0.68**	-0.79	-1.25***	-0.48	-0.50
	[0.00]	[0.12]	[0.53]	[0.08]	[0.32]	[0.29]
Observations	465	153	540	339	153	1650
#Trades	0.24	-0.51**	-0.49	-0.89*	-0.54	-0.37*
	[0.14]	[0.09]	[0.32]	[0.27]	[0.35]	[0.20]
Observations	465	153	540	339	153	1650
Volatility	0.15	-0.25**	-0.78	-0.06	-0.12	-0.28
	[0.11]	[0.03]	[0.61]	[0.04]	[0.19]	[0.26]
Observations	465	153	540	281	152	1591
Amihud	-0.06*	0.05*	0.05	0.13	-0.00	0.02
	[0.02]	[0.01]	[0.02]	[0.33]	[0.00]	[0.04]
Observations	465	153	540	281	152	1591
Roll	-0.15	-0.08	0.19*	-0.18	0.38***	0.05
	[0.17]	[0.14]	[0.05]	[0.20]	[0.03]	[0.09]
Observations	464	153	540	132	152	1441

Table A35: Effect of Cash Venue Outages on 10y German FGBL Future. See Table 13 for a description of the different dependent variables (rows). All regressions include time-fixed effects.

E.2 Bloomberg Outage

During the Bloomberg outage, aggregate trading volumes decrease on the cash and to a lesser extent also on the futures market (see Table A33 and Table 13). Looking at individual countries, Table A34 shows that trading volumes do considerably decrease in German and French bond futures. But this is offset by a substantial increase in trading volumes in Italian bond futures. This evidence is in line with Bouveret, Haferkorn, Gaetano, and Panzarino (2022). They document a similar divergence for flash crash episodes: trading activity in Italian bonds surges on the futures market and plummets on the cash market. Figure A22 provides results for the MTS platform. The liquidity provision was slightly lower than normal during the Bloomberg outage, while the executed trading volumes were barely affected. Figure A23 shows that the lower liquidity was restricted to Italian bonds.

E.3 CME Outage

Recall that Figure 13 shows that neither the aggregate trading activity on Eurex, nor the order book liquidity of the 10-year Bund future is noticeably affected by the outage on the US futures market in 2019. One worry might be that this null effect is due to timing of the outage very early in the morning for European traders. We address this issue by studying six older outages of the US futures market that occurred between 2006-2007 (see Harding and Ma, 2010). These outages occurred on the Chicago Board of Trade (CBOT) exchange. After a merger in 2006, CBOT's trading software migrated to CME's trading system in 2008. Since we do not have order book data for this early sample, we only look at trading volumes. Figure A24 shows that the null effect is indeed a robust finding. Trading volumes in German Bund futures do not systematically differ during US futures market outages. We have verified this is also for other futures, e.g. 2-year German bond futures or 10-year futures of other countries, and for other measures or market functionality, e.g. realized volatility.

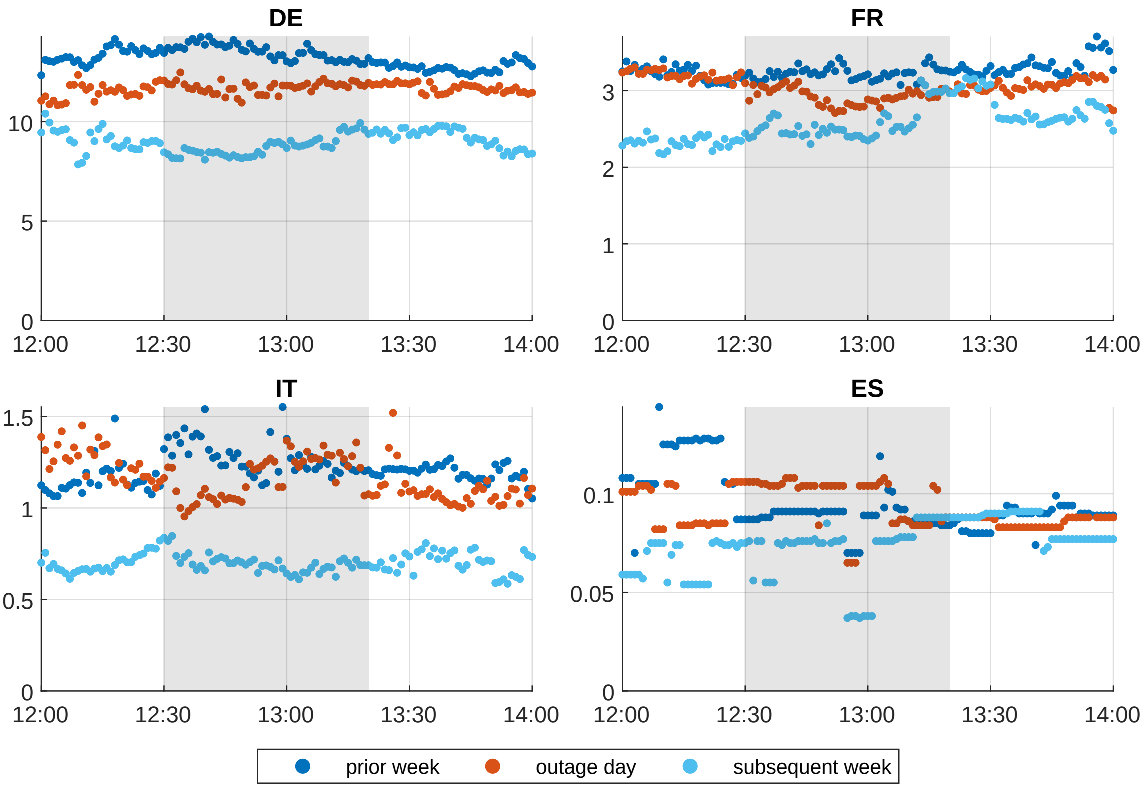


Figure A20: Order Book Depth of 10-year Bond Futures during suspected MTS Outage on 26 July 2019. This figure shows the total number of contracts (in thousands) quoted at the first fifteen levels on both sides of the order book, at minutely snapshots. Red dots refer to the suspected MTS outage day on 26 July 2019, dark and light blue dots refer to the previous and subsequent week.

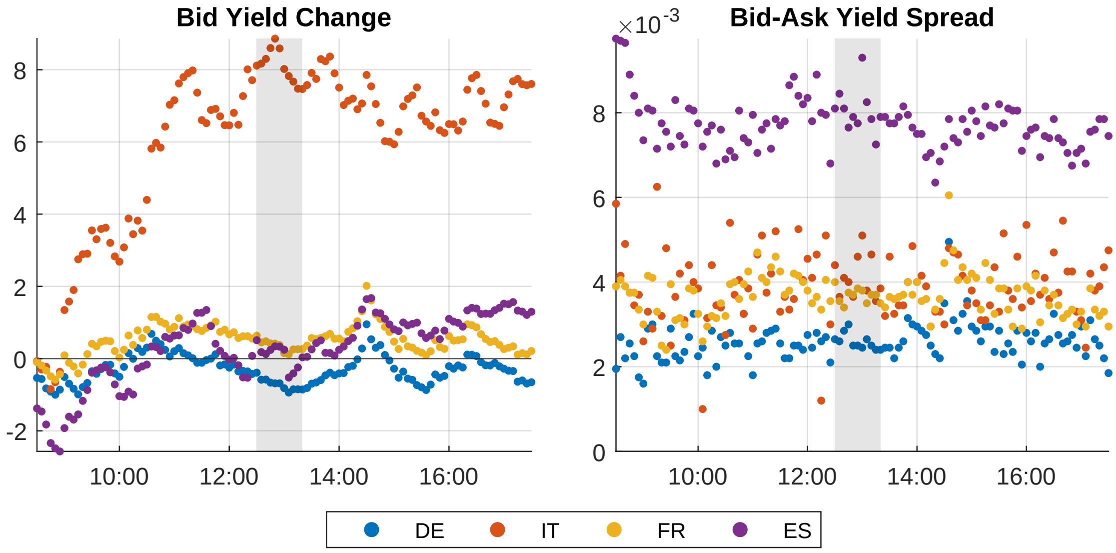


Figure A21: Indicative Quotes on Bloomberg on 26 July 2019. The left panel shows bid yield changes (in basis points since 8:00 a.m.), the right panel shows bid-ask yield spreads (in basis points). All data refers to 10-year cheapest-to-deliver bonds. The grey areas mark the times of the suspected MTS outage.

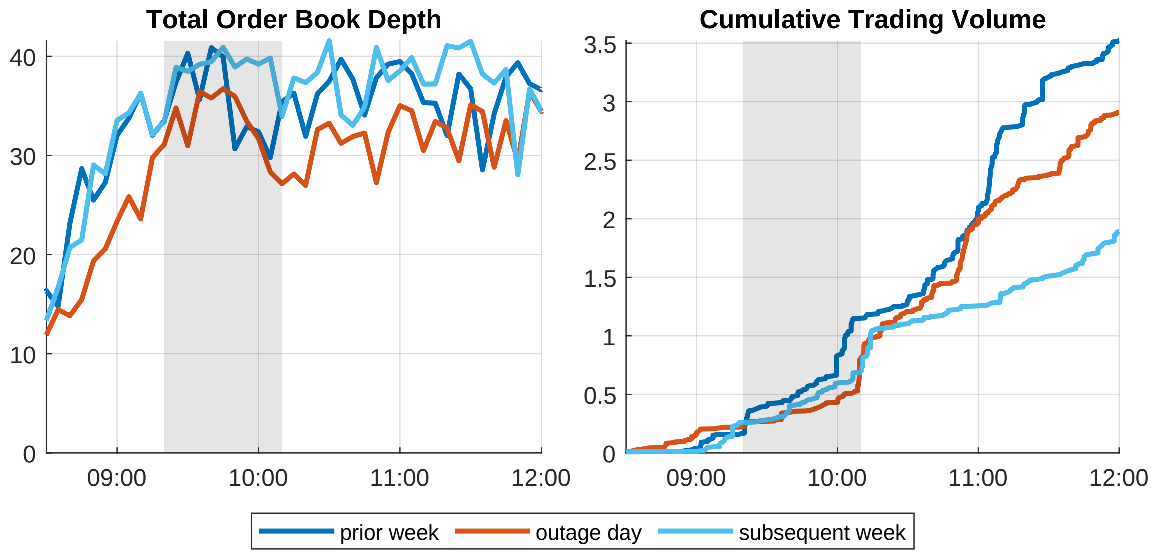


Figure A22: MTS Order Book Depth and Trading Volume during Bloomberg Outage. The left panel shows the total order book depth at 5-minute snapshots (in billion €), the right panel shows the cumulative trading volume (in billion €) in all German, French, Italian and Spanish sovereign bonds on MTS.

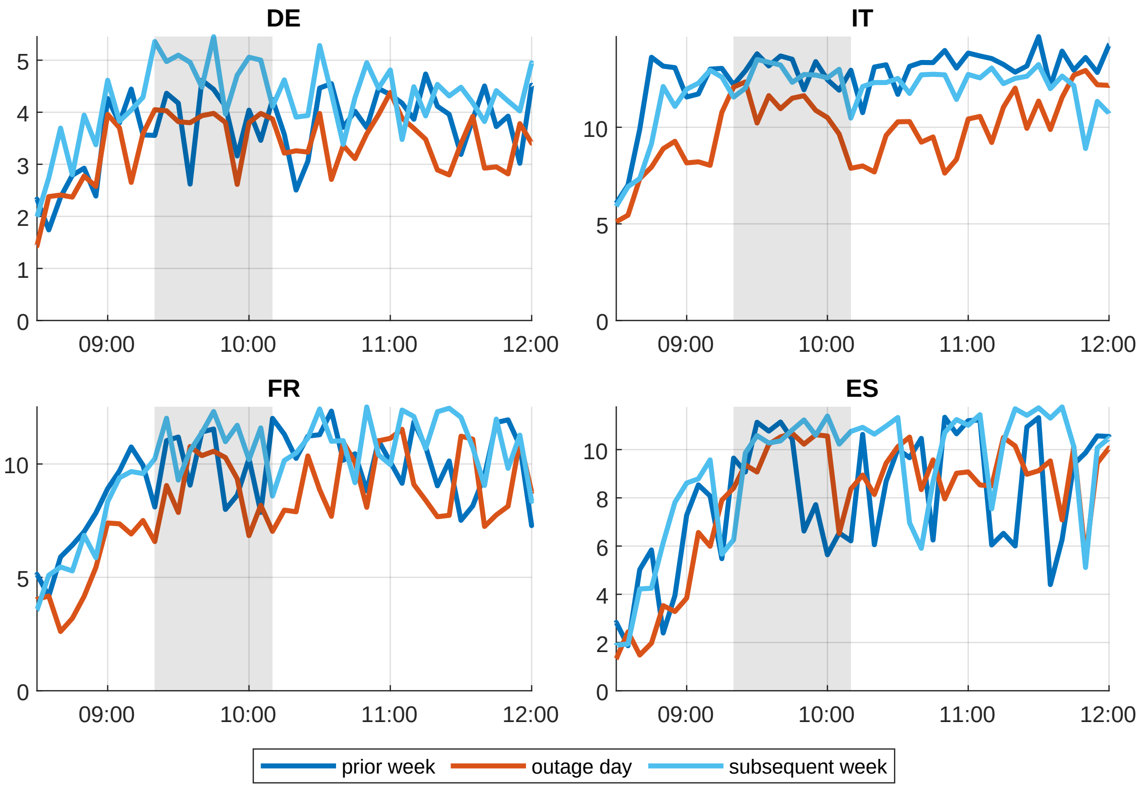


Figure A23: MTS Order Book Depth during Bloomberg Outage across Countries. This figure shows the total order book depth for German, French, Italian and Spanish sovereign bonds on MTS, at 5-minute snapshots (in billion €).

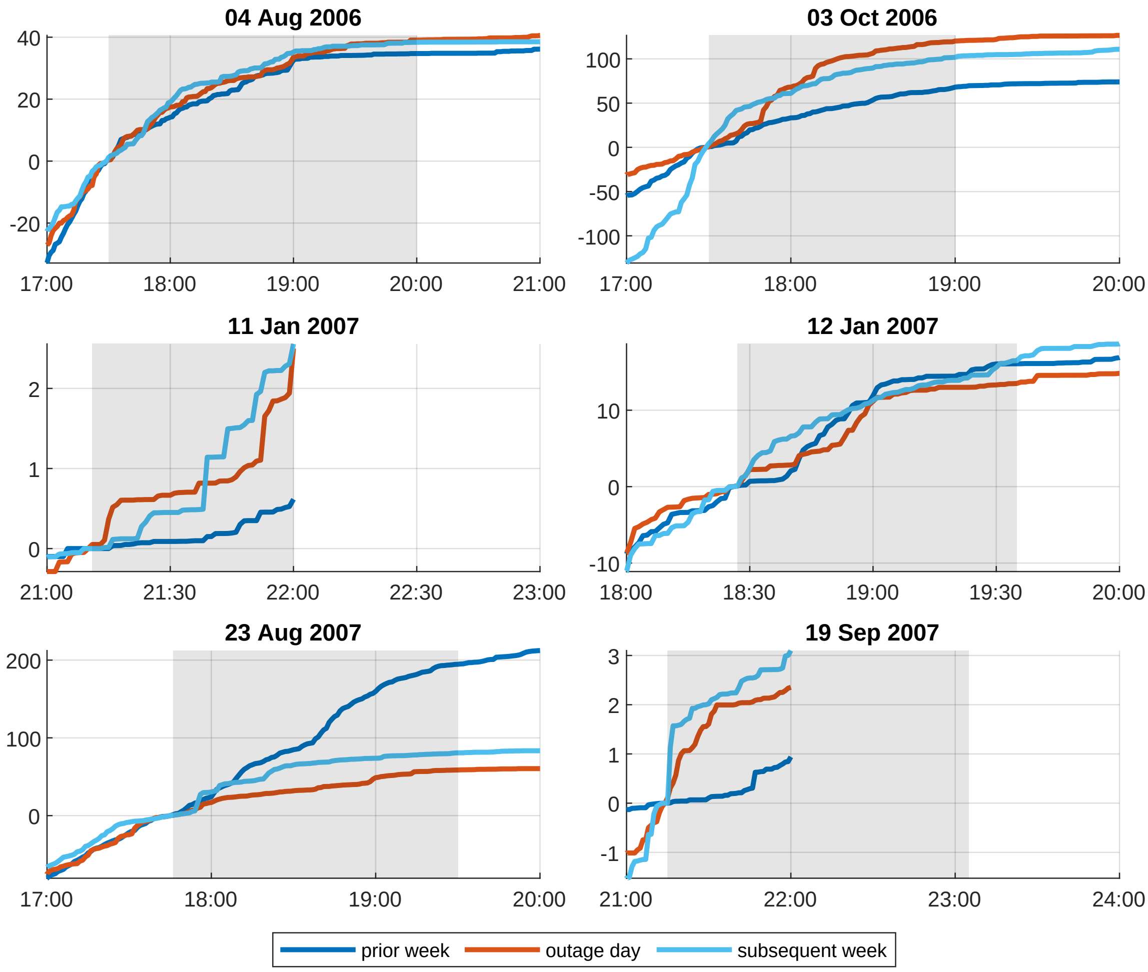


Figure A24: German Bund Future Trading Volume during CBOT Outages. This figure shows the cumulative trading volume of 10-year German bond futures around CBOT outages (in thousands of contracts, normalized to zero at the intraday time of the outage). Red lines refer to the outage day, dark and light blue lines refer to the previous and subsequent week. The grey areas mark the outage times of CBOT, taken from Harding and Ma (2010). In 2006-2007, trading hours on Eurex ended at 22:00 CET.

Appendix F Narrative Evidence

Appendix F.1 contains selected quotes from market participants regarding the euro area government bond market and Appendix F.2 cites from an internal memo of one of the major dealers in this market. Overall, this narrative evidence is in line with our empirical result that proper market functioning for EGBs vitally depends on an active futures market.

F.1 ESMA Consultations

The European Securities and Markets Authority (ESMA) has published two consultation papers that contain valuable information about euro area bond market functioning. The below sections summarize the most informative responses by market participants.

F.1.1 Market Outages

The below quotes refer to investor responses to the ESMA Consultation Paper on Market Outages. The final report was published on 24 May 2023. The report's focus is on stocks and the substitutability among stock exchanges, but some questions also concern the fixed-income market, e.g. question 12: *'Is there any particular issue relating to trading of non-equity instruments that should be taken into account in the case of an outage? Where possible please differentiate between bonds and derivatives.'* The below quotes refer to investor responses to this question. We emphasize particularly informative bits in **bold font**.

Electronic Debt Markets Association (EDMA, 6 members are: BGC Fenics, Bloomberg, BrokerTec, MarketAxess, MTS and Tradeweb): 'non-equity trading on EU trading venues is **less affected by outages, including fixed income markets, with trading more naturally moving to alternative platforms** [..] Given that end users have a plethora of alternative trading venues available to them trading the same financial securities, there is already appropriate (commercial) pressure on trading venues to reopen as quickly as it is safe to do so.'

Euronext: 'in the fixed income market, it is **quite fragmented and trading generally moves to other venues when there are outages** in any case so there is less of an impact.'

Federation of European Securities Exchanges: 'In particular for fixed income market, it is important to consider the different structure of the market, where there is **not the same reliance on the primary market as is the case for equity, and trading is distributed more widely across several trading venues and systematic internalisers, so there is less of an impact in case of an outage** of a single trading venue'

The Investment Association: 'From a fixed income, bonds perspective, we echo the observation outlined by ESMA [..] that the trading of bonds is less affected by an outage regardless of the type of trading venue the outage occurs on, as trading does more naturally gravitate towards an alternative platform. Partly this is due to the vast differences in the trading landscape of equity and bond instruments.' 'Furthermore, we recommend that ESMA consider the **impact of market outages on futures exchange markets [..] and the trading of bond futures as an outage would most likely have significant implications on the liquidity portfolio of many government securities**'

F.1.2 Algorithmic Trading

The below quotes refer to investor responses to the ESMA Consultation Paper on Algorithmic Trading. While the report's focus is on stocks, some questions are informative also for the fixed-income market, e.g. question 36 on market outages: *'Do you believe any initiative should be put forward to ensure there is more continuity on trading in case of an outage on the main market, e.g. by requiring algo traders to use more than one reference data point?'* The below quotes refer to investor responses to this question. We emphasize particularly informative bits in **bold font**.

Deutsche Börse: 'Regarding, initiatives aiming at continuity of trading in case of an IT incident/outage, DBG does not believe that such an initiative should be put forward given a close to 100% system performance of main markets. We would caution against forcing algorithms to include different sources of information. **The underlying assumption seems to be that regulated markets, MTFs (multilateral trading facilities) and potentially SIs are set on the same level in terms of price formation and information, with easy switch from one to the other, putting aside respective market shares and the notion of reference market.** The explored initiative would hence introduce an artificial change to the current market structure which is at odd with MiFID. To the contrary, the flight to execution quality at the height of volatility in the COVID-19 crisis proved once more that there was a need by investors to trade on transparent regulated markets when looking at the migration of volumes from dark, SI, and OTC trading to regulated markets. Last but not least, **it should be up to the trading participants to decide if they see merit in connecting to more than one reference data point or not**, but they should not be forced upon by regulation.'

Federation of European Securities Exchanges: 'FESE considers that **declines in trading following outages are linked to the importance of price formation**. Despite the ability to trade on alternative venues, the **low confidence of traders in the price formation on alternative venues may deter them from trading on those markets** during the outage period.'

German Banking Industry Committee: '**we strongly oppose the notion that outages might be compensated by obliging intermediaries, i.e. investment firms, to connect to more than one trading venue so that in the event of an outage, trading can continue seamlessly on another venue**. This would mean market participants would have to maintain double memberships in all relevant main markets. This proposal is completely unproportionate, it might also lead to liquidity reduction in those main markets and will increase costs for intermediaries and clients alike. Neither do we see how the notion to require algo traders to use more than one reference data point might solve the real problem, nor do alternative markets exist for all financial instruments.'

Virtu: 'Virtu believes that it is in the best interests of the market and orderly trading for the appropriate amount of time to be taken to properly resolve an incident and to restart afterward, instead of forcing trading venues to adhere to an arbitrary two hours of restart time. [..] **The market would be better served by improved resilience across the system as a whole, with true alternatives to primary markets (or any individual venue)**, rather than a specific and arbitrary focus on restart times.'

ACI Financial Markets Association: 'If an outage suspends trading on the main market, it is important to be able to migrate to another trading venue for the use of reference data points to ensure that market liquidity is not affected, since the **simultaneous suspension of Algorithmic trading by numerous market participants could result in high volatility and a drastic reduction in market liquidity**.'

World Federation of Exchanges (WFE): 'The question as to whether to require use of more than one reference data point will, however, be a function of how well the alternative data points reflect the market in question. **Fragmentation of markets can bring choice (and competition in terms of execution costs) but not all alternative venues generate (or are capable of generating) meaningful price discovery of their own, instead relying on 'main' venues to do so**.'

Chicago Board Options Exchange (CBOE): 'Technical outages by European trading venues are a reasonably regular occurrence and largely inevitable. When they do happen, they are highly disruptive, particularly when experienced by national stock exchanges ('primary outages'), which facilitate trading in the stocks they list and are the sole operators of official opening and closing auctions for those stocks. **Primary outages in recent years have seen market-wide trading in instruments listed on those exchanges dry up to almost nothing**.'

All Options International: '**The added liquidity and/or other fail-over benefits that the fragmented market structure and its supporters claim to have in practice is just false**. This is shown by the drop of liquidity of secondary venues the moment the primary venue has an outage. **We believe that the best way to maintain liquid markets is to concentrate all liquidity on one, single venue. Real price forming always happens on the primary market**. In order to generate a better, more liquid market in all scenarios the fragmentation of markets needs to be stopped and all off-book and SI trading needs to be prohibited.'

F.2 Citigroup incident

In 2005, the UK's Financial Services Authority (FSA) ordered Citigroup to pay almost £14 million in fines for a trading strategy the bank had executed in August 2004, see e.g. the FSA's final notice for a detailed description of the trading strategy and a timeline of events and this Guardian article for further background information.

What makes this incident particularly informative for our purposes is an internal memo cited by the FSA and in news articles by the Financial Times, New York Times and Euroweek (now GlobalCapital). This memo was titled *'Challenging the dominance of Eurex futures'* and was written by a member of Citigroup's European government bond trading desk in London.

According to the FSA, the memo summarized the goal of Citigroup's trading strategy as *'imposing a cost on competitors for offering liquidity on MTS, reducing the attractiveness of using the Bund future to hedge, widening cash market bid-offer spreads, [..] and helping remove some of the smaller primary dealers from the cash market.'* The news articles quote the memo as saying *'Overall, these trades may help to reduce the markets reliance on the Bund future and turn the European Government bond market into one that more closely resembles the US government bond market.'*

These quotes are in line with our evidence that proper EGB market functioning vitally depends on an active futures market.