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Mark Kerssenfischer, Caspar Helmus

Outages in sovereign bond markets

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Abstract

We use outages as natural experiments to study sovereign bond market functioning. When the euro area futures market goes down, trading activity on the cash market declines, liquidity evaporates, and transaction prices deviate from fundamental values. Tracing back this macro-level market breakdown to the micro-level, we show that particularly dealers withdraw from the cash market during outages. While most of their remaining trades remain fairly priced, dealer's capacity to intermediate trades on the cash market is reduced, forcing more clients to trade directly with each other, leading to substantial mispricing. Lastly, outages on cash trading venues barely affect the futures market, suggesting that price formation and liquidity provision is a one-way street, and outages on the US and euro area futures market barely affect each other, in stark contrast to the significant price spillovers. Our results reveal the trade-offs between a (de)centralized market structure, they support cross-asset learning models to explain the link between liquidity and arbitrage, and they demonstrate how financial intermediaries can impose important limits to arbitrage.

Keywords: Yield curve, market microstructure, natural experiment.

JEL classification: G12, G14, G23

Non-technical summary

Sovereign bond markets are at the core of the financial system. This paper uses outages as natural experiments to improve our understanding of how these markets function. We study several outages on different trading venues affecting different financial instruments. All of these outages were caused by unanticipated and exogenous technical glitches. Hence, how the different trading venues, instruments, and market participants reacted to these rare outage events is highly informative about how the sovereign bond market functions in normal times.

Our first key result is that the cash market for euro area sovereign bonds vitally depends on bond futures. Bond futures oblige the buyer to buy (or the seller to sell) a sovereign bond at a predetermined price and date in the future. When these bond futures stop trading due to an outage of the Eurex futures exchange, bonds on the cash market trade less frequently, their liquidity evaporates, and their transaction prices deviate from their fundamentally fair values.

Thanks to our non-anonymous transaction dataset, we can pinpoint the micro-level mechanisms underlying these macro-level results. The behavior of financial intermediaries, most importantly dealers, turns out to be crucial. These dealers are mostly large banks participating in the auctions of new sovereign bonds. They reduce their cash market presence the most during Eurex outages. If they do trade, they trade at fundamentally fair prices, but they largely stop to take on inventory risk to intermediate trades between clients, such as investment funds, insurance companies or non-financial corporations. Hence, clients trade directly with each other, and precisely these client-to-client trades often occur at prices far from fundamentally fair values.

The dichotomy between dealers and clients also explains a number of other phenomena we observe on the cash market during Eurex outages. For instance, trading volumes and market liquidity drop more – but pricing errors increase less – for bonds of longer maturity, where dealers are comparatively more active. Similarly, small transactions become most mispriced, as these are usually executed between clients. Taken together, our micro-level evidence shows that dealers have an informational advantage over clients, in the sense that dealers properly price risk-free sovereign bonds even without bond futures. At the same time, dealers impose important limits to arbitrage, since they rely heavily on the futures market for hedging purposes. In effect, the Eurex outage acts as an exogenous shock reducing their intermediation capacity. Unable to hedge any additional inventory risk, dealers retract from the cash market, where clients push market prices away from fundamental values.

We also look at the other direction and study outages on four different bond trading platforms on the cash – rather than future – market. We find that these outages have rather small effects, not only within the cash market, but also on the futures market. This suggests that price formation and liquidity provision is more of a one-way street from the futures to the cash market. Lastly, we study transatlantic spillovers. We find little evidence that outages on Eurex affect the market functioning on CME, the main US futures exchange. Even more surprisingly, we also find no effect in the other direction. Whereas a large literature documents strong price spillovers from the US to Europe, we find virtually no liquidity spillovers.

1 Introduction

The risk-free yield curve builds the foundation of all 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 the different trading venues, financial instruments, and investor types reacted to these outages 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 caused trading on the euro area futures exchange Eurex to stop suddenly 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 fairly simple methods. In particular, we compare variables of interest during the outage to values just before and just after the outage. 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 the outage. We first focus on the macro-level effects of outages, namely in terms of *trading volumes*, *market liquidity*, and *pricing errors*. Then, we trace these effects back to the micro-level by studying different trading venues and investor types.

Trading volumes on the cash market decline sharply when Eurex goes down. This is true for government bonds of all four euro area countries we study (Germany, France, Italy, Spain). Trading volumes drop particularly strongly for bonds with longer maturity and for recently issued 'on-the-run' bonds.

Market liquidity declines dramatically during futures market outages, with some differential effects across countries. Executable quotes, which are only available on MTS's dealer-to-dealer platform, vanish virtually entirely for Germany and almost entirely for 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 should provide a good estimate of current bond prices, 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 quotes are not disclosed, our results show that bond future prices are a vital input.

[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.

Finally, *pricing errors* on the cash bond market spike when the futures market is down. The remaining transactions in German bonds, the risk-free benchmark asset for the euro area, that do occur on the spot market during the outages exhibit large price deviations from fundamental values. Observed market yields usually lie on a smooth fitted yield curve, in line with arbitrage forces, but not when Eurex is offline. During the outages, pricing errors – the difference between observed and fitted yields – increase sharply and are many times higher than normal. In fact, the root mean squared pricing error – Hu, Pan, and Wang (2013)'s noise measure – is comparable to or even higher than at 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. We show that small trades in short-term bonds exhibit particularly large pricing errors.

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 go one step further and exploit the granularity of our transaction dataset to provide *micro*-level evidence on the price formation process underlying the risk-free yield curve. We find that dealers reduce their market presence the most during Eurex outages but their remaining trades remain rather fairly priced. Correspondingly, trading volumes and market liquidity drop more but pricing errors increase less for long-term bonds, where dealers are comparatively more active. Similarly, we find that outages increase pricing errors most for small transactions, which are disproportionately executed between clients and rarely involve dealers. This evidence suggests that dealers are better informed than clients, and that clients rely heavily on bond futures to properly price the risk-free yield curve. At the same time, dealers are 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, forcing clients to trade directly with each other, often pushing transaction prices far from fundamental values.

Having established the dramatic effects of futures market outages on the cash market, our third and last major contribution is to document how unique these outage effects are. To do so, we first show that outages on cash trading platforms have much smaller effects, not only on the futures market, but also across cash market platforms. 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 traders worldwide were not able to access their Bloomberg terminals for about two hours. This outage does significantly reduce trading volumes on the futures market, but barely affects more direct measures of market functioning. The illiquidity measures of Roll (1984) and Amihud (2002) e.g. 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. For euro area futures, this might not be too surprising, since Brokertec has a negligible market share in EGBs. But the null finding 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 test for spillovers between outages on Eurex and outages on the main US futures exchange in Chicago. We find little evidence for spillovers in either direction. In particular, the order book depth of US Treasury futures does not decrease when Eurex goes down. Looking at the other direction, we exploit an outage on the US futures market on 26 February 2019 and six older outages between 2006-2007 (see Harding and Ma, 2010). We find no systematic decrease in liquidity or trading activity of European bond futures during US futures market outages. This lack of liquidity spillovers stands in stark contrast to the strong price spillovers, particularly from the US to Europe (see e.g. Boehm and Kroner, 2023). 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, it confirms that financial intermediaries impose important 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. Bond transactions on the decentralized spot market 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, in line with the model by 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 better price discovery. This is in line with Kutai, Nathan, and Wittwer (2023), 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

[3] de Roure, Moench, Pelizzon, and Schneider (2019) 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.

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.[5]

Liquidity and Arbitrage. We use our natural experiments to test competing theories of liquidity spillovers. 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 spot 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 spot 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 spot 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 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 cash bonds.[6]

Limits to Arbitrage and Intermediary Asset Pricing. A closely related literature studies the limits to arbitrage, due to the importance of intermediaries in financial markets (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). In a recent paper on the U.S. Treasury market, e.g., Duffie, Fleming, Keane, Nelson, Shachar, and Van Tassel (2023) show that market functionality is impaired when dealers exhaust their balance sheet capacity to intermediate trades, as observed in March 2020. Viewed from this perspective, the outages

[5] Even though the outages we study were not caused with malicious intent, our results can inform the recent literature on cyber risks. Eisenbach, Kovner, and Lee (2022) show how a cyber attack on the US wholesale payments network could affect the U.S. financial system. Kashyap and Wetherilt (2019) provide principles for regulating cyber risk, with a focus on banks. A recent Consultation Paper by the European Securities and Markets Authority (ESMA) provides guidance on how trading venues should react in the case of outages, with a focus on stocks and stock exchanges. Fortunately, the Eurex outages we study lasted only a few hours. But longer-lasting outages – potentially due to a cyber attack – could have much broader effects, since government bond yields are the benchmark to price other financial instruments, from corporate bonds to bank loans.

[6] Numerous papers 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 do not only incorporate new information faster, 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 spot market trading venues are satellite markets.

we study serve as a clear natural experiment corroborating 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.

2 European Government Bond Market Structure

This section briefly outlines the market microstructure for euro area government bonds (EGBs) on the future and cash 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 in terms of underlying value is roughly ten times larger on the futures than the cash market. 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.

The cash market for EGBs is 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. (2019) 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. Tradeweb e.g. uses a request-for-quote (RFQ) mechanism, i.e. clients request quotes for a certain bond from dealers.[7] On Bloomberg, market participants typically express their trading interest by voice over the phone, or using the terminals' chat functionality.

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.[8] To capture this heterogeneous bond market as much as possible, we combine a number of different data sources. The following subsections briefly describe the various data sources we exploit.

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 is relatively new and to the best of our knowledge, we are the first to use it for academic research. By and large, however, the dataset is similar to the Bafin dataset used in prior work, see e.g. de Roure et al. (2019) and Gündüz, Ottonello, Pelizzon, Schneider, and Subrahmanyam (2023), 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

[7] 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).

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

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.

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 the Register of Institutions and Affiliates Database (RIAD, see Perrella and Catz, 2020). We differentiate between banks, non-bank financial institutions (NBFI), investment 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 Future 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 they 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.

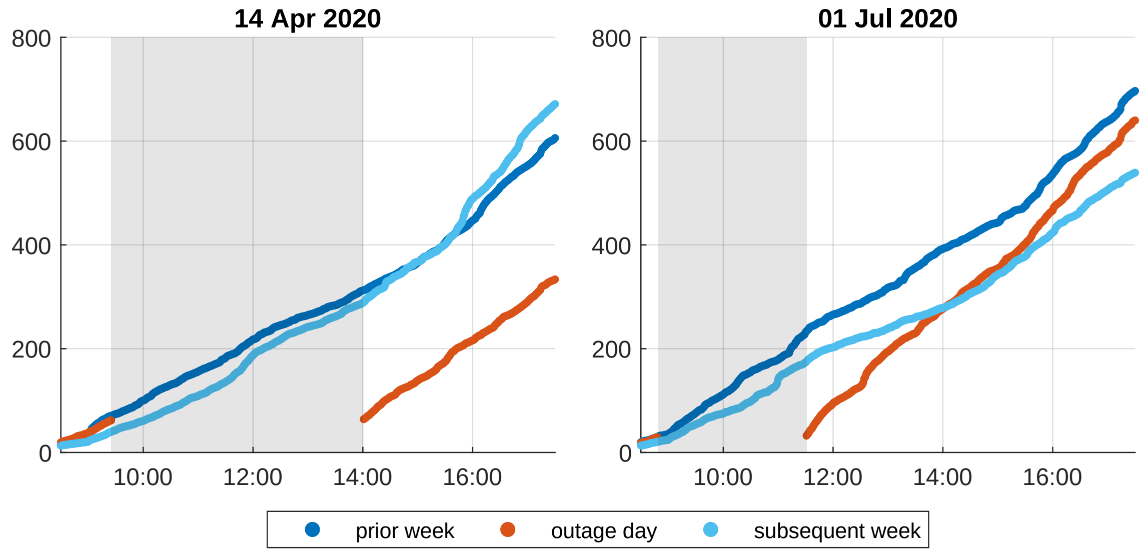


Figure 1: Cumulative Trading Volume of 10-year Bond Futures. This figure shows the cumulative number of traded contracts (in thousands). Red dots refer to the outage day, dark and light blue dots refer to the previous and subsequent week.

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

3.1 Trading Activity

Figure 2 plots the total cumulative bond trading volume on the cash market, based on our extensive transaction-level dataset. We can already see from this raw data that trading volumes are much lower while Eurex is offline.

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 keep periods with zero trading volume.[9]

Table 1 reports the results.[10] Model (1) confirms that trading volumes on the cash market

[9]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.4 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.

[10]Throughout this paper, *,**,*** indicates statistical significance at the 10%, 5% and 1% level, respectively

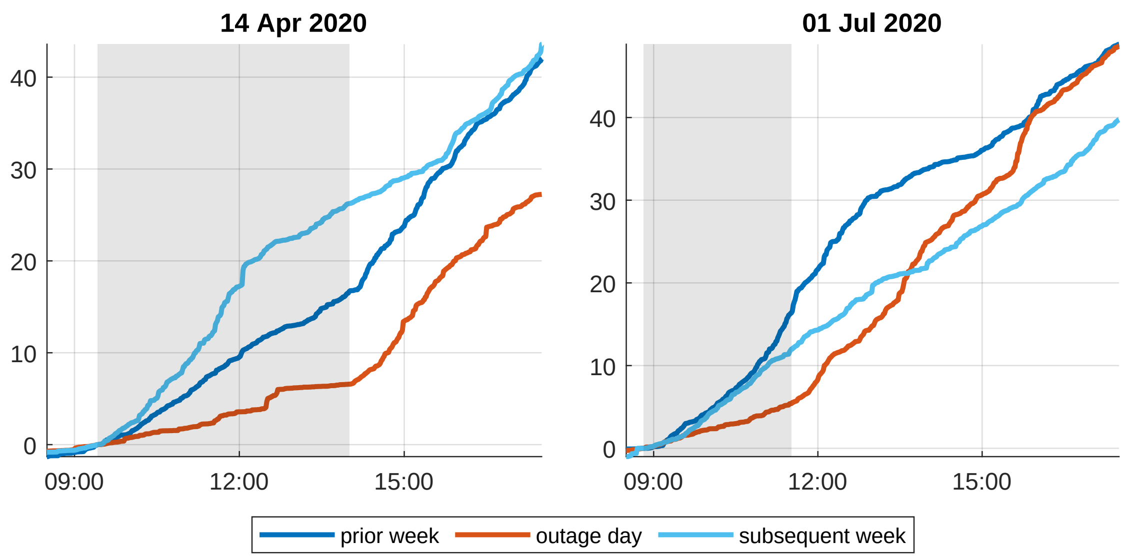


Figure 2: Cash Market Trading Volume in EGBs. This figure shows the cumulative trading volume in all German, French, Italian and Spanish sovereign bonds (in billions of Euro, normalized to zero at the intraday time of the outage). Red dots refer to outage days, dark and light blue dots to the previous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

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) Aggregate	(2) Maturities	(3) Countries
Outage	-3.11*** [0.56]		
Outage × <2.5y		-1.07** [0.35]	
Outage × 2.5-5.5y		-3.70*** [0.47]	
Outage × 5.5-10.5y		-3.82*** [0.65]	
Outage × >10.5y		-3.84** [1.01]	
Outage × DE			-2.78*** [0.36]
Outage × FR			-3.36** [1.04]
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	0.325	0.336	0.324

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.

and standard errors (shown in brackets) are clustered at the daily level.

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.[11] We will come back to this question in Section 4.

3.2 Market Liquidity

3.2.1 Executable Quotes

MTS is the dominant trading venue for euro area sovereign cash 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.[12]

Figure A16 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, i.e. the quoted order book depth is zero. The first quotes reappear only at 14:06, i.e. six minutes after trading on Eurex had 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, i.e. 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 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 was much more widespread.

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 dramatic fall in trading and quoting activity on a major electronic spot market trading platform (Espeed). They attribute this finding to high-frequency trading firms that are only active on the spot 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.[13] The fact that liquidity on MTS evaporates nonetheless 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 spot market deteriorates dramatically.

To investigate the dependency of MTS on Eurex in more detail, we estimate dummy regres-

[11] This is in line with the narrative evidence we present in Appendix F. In Appendix D.1, we find little evidence for an alternative explanation based on duration risk. In particular, we show that interest rate swaps provide a reliable indicator of 'fair' short-term rates during the Eurex outages. Hence, it seems unlikely that longer-term bonds are traded less frequently just because their prices are more sensitive to changes in the short rate.

[12] See Appendix A.4 for the ISIN of each CTD bond. Appendix D.2 confirms that the results presented here are not confined to these particular bonds.

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

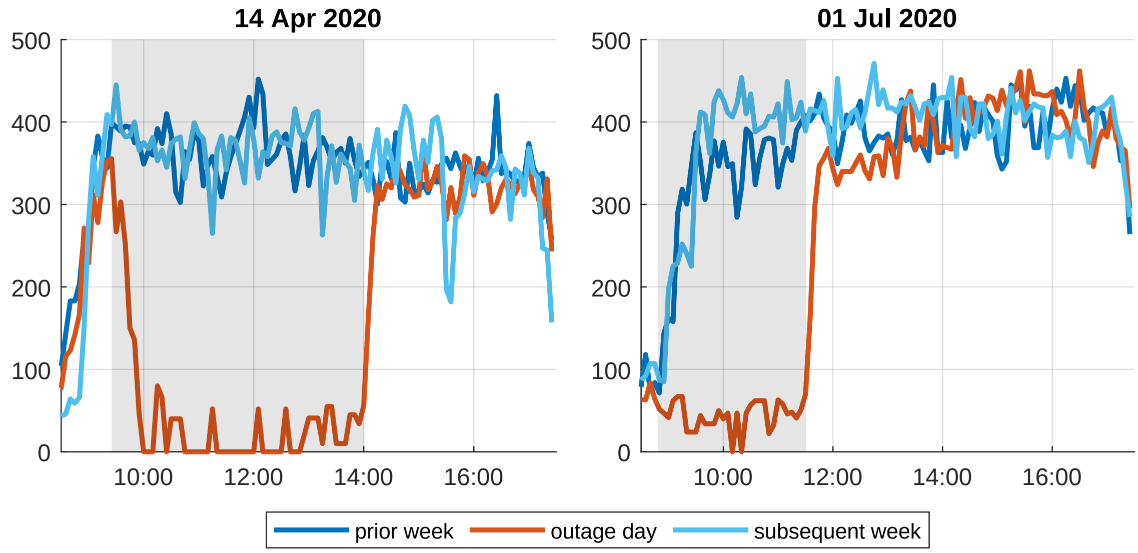


Figure 3: Order Book Depth on MTS. This figure shows the total quoted volume for German, French, Italian and Spanish 10-year CTD bonds (in million €) across all three levels and both sides of the order book, at 5-minute snapshots.

sions 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 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 91 intraday observations per day (5-minute snapshots from 08:30 a.m. to 4:00 p.m.). We use $log(1 + OBdepth_{cmt})$ to keep periods with empty order books.[14]

Table 2 shows the results. For most countries and maturity buckets, the order book depth on MTS drops dramatically when Eurex goes down, i.e. liquidity essentially evaporates, see model (1). Model (2) shows that bonds with longer maturity are affected more than short-term bonds, in line with the trading volume results above.

Before looking at the differential effect across countries, recall that MTS is the main trading platform for Italian bonds and that the aggregate trading volume in Italian bonds is of similar magnitude on the cash and futures market. This is in stark contrast to Germany e.g., where the trading volume in bond futures is roughly ten times larger than in cash bonds 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) shows that compared to German bonds, where liquidity evaporates entirely during the Eurex outage, other countries are less affected. We see that the liquidity in Italy is most robust, followed by

[14] Appendix D.4 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.

Spain and France. Still, while Italian bonds were quoted more consistently, our results suggest that market functioning on MTS was severely impaired by the Eurex blackout even for Italian bonds.

	(1) Aggregate	(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.

3.2.2 Indicative Quotes

Apart from the executable quotes on MTS, there are several providers of indicative quotes for EGBs. We were able to obtain data from three different providers, namely Bloomberg, Refinitiv and TPICAP. Bloomberg terminals and Refinitiv's Eikon application are the two most widely used 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.[15] TPICAP, lastly, is an interdealer broker. To facilitate the intermediation of trades between two dealers (usually large banks), TPICAP surveys trading interests and publishes indicative prices for individual bonds.

Figure 4 shows that across all three data providers, the indicative quotes become stale when Eurex suffers an outage. The number of quote updates drops dramatically the moment Eurex

[15] 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 large European banks. For Italian and Spanish bonds, only a 'composite price', computed by Refinitiv, is available.

goes down and quickly recovers once it is back online.[16]

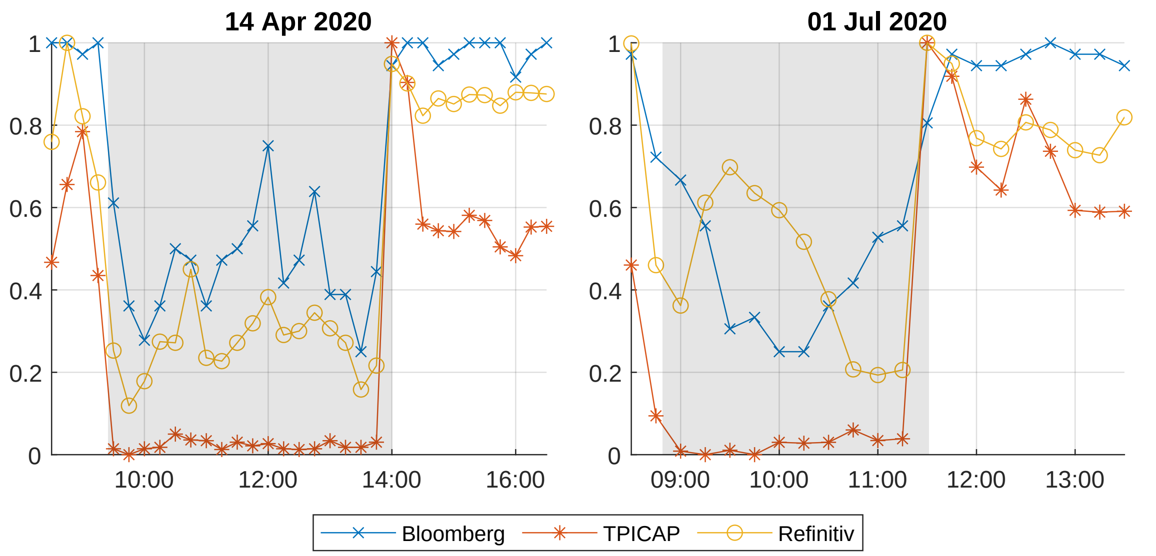


Figure 4: Quote Update Frequency for 10-Year Government Bonds on Different Platforms. Bloomberg and TPICAP data refer to quote updates in the cheapest-to-deliver bond, Refinitiv data to quote updates in the on-the-run ('benchmark') bond. Results for TPICAP and Refinitiv are based on the exact number 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.

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 seem to be a mere reflection of bond future prices on Eurex, with little value added.

3.3 Pricing

We have documented that future 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 lack 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.[17] 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 even covered by any bond future. Despite this low default and duration risk, Dutch authorities

[16] Appendix D.5 contains further evidence on how indicative quote react Eurex outages, both across countries and across data sources.

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

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 transaction prices observed in the market into par yields and then fit a term structure model to these observed yields.[18] 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.

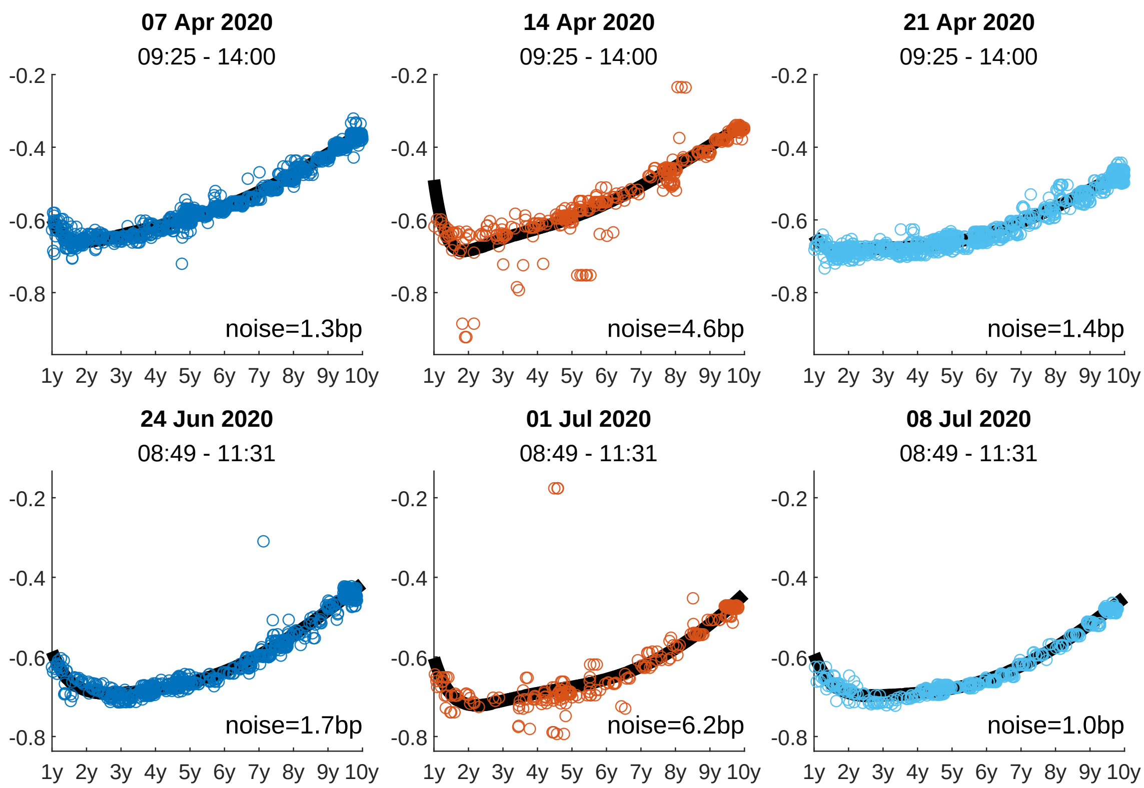


Figure 5: German Yields and Fitted Yield Curves. Each circle shows the implied yield of a transaction in German bonds during the intraday windows stated at the top of each panel. Red circles refer to the two Eurex outage days (middle column), dark and light blue circles refer to the same intraday window in the previous and subsequent week (left and right column, respectively). The horizontal axis refers to the remaining maturity of the bonds in years. The black lines are fitted yield curve 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. Some

[18]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.

market participants apparently struggle to price risk-free German sovereign bonds without bond futures as a guidepost. 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.

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 pricing errors we compute for German bonds are 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 see a spike only in German bond pricing errors.

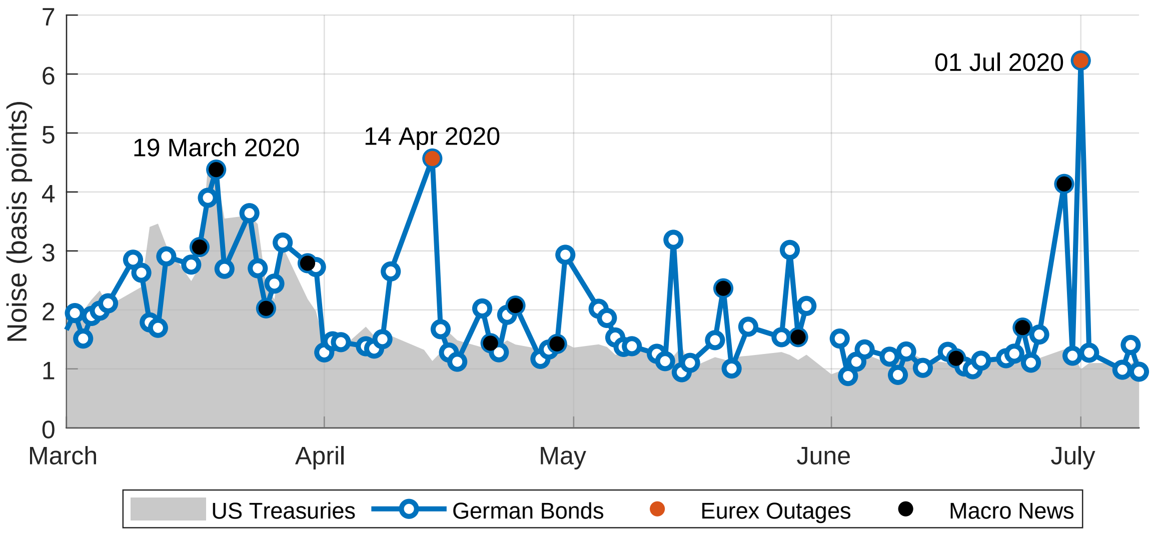


Figure 6: Yield Curve Noise during 2020. The grey area is the US Treasury noise measure published by Hu et al. (2013). It refers to the root mean squared pricing error, based on the cross-section of end-of-day bond prices from the CRSP database and using the Svensson (1994) method to fit yield curves. 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.

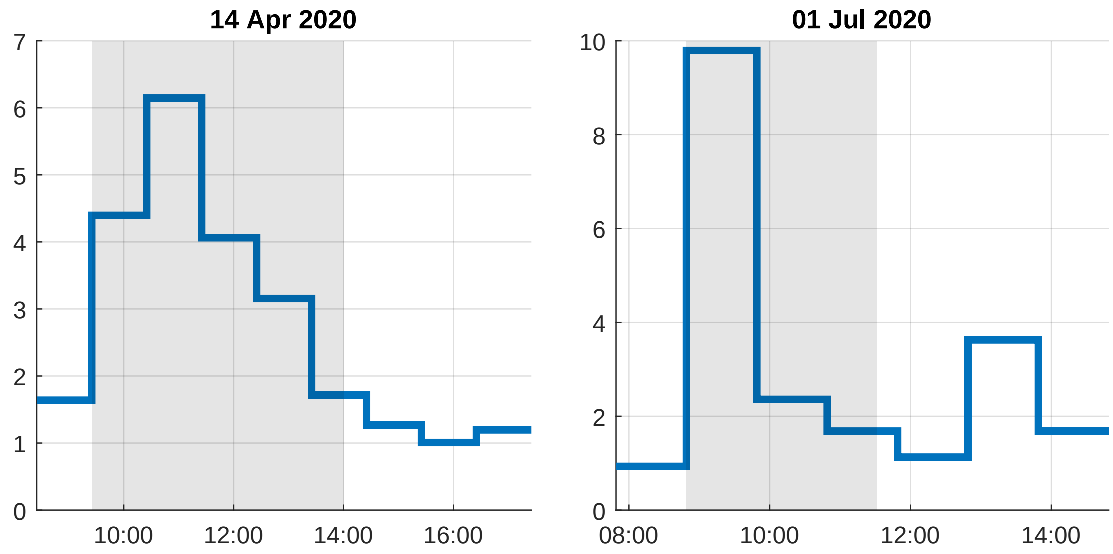


Figure 7: German Yield Curve Noise on Eurex Outage Days. This figure shows the noise measure proposed by Hu et al. (2013) on the two Eurex outage days, from one hour before the outage till four hours after the outage. For each one hour window, we fit a Svensson (1994) curve to the observed market yields 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 Evidence on Price Formation

This section traces the macro-level effect of outages back to the micro-level, highlighting the roles of different trading venues and investor types in the price formation process underlying 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 Types

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.

More importantly, the venue-level results are closely related to 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 setting, a pure 'urgency shock' would *increase* aggregate trading volumes, so this cannot be the primary mechanism through which Eurex outages affect markets.

	(1) Venue	(2) Segment	(3) Eurex
Outage × OTC bilateral	-5.38*** [1.13]		
Outage × OTC via IDB	-3.27*** [0.70]		
Outage × OTC via SI	-4.05*** [0.41]		
Outage × electronic platforms	-2.97*** [0.35]		
Outage × MTS	-2.56*** [0.37]		
Outage × regular exchange	-0.18 [0.64]		
Outage × C2C		-1.60* [0.72]	
Outage × D2C		-2.45*** [0.44]	
Outage × D2D		-5.53*** [0.92]	
Outage × none			-3.47*** [0.67]
Outage × one			-2.18*** [0.32]
Outage × both			-4.17*** [0.50]
FE Day	✓	✓	✓
FE Time	✓	✓	✓
FE Maturity Bucket	✓	✓	✓
Observations	2160	1080	1080
Adjusted R^2	0.452	0.363	0.332

Table 3: Effect of Eurex Outages on Cash Trading Volumes across Venues, Investor Segments, and depending on Investor's Eurex Activity. The dependent variable is the log of the transaction volume of German bonds in a given maturity bucket, executed on a given venue, measured in 30-minute intervals, analogous to Equation 1. Model (2) differentiates between client-to-client trades, dealer-to-client and dealer-to-dealer trades while model (3) differentiates between trades in which both, only one, or none of the counterparties is usually active on Eurex, see Appendix A.6 for details.

A first step to reconcile this is to compare 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. In model (3), we separate investors into those that are usually active on Eurex and those that are not. We see that trading volumes drop most if both or none of the two counterparties usually trade on Eurex. That means trading volumes drop least if one –

and only one – counterparty usually trades on Eurex. This is a first hint at the importance of information asymmetries between investors, on which we will expand below.

4.2 Pricing Errors across Bonds and Trades

To dig deeper, we now relate each pricing error to bond and trade characteristics. In particular, we focus on the same set of transactions as shown in Figure 5, i.e. all transactions in German bonds with one to ten years to maturity that occurred during the Eurex outages or during the same intraday window in the previous or subsequent week. Table 4 reports the results. Model (1) confirms that the absolute pricing errors are significantly larger when Eurex is offline. On average, the mispricing increases from 1 basis point to 2.2 basis points. Model (2) shows that this is also true when controlling for the size of the transaction and for a number of bond characteristics.

	(1)	(2)	(3)
Outage	1.25*** [0.12]	1.16*** [0.15]	1.75*** [0.38]
log(Volume)		-0.14 [0.08]	-0.03** [0.01]
CTD		-0.33 [0.18]	-0.20*** [0.03]
OTR		0.26 [0.15]	0.26*** [0.05]
Zero Coupon		0.03 [0.28]	0.09 [0.11]
Years since Issuance		0.06* [0.03]	0.06 [0.03]
Years to Maturity		-0.08 [0.04]	-0.03 [0.04]
Outage × log(Volume)			-0.69*** [0.04]
Outage × CTD			-1.02** [0.29]
Outage × OTR			-0.59 [0.38]
Outage × Zero Coupon			-0.06 [0.70]
Outage × Years since Issuance			0.02 [0.03]
Outage × Years to Maturity			-0.15** [0.05]
Constant	0.98*** [0.08]	1.20** [0.36]	0.88** [0.34]
FE Minute	✓	✓	✓
FE ISIN	✓		
Observations	3381	3359	3359
Adjusted R^2	0.115	0.126	0.223

Table 4: Explaining Pricing Errors with Bond and Trade Characteristics. 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. 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.

Model (3), lastly, includes interaction terms between the bond and trade characteristics and the outage dummy. 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 exhibit particularly large pricing errors. Conversely, large trades in long-term bonds exhibit less pricing errors, as do trades in CTD bonds.[19] Note that pricing errors for CTD bonds, i.e. bonds that are cheapest-to-deliver into bond futures, are smaller also when Eurex is online. This is in line with our claim that market participants rely on bond futures to price the risk-free yield curve.

4.3 Pricing Errors across Trading Venues and Investor Segments

Let us now study *where* and *which* investors misprice bonds during futures market outages. Table 5 model (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 Table 5 model (2), reveal that client-to-client trades become most mispriced during the outages, followed by dealer-to-client trades. Pricing errors of dealer-to-dealer trades, in contrast, do not increase at all.

In model (3) in Table 5, we separate investors into those that are usually active on Eurex and those that 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.

Recall that we already know from Table 4 that the spike in pricing errors differs greatly depending on the size of a transaction. Therefore, models (4)-(6) in Table 5 re-run the previous regressions while controlling for the transaction volume. In model (4), we see that the spike in pricing errors on electronic platforms and regular stock exchanges are mostly due to the fact that trading volumes are lower on these venues. Once we control for this, pricing errors most clearly increase for bilateral OTC trades. This is roughly in line with the pecking order of dealer trades documented by de Roure et al. (2019): on-exchange trades are most informed, followed by OTC trades via IDBs, while bilateral OTC trades are uninformed. We show that these uninformed trades become most mispriced during Eurex outages.

Model (5) shows that the differential effects across investor segments are also partly driven by the different transaction sizes. Pricing errors of client-to-client trades increase only half as much during Eurex outages when controlling for the smaller trade sizes. For the dealer-to-dealer trades, in contrast, the pricing error increase becomes significant. In model (6), lastly, controlling for the transaction size produces a rather uniform increase in pricing errors, regardless of how many counterparties are usually active on Eurex.

To sum up, dealers reduce their market presence the most during Eurex outages but their remaining trades remain rather fairly priced. This explains why trading volumes and market liquidity drop *more* but pricing errors increase *less* at the long end of the yield curve, where dealers are comparatively more active. It also explains why large trades have smaller pricing

[19] The finding that large trades have *smaller* pricing errors might surprise at first but it is in line with Pintér, Wang, and Zou (2024): the 'size discount' is driven by cross-sectional variation and turns into a 'size penalty' when comparing trades of the same investor type.

	Baseline			Controlling for Transaction Size		
	(1) Venue	(2) Segment	(3) Eurex	(4) Venue	(5) Segment	(6) Eurex
Outage × OTC bilateral	1.97***			1.37***		
	[0.40]			[0.17]		
Outage × OTC via IDB	0.14			0.27		
	[0.28]			[0.27]		
Outage × OTC via SI	0.18			0.30		
	[0.25]			[0.22]		
Outage × electronic platforms	0.91***			0.50*		
	[0.17]			[0.24]		
Outage × regular exchange	4.46***			2.06		
	[0.97]			[1.37]		
Outage × C2C		2.39***			1.20***	
		[0.09]			[0.13]	
Outage × D2C		0.65***			0.40**	
		[0.11]			[0.13]	
Outage × D2D		0.32			0.57*	
		[0.21]			[0.24]	
Outage × none			2.07***			0.66***
			[0.25]			[0.12]
Outage × one			1.27***			0.66***
			[0.14]			[0.11]
Outage × both			0.43**			0.60***
			[0.14]			[0.14]
Outage × log(Volume)				-0.59***	-0.61***	-0.65***
				[0.07]	[0.01]	[0.01]
FE Minute	✓	✓	✓	✓	✓	✓
FE ISIN	✓	✓	✓	✓	✓	✓
Observations	3084	3207	3063	3062	3207	3063
Adjusted R^2	0.166	0.128	0.116	0.210	0.201	0.198

Table 5: 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 4 for details. For brevity, the table shows results only for the outage dummy interaction terms. In model (1) and (4), 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 model (2) and (5), we differentiate between client-to-client, dealer-to-client and dealer-to-dealer trades, whereas in model (3) and (6) 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.

errors, namely because these trades are disproportionately executed between dealers, which are better informed than clients (see e.g. Hortaçsu and Kastl, 2012; Paiardini, 2015).

Lastly, our results provide quasi-experimental evidence that dealers are important for market functionality (see e.g. Duffie et al., 2023). Futures market outages reduce dealers' capacity to intermediate bond trades on the cash market, as they are unable to hedge additional inventory risk. Consequently, clients with an urge to trade have to trade with other clients, leading to large pricing errors.

4.4 Pricing Errors across Investor Types

So far, we have compared pricing errors across different investor *segments*, i.e. dealers versus clients, which is a rather coarse distinction. Let us now look at the underlying investor *types*, i.e. banks, non-bank financial institutions (NBFI), investment funds (including hedge funds), insurance companies and pensions funds (ICPF), non-financial corporations (NFC), the official sector (including central banks) and households (retail investors).[20]

Table 6 columns (1)-(2) show that the spike in pricing errors during Eurex outages is mostly driven by three types of investors: banks, particularly non-dealer banks, investment funds, and households.[21]

	absolute pricing error		net pricing error	
	(1) Buy	(2) Sell	(3) Buy	(4) Sell
Outage × Bank Dealer	0.40* [0.16]	0.94** [0.26]	0.10 [0.65]	-0.07 [0.21]
Outage × Bank Non-Dealer	1.63** [0.45]	1.50*** [0.31]	-0.03 [0.79]	-0.55 [0.75]
Outage × NBFI Dealer	-0.06 [0.24]	0.36** [0.10]	0.58 [0.80]	0.03 [0.78]
Outage × NBFI Non-Dealer	1.81 [0.96]	0.41 [0.22]	0.68* [0.29]	-0.16 [0.37]
Outage × Investment Fund	0.95*** [0.22]	3.55*** [0.45]	-0.32 [0.30]	-3.00*** [0.26]
Outage × ICPF	0.33 [0.53]	-0.01 [0.77]	-0.16 [0.65]	-0.55 [0.86]
Outage × NFC	2.28 [2.03]	0.73 [0.68]	-1.93 [2.51]	-3.00*** [0.50]
Outage × Official	-0.02 [0.16]	0.66 [0.41]	0.05 [0.54]	0.70** [0.22]
Outage × HHs	4.14* [1.68]	4.79*** [0.85]	-2.71** [0.95]	5.64*** [1.02]
FE Minute	✓	✓	✓	✓
FE ISIN	✓	✓	✓	✓
Observations	3085	3095	3085	3095
Adjusted R^2	0.145	0.172	0.148	0.202

Table 6: Effect of Eurex Outages on Absolute and Net Pricing Errors across Investor Types. The dependent variable is the transaction-level pricing error, in basis points of yield, in absolute (columns 1-2) or net terms (columns 3-4). Positive coefficients in column (3) imply that an investor type profits from the outage, buying bonds at a yield above fair value (price below fair value). Positive coefficients in column (4) imply that an investor type incurs losses during the outage, selling bonds at a yield above fair value (price below fair value). For brevity, the table shows results only for the outage dummy interaction terms.

Rather than representing a truly impaired price discovery process, one remaining possibility is that the spike in pricing errors we observe is merely due to investors quoting defensive prices, i.e. low bids and high asks. If that were the case, these investors should have made consistent trading profits during the outage. Table 6 columns (3)-(4) test this prediction by looking at *net*

[20] Kondor and Vayanos (2019) e.g. note that 'It is reasonable to conjecture that not all types of clients engage in speculative trading on treasury markets. Pension funds, foreign central banks, other government organizations, insurance companies, and commercial banks are less focused on future price movements of treasuries compared to hedge funds and asset managers.' Czech, Huang, Lou, and Wang (2021) study the UK gilt market empirically and find that hedge funds and mutual funds are the best informed investors.

[21] For investment funds, pricing errors are much larger on the sell side, but these are not due to fire sales. Recall that classic examples for fire sale events are margin calls and fund withdrawals (see Shleifer and Vishny, 2011, for a literature overview). What we observe during Eurex outages, instead, is that investment funds sell bonds at excessively low yields (i.e. high prices).

instead of *absolute* pricing errors. We see that few investor types systematically incur trading profits or losses while Eurex is down. Banks, for instance, buy and sell bonds at dislocated prices, but the net pricing errors cancel out for the group as a whole. This suggests that banks did not simply increase bid ask spreads during the outage.

Only households consistently incur losses, buying bonds at excessively low yields (i.e. high prices) and selling bonds at excessively high yields (low prices). A simple explanation for the *net* pricing error results is that retail investors, unaware of any outage, submit orders on regular exchanges. Since most liquidity providers (dealers) are absent, these orders are executed at prices far from fundamental values. The main beneficiaries are investment funds, non-bank financial intermediaries, and non-financial corporations. Importantly, however, retail clients do not account for the widespread mispricing of risk-free bonds during future market outages, as they account for only few transactions (see Appendix A.6).

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 have rather small effects, not only within the cash market, but also on the futures market. 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:[22] MTS, Bloomberg, the Frankfurt stock exchange (Frankfurter Wertpapier Börse), and Brokertec.

The aim here is simply to document a strong asymmetry: outages on individual cash venues have much smaller effects than outages on the futures market. That is why we focus on average effects below, see Appendix E for more granular country-level results.[23] In particular, to study the effect of cash venue outages on the cash and futures market, we run dummy regressions like

[22] 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).

[23] 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.

below:

$$Y_{it} = \alpha + \beta \times D_t + \gamma \times FE + \epsilon_{it} \tag{3}$$

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.

Table 7 contains results. We see that all cash venue outages reduce the aggregate trading volume on the cash market. This is somewhat 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. The number of trades, however, drops much less and overall, the drop in trading activity is less dramatic than during outages on the futures market (see Section 3.1).

More importantly, the lower panel in Table 7 shows that only few cash venue outages have large impacts on the futures market. The most consistent effect is a reduction in trading activity, with three out of five outages significantly lowering the number of trades and number of traded contracts on Eurex. 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, all measures (except for realized volatility) imply a slight reduction in market functioning on Eurex, but the magnitude and statistical significance of these effects is rather small. The illiquidity measures of Amihud (2002) and Roll (1984), e.g., increase by only 5% and 9% of a standard deviation, respectively.

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

MTS Outage

We know from Section 3.2 that the MTS spot 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 7 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

	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
Cash market						
Volume	-1.33***	-4.45***	-0.43*		-2.35*	-1.46***
	[0.11]	[0.13]	[0.10]		[0.69]	[0.44]
Adjusted R^2	0.455	0.302	0.464	.	0.528	0.498
Observations	384	132	444	368	132	1460
#Trades	-0.17***	-0.38	-0.08		-0.28***	-0.17***
	[0.00]	[0.17]	[0.08]		[0.01]	[0.05]
Adjusted R^2	0.575	0.301	0.433	.	0.747	0.494
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]
Adjusted R^2	0.904	0.583	0.705	0.457	0.594	0.622
Observations	3720	1224	4320	2712	1224	13200
#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]
Adjusted R^2	0.892	0.679	0.761	0.515	0.676	0.620
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]
Adjusted R^2	0.199	0.082	0.129	0.599	0.123	0.147
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]
Adjusted R^2	0.181	0.044	0.052	0.113	0.065	0.119
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]
Adjusted R^2	0.047	0.008	0.016	0.233	0.049	0.047

Table 7: 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 refers to the sum of absolute log returns, Amihud (2002) to the ratio Volatility/Volume, and Roll (1984) to a bid-ask spread estimate. The last three measures are normalized to mean zero and unit variance. All regressions include fixed effects for the minute within a day and for each country or bond future.

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. 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.

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 7 shows that this cash venue outage has the biggest impact on the future 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 3 and 8 % of a standard deviation, 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 7 shows that this outage reduces trading activity in euro area bond futures, but does not affect actual market functioning.[24]

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 8 shows that the order book depth in German Bund futures seems unaffected by the outage on Brokertec. For US Treasury futures, if anything, we observe a minor *uptick* in liquidity shortly after the outage, which is reversed once Brokertec goes back online (we provide a potential explanation in the next section). This is suggestive evidence 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.

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.

[24]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.

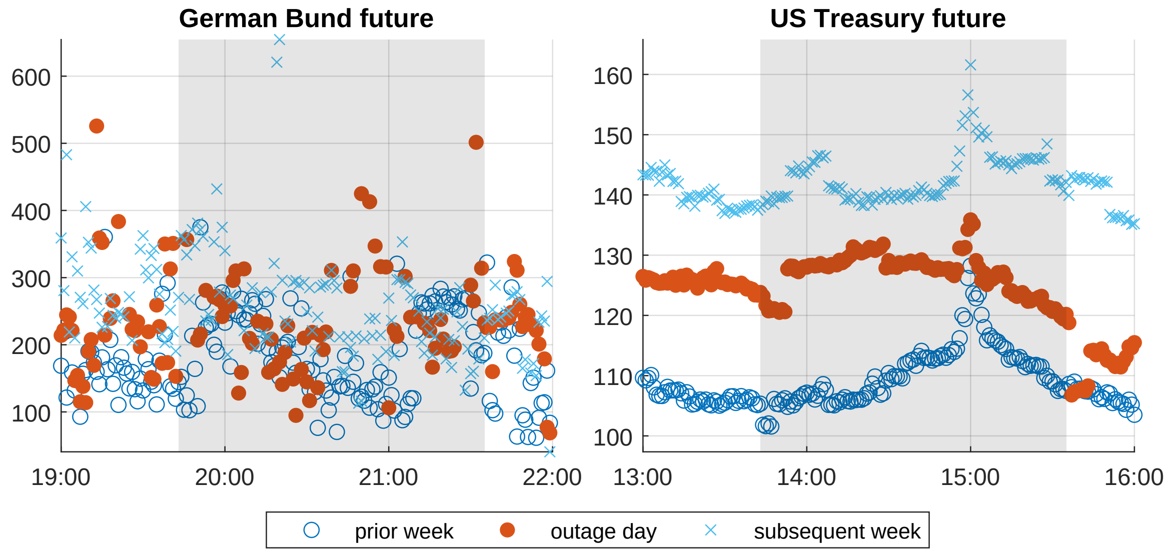


Figure 8: Order Book Depth of Bond Futures during Brokertec outage on 11 January 2019. This figure shows the number of quoted contracts in 10-year German Bund futures on Eurex (left panel; covering both sides of the first three levels of the order book; data comes from Bloomberg, since our Eurex order 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.

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.

On the other hand, 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.[25]

[25] 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.

So do outages spill over across the Atlantic? Let us first look at the effect of Eurex outages. Figure 9 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 (2023). 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.

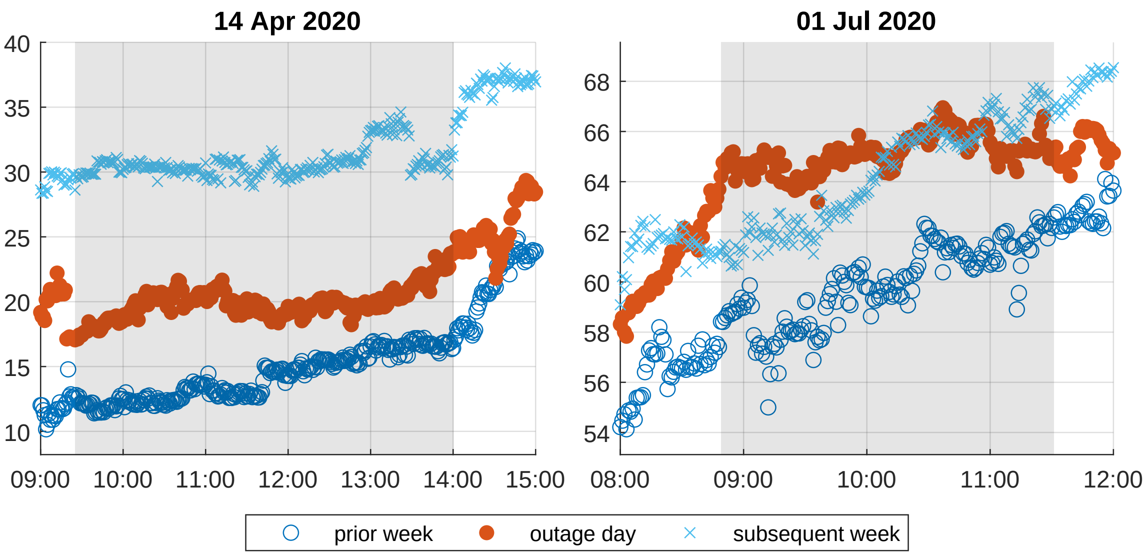


Figure 9: Order Book Depth of US Treasury Futures during Eurex outages. This figure shows the number of quoted contracts (in thousands) at the first 15 levels of both sides of the order book for 10-year Treasury futures. The grey area refers to the outage period on Eurex.

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.[26]

More importantly, Figure 10 shows that the 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.[27] 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, 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 (2023) and references therein.

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

[27] 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, namely the one expiring in March 2019, avoiding complications due to the roll-over to the next-nearest contract that occurred in early March.

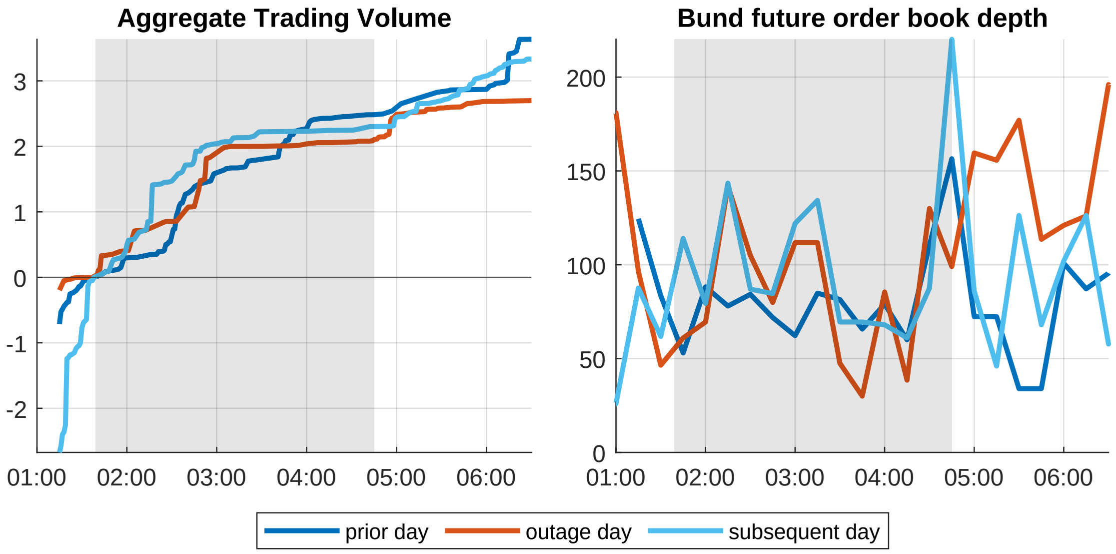


Figure 10: Eurex Activity during the CME Outage on 26 February 2019. The left panel shows the cumulative trading volume in all euro area bond futures on Eurex (in thousands of contracts, normalized to zero at the intraday time of the outage). The right panel shows the order book depth of 10-year German 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.

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 any asset. 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 unique non-anonymous transaction-level dataset, we can trace these macro-level effects back to the micro-level. In particular, we show that dealers withdraw disproportionately from the cash market during Eurex outages. While most of their remaining trades remain fairly priced, the absence of a hedging instrument constrains their capacity to intermediate bond trades on the cash market, thus forcing clients to trade directly with each other. These client-to-client trades exhibit large pricing errors, suggesting that bond futures serve different purposes for different investors. Dealers use futures mostly as a hedging instrument for inventory risk while clients use it as a pricing signal.

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.

References

Admati, A. R. (1985). A noisy rational expectations equilibrium for multi-asset securities markets. *Econometrica 53*(3), 629–657.

Allen, J. and M. Wittwer (2023a). Centralizing over-the-counter markets? *Journal of Political Economy 131*(12), 3310–3351.

Allen, J. and M. Wittwer (2023b). Intermediary Market Power and Capital Constraints. *Bank of Canada Working Paper 2023-51*.

Amihud, Y. (2002). Illiquidity and stock returns: cross-section and time-series effects. *Journal of financial markets 5*(1), 31–56.

Andersen, T. G., T. Bollerslev, F. X. Diebold, and C. Vega (2003). Micro Effects of Macro Announcements: Real-time Price Discovery in Foreign Exchange. *American Economic Review 93*, 38–62.

Andersen, T. G., T. Bollerslev, F. X. Diebold, and C. Vega (2007). Real-time price discovery in global stock, bond and foreign exchange markets. *Journal of International Economics 73*(2), 251–277.

Asriyan, V., W. Fuchs, and B. Green (2017). Information spillovers in asset markets with correlated values. *American Economic Review 107*(7), 2007–40.

Biais, B. and R. Green (2019). The microstructure of the bond market in the 20th century. *Review of Economic Dynamics 33*, 250–271.

Boehm, C. E. and T. N. Kroner (2023). The US, economic news, and the global financial cycle. Technical report, National Bureau of Economic Research.

Boudiaf, I. A., I. Frieden, and M. Scheicher (2024). The market liquidity of interest rate swaps. *ESRB Working Paper Series 2024/1479*.

Bouveret, A., M. Haferkorn, G. Gaetano, and O. Panzarino (2022). Flash Crashes on Sovereign Bond Markets - EU Evidence. *ESMA Working Paper*.

Brandt, M. W. and K. A. Kavajecz (2004). Price discovery in the US Treasury market: The impact of orderflow and liquidity on the yield curve. *The Journal of Finance 59*(6).

Brunnermeier, M. K. and L. H. Pedersen (2008). Market Liquidity and Funding Liquidity. *The Review of Financial Studies 22*(6), 2201–2238.

Cespa, G. and T. Foucault (2014). Illiquidity Contagion and Liquidity Crashes. *The Review of Financial Studies 27*(6), 1615–1660.

Chen, J. and J. Roth (2023). Logs with Zeros? Some Problems and Solutions. *The Quarterly Journal of Economics*, qjad054.

Cheung, Y. C., B. Rindi, and F. De Jong (2005). Trading European sovereign bonds: the microstructure of the MTS trading platforms. *Available at SSRN 424936*.

Clark-Joseph, A. D., M. Ye, and C. Zi (2017). Designated market makers still matter: Evidence from two natural experiments. *Journal of Financial Economics 126*(3), 652–667.

Czech, R., S. Huang, D. Lou, and T. Wang (2021). Informed trading in government bond markets. *Journal of Financial Economics 142*(3), 1253–1274.

Dalla Fontana, S., M. Holz auf der Heide, L. Pelizzon, and M. Scheicher (2019). The anatomy of the euro area interest rate swap market. *ECB Working Paper*.

de Roure, C., E. Moench, L. Pelizzon, and M. Schneider (2019). OTC Discount. *Deutsche Bundesbank Discussion Paper* (No 42/2019).

Deuskar, P. and T. C. Johnson (2011). Market Liquidity and Flow-driven Risk. *The Review of Financial Studies 24*(3), 721–753.

Dobreva, D. and E. Schaumburg (2023). High-frequency cross-market trading: Model free measurement and testable implications. *Working Paper*.

Duffie, D. (2023). Resilience redux in the US Treasury market. *Jackson Hole Symposium, Federal Reserve Bank of Kansas City*.

Duffie, D., P. Dworzcak, and H. Zhu (2017). Benchmarks in search markets. *The Journal of Finance 72*(5), 1983–2044.

Duffie, D., M. J. Fleming, F. M. Keane, C. Nelson, O. Shachar, and P. Van Tassel (2023). Dealer capacity and US Treasury market functionality. *FRB of New York Staff Report* (1070).

Dugast, J., S. Üslü, and P.-O. Weill (2022). A Theory of Participation in OTC and Centralized Markets. *The Review of Economic Studies 89*(6), 3223–3266.

Eisenbach, T. M., A. Kovner, and M. J. Lee (2022). Cyber risk and the U.S. financial system: A pre-mortem analysis. *Journal of Financial Economics 145*(3), 802–826.

Faust, J., J. H. Rogers, S.-Y. B. Wang, and J. H. Wright (2007). The high-frequency response of exchange rates and interest rates to macroeconomic announcements. *Journal of Monetary Economics 54*(4), 1051–1068.

Fleming, M., G. Nguyen, and F. Ruela (2024). Tick size, competition for liquidity provision, and price discovery: Evidence from the U.S. Treasury Market. *Management Science 70*(1), 332–354.

Fleming, M. J. and E. M. Remolona (1999). Price formation and liquidity in the US Treasury market: The response to public information. *The Journal of Finance 54*(5).

Gabaix, X. and R. S. J. Koijen (2021). In Search of the Origins of Financial Fluctuations: The Inelastic Markets Hypothesis. *NBER Working Paper 24122*.

Gabaix, X. and M. Maggiori (2015). International liquidity and exchange rate dynamics. *The Quarterly Journal of Economics 130*(3), 1369–1420.

Green, T. C. (2004). Economic news and the impact of trading on bond prices. *The Journal of Finance 59*(3), 1201–1233.

Gromb, D. and D. Vayanos (2002). Equilibrium and welfare in markets with financially constrained arbitrageurs. *Journal of Financial Economics 66*(2), 361–407.

Gromb, D. and D. Vayanos (2010). Limits of arbitrage. *Annu. Rev. Financ. Econ. 2*(1), 251–275.

Gromb, D. and D. Vayanos (2018). The dynamics of financially constrained arbitrage. *The Journal of Finance 73*(4), 1713–1750.

Guillaumie, C., G. Loiacono, C. Winkler, and S. Kern (2020). Market impacts of circuit breakers: Evidence from EU trading venues. *ESMA Working Paper*.

Gündüz, Y., G. Ottonello, L. Pelizzon, M. Schneider, and M. G. Subrahmanyam (2023). Lighting up the dark: liquidity in the German corporate bond market. *The Journal of Fixed Income*.

Gürkaynak, R. S., B. Kısacıkoğlu, and J. H. Wright (2020). Missing Events in Event Studies: Identifying the Effects of Partially-Measured News Surprises. *American Economic Review 110*(12), 3871–3912.

Hagströmer, B. and A. J. Menkveld (2023). Trades, Quotes, and Information Shares. *Available at SSRN*.

Harding, M. and P. Ma (2010). The impact of high frequency market makers upon market liquidity: Evidence from exchange outages. *Stanford University, Tech. Rep.*.

Hasbrouck, J. (1995). One security, many markets: Determining the contributions to price discovery. *The Journal of Finance 50*(4), 1175–1199.

He, Z. and A. Krishnamurthy (2013). Intermediary asset pricing. *American Economic Review 103*(2), 732–70.

Hortaçsu, A. and J. Kastl (2012). Valuing dealers' informational advantage: A study of Canadian Treasury auctions. *Econometrica 80*(6), 2511–2542.

Hu, G. X., J. Pan, and J. Wang (2013). Noise as Information for Illiquidity. *The Journal of Finance 68*(6), 2341–2382.

Jappelli, R., K. Lucke, and L. Pelizzon (2022). Price and liquidity discovery in European sovereign bonds and futures. *SAFE Working Paper*.

Kashyap, A. K. and A. Wetherilt (2019). Some Principles for Regulating Cyber Risk. *AEA Papers and Proceedings 109*, 482–87.

Kerssenfischer, M. and M. Schmeling (2024). What Moves Markets? *Journal of Monetary Economics forthcoming.*

Kondor, P. and D. Vayanos (2019). Liquidity risk and the dynamics of arbitrage capital. *The Journal of Finance 74*(3), 1139–1173.

Kutai, A., D. Nathan, and M. Wittwer (2023). Exchanges for government bonds? Evidence during COVID-19. *Available at SSRN 3882548*.

Lee, T. and C. Wang (2024). Why trade over-the-counter? *Journal of Finance forthcoming.*

Long, J. B. D., A. Shleifer, L. H. Summers, and R. J. Waldmann (1990). Noise trader risk in financial markets. *Journal of Political Economy 98*(4), 703–738.

Menkveld, A. J., B. Z. Yueshen, and H. Zhu (2017). Shades of darkness: A pecking order of trading venues. *Journal of Financial Economics 124*(3), 503–534.

Mitchell, M., L. H. Pedersen, and T. Pulvino (2007). Slow moving capital. *American Economic Review 97*(2), 215–220.

Mizrach, B. and C. J. Neely (2008). Information shares in the US Treasury market. *Journal of Banking & Finance 32*(7), 1221–1233.

Nelson, C. R. and A. F. Siegel (1987). Parsimonious modeling of yield curves. *Journal of business*, 473–489.

Paiardini, P. (2015). Informed trading in parallel bond markets. *Journal of Financial Markets 26*, 103–121.

Pasquariello, P. and C. Vega (2007). Informed and Strategic Order Flow in the Bond Markets. *The Review of Financial Studies 20*(6), 1975–2019.

Perrella, A. and J. Catz (2020). Integrating microdata for policy needs: the ESCB experience. *ECB Statistics Paper* (33).

Pintér, G., C. Wang, and J. Zou (2024). Size discount and size penalty: trading costs in bond markets. *Review of Financial Studies forthcoming.*

Roll, R. (1984). A simple implicit measure of the effective bid-ask spread in an efficient market. *The Journal of Finance 39*(4), 1127–1139.

Schestag, R., P. Schuster, and M. Uhrig-Homburg (2016). Measuring Liquidity in Bond Markets. *The Review of Financial Studies 29*(5), 1170–1219.

Shkilko, A. and K. Sokolov (2020). Every Cloud Has a Silver Lining: Fast Trading, Microwave Connectivity, and Trading Costs. *The Journal of Finance 75*(6), 2899–2927.

Shleifer, A. and R. Vishny (2011). Fire sales in finance and macroeconomics. *Journal of economic perspectives 25*(1), 29–48.

Shleifer, A. and R. W. Vishny (1997). The limits of arbitrage. *The Journal of Finance 52*(1), 35–55.

Svensson, L. E. (1994). Estimating and interpreting forward interest rates: Sweden 1992-1994. *National Bureau of Economic Research Working Paper No. 4871.*

Upper, C. and T. Werner (2007). The tail wags the dog: time-varying information shares in the Bund market. *BIS Working Paper No 224.*

Veldkamp, L. L. (2006). Information Markets and the Comovement of Asset Prices. *The Review of Economic Studies 73*(3), 823–845.

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.[28]

[28]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).

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.[29] 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.

[29] de Roure et al. (2019) 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 20% 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.

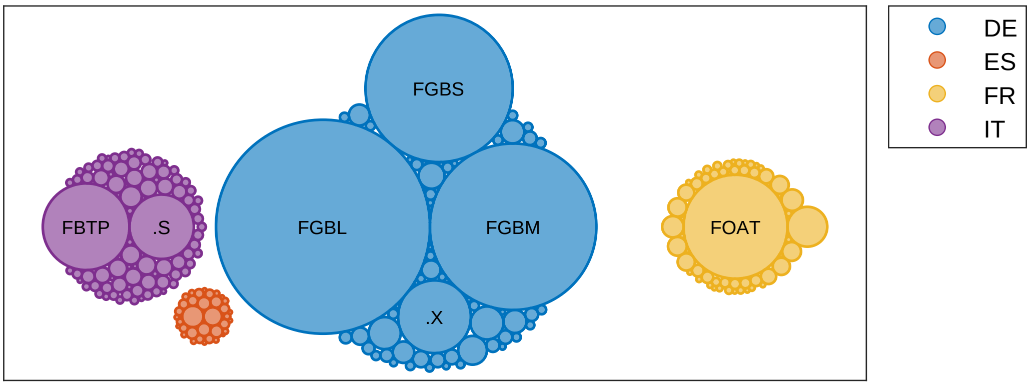


Figure A1: EGB Trading Volumes at the Instrument-Level. Each circle refers to an individual bond or bond future. Bond futures are labelled, e.g. 'FGBL' for the 10-year Bund future. The size of each circle is proportional to the trading volume in that instrument. In particular, the relative trading volume 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).

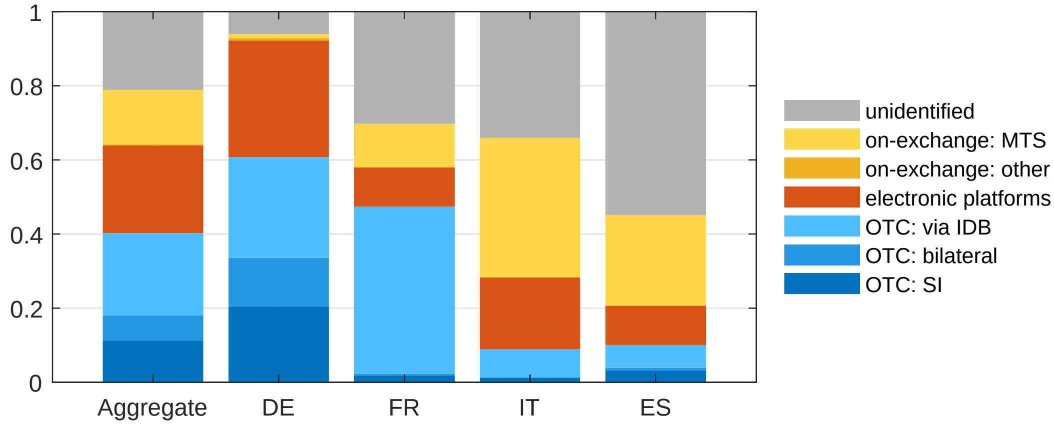


Figure A2: Market Shares of Cash Trading Venues. This figure breaks down the aggregate and country-level trading volume in EGBs into different cash trading venues. Results are based on our transaction dataset for all four non-outage days (i.e. April 7 and 21, June 30 and July 8, 2020), see Section A.5. '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	3.0	6.3	46.6
Years since Issuance	0.0	2.4	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	51	158
$2.5 - 5.5$ years	14	13	12	24	63
$5.5 - 10.5$ years	15	15	14	18	62
> 10.5 years	11	12	16	21	60
Total	77	64	88	114	343

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.4, 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 Spain, the 1-year OTR bond changed to ES0L02104161 on 17 April 2020, i.e. after the first Eurex outage.

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).[30] These reports usually contain the intraday timestamp, ISIN, price and volume of a traded bond, with some exceptions.[31] Transaction reports, in contrast, contain additional information, most importantly about the counterparties involved in each trade.[32] 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).[33] See below for further details on how we define duplicates and clean the data.

[30] 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.

[31] 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.

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

[33] 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	17258	1821	13172	1950	34201
Tradeweb	535	1738	2365	1379	6017
MTS	55	431	5278	461	6225
BondVision	125	206	2711	218	3260
Interdealer Broker	601	660	516	103	1880
Total	18574	4856	24042	4111	51583

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

	DE	FR	IT	ES	Total
Total	24.4	6.0	13.5	4.0	47.9
in % of total	51	13	28	8	

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.

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, 28% 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 bonds with less than one or more than ten years to maturity and we drop transactions with implausible prices. For the latter filter, we convert each transaction price to an implied yield[34] 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.

[34] 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	9.93	1292.00
Years to Maturity	1.00	5.61	5.78	9.86
Years since Issuance	0.11	2.23	3.25	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	-12.24	-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 Types and Segments

The regulatory transaction data mentioned above is non-anonymous, i.e. it contains a unique legal identifier (LEI) for at least one of the two counterparties involved in each cash transaction. We can thus use the Register of Institutions and Affiliates Database (RIAD database, see Perrella and Catz, 2020) to classify investors into the following categories: banks, non-bank financial institutions (NBFI), investment funds, insurance companies and pensions funds (ICPF), non-financial corporations (NFC), an official sector (including central banks) and households (retail investors). Table A11 gives an overview of the number of investors of each type and Table A12 of their number of transactions.

	Total	Dealer	Active on Eurex
Bank	296	33	81
NBFI	483	9	30
Investment Fund	768		37
ICPF	177		5
NFC	81		
Official	48		3
Households	1		
Total	1854	42	156

Table A11: Number of Investors by Type. The category 'households' comprisess an unknown number of retail investors, as these are not uniquely identifiable via a LEI.

	No Outage	Outage	Total
Bank Dealer	1567	313	1880
Bank Non-Dealer	519	163	682
NBFI Dealer	846	110	956
NBFI Non-Dealer	1205	284	1489
Investment Fund	391	83	474
ICPF	95	11	106
NFC	31	12	43
Official	323	25	348
HHs	137	65	202
Total	5114	1066	6180

Table A12: Number of Cash Transactions by Investor 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 banks and NBFIs, it is important to differentiate between (non)dealers. We identify dealers by exploiting the fact that only they are allowed to trade on MTS. Hence, we classify any investor that has executed at least 20 trades on MTS in 2020, in any of the bonds from Section A.4, as a dealer. This approach identifies a list of 42 dealers, 33 of which are 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 (identified via its LEI) 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', which applies to more than 150 investors. This way we can differentiate between cash market trades in which both, only one, or none of the two counterparties is usually active on Eurex.

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 contains newspaper reports on the two Eurex outages studied in Section 3 of the paper, Appendix B.3 does the same for the previous Eurex outages studied in Appendix C, and Appendix B.4 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.3. 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.

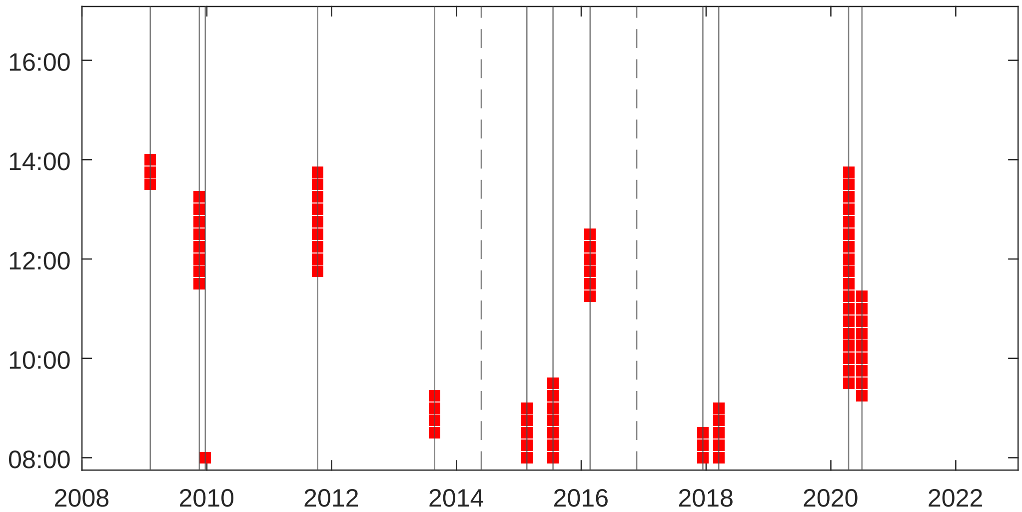


Figure A3: System-Wide Eurex Outages since 2008. For each trading day since 2008, red squares mark 15-minute intraday windows with no trading in the German 10-year bond future (FGBL), which line up perfectly with the twelve known outage days, marked by solid vertical lines. The two dashed lines mark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

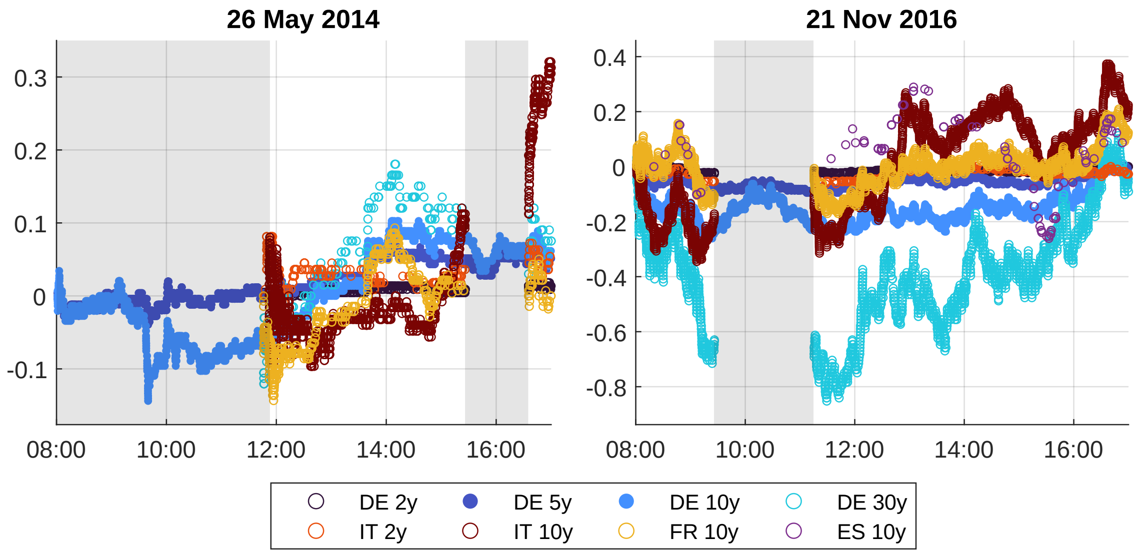
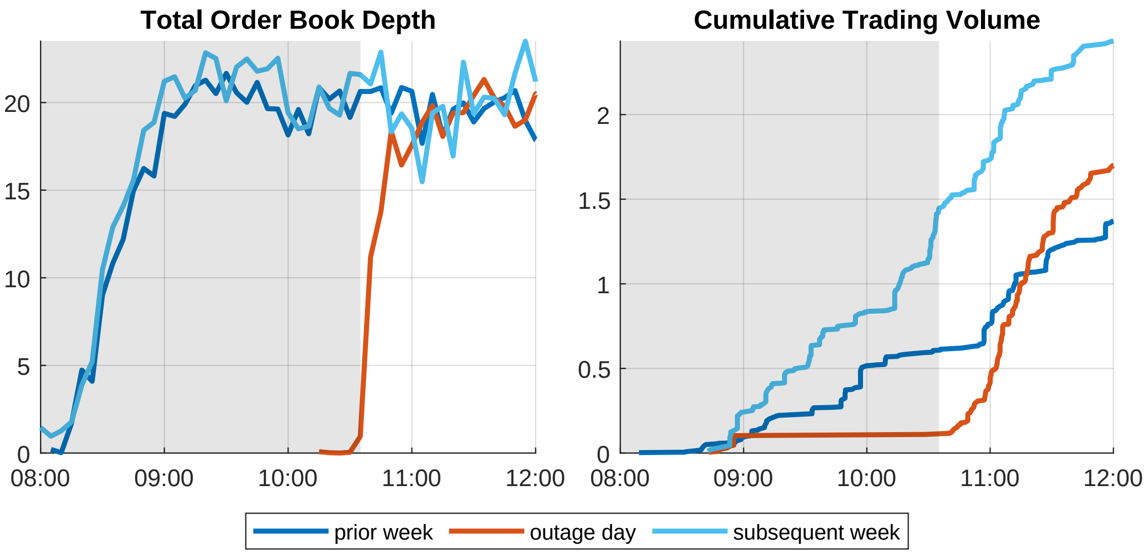


Figure A4: Partial Outages on Eurex. This figure shows intraday transaction prices of all euro area government bond futures (in percentage changes since 8:00 a.m.). The grey areas mark the outage times that affected all futures except those for 5-year and 10-year German bonds. The Spanish 10-year future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

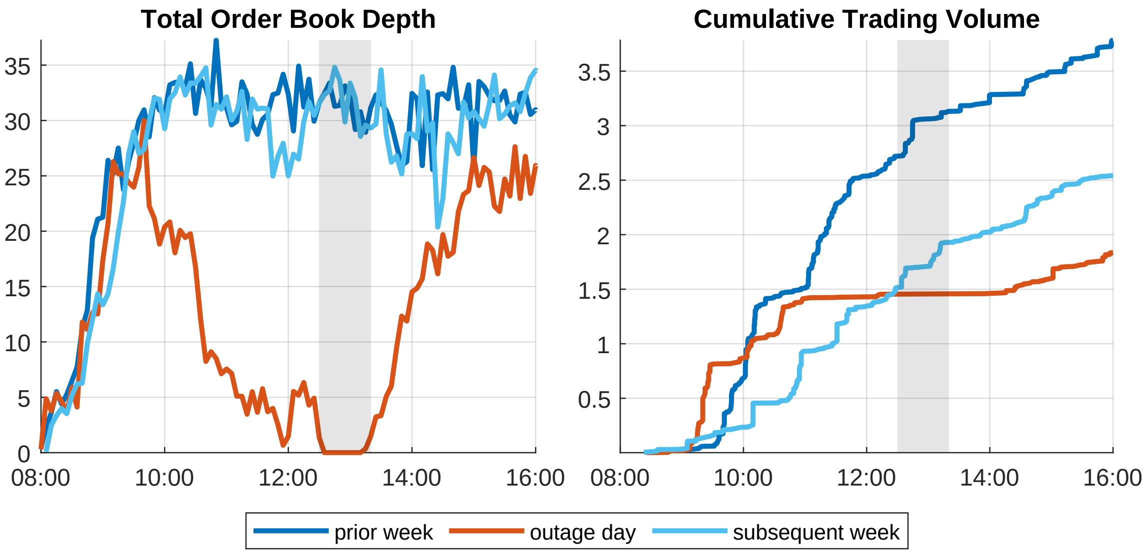


Figure A5: Outages on MTS. The left panels show the total quoted volume (in billion €), across all German, French, Italian and Spanish sovereign bonds and all market segments, in 5-minute intervals. The right panels show the total cumulative trading volume (in billion €). Red lines refer to the (suspected)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

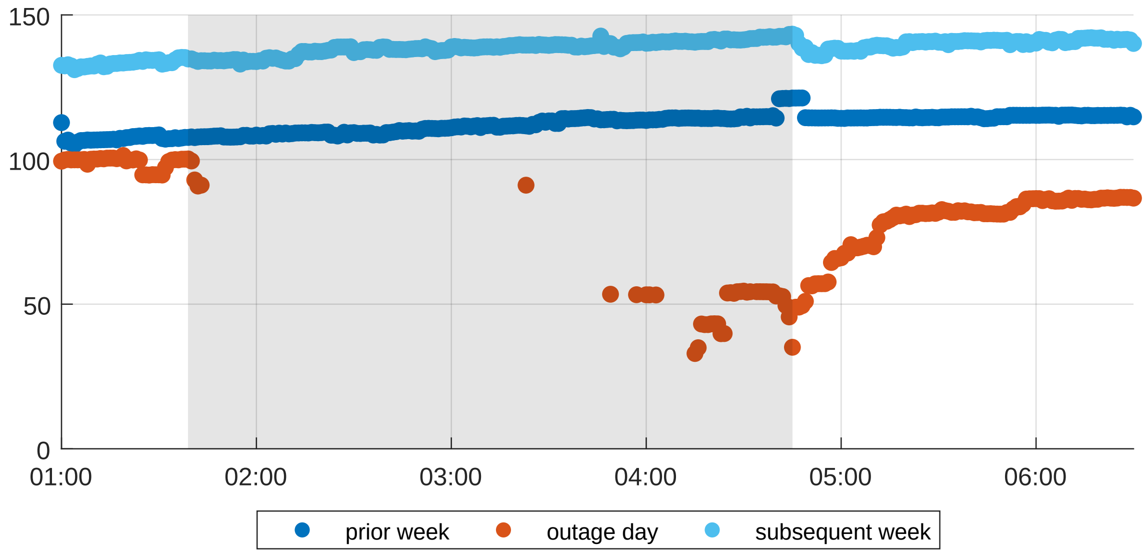


Figure A6: CME Outage on 26 February 2019. This figure shows the order book depth of 10-year US Treasury futures, i.e. the number of contracts (in thousands) quoted on both sides of the first 15 order book levels. The Red line refers to the outage day, dark and light blue lines refer to the previous 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 in 2020

The official Eurex Twitter account released the following info about the outages.

On 14 April 2020 at 10:32 a.m.: *'Due to technical problems, the Eurex T7 system is not available at the moment. We are investigating and will keep you informed'.*

At 1:19 p.m. the same day: *'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'.*

On 1 July 2020 at 10:11 a.m.: *'Due to technical problems the trading system T7 is not currently available'.*

At 11:54 a.m. the same day: *'Update on the disruption: continuous trading on Eurex resumed at 1130'.*

The first Dow Jones news article on the 14 April 2020 outage was released at 11:47 a.m. and stated:
'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.'

A subsequent Reuters news article explained:
'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.'

The first Reuters news article on the 1 July 2020 outage was released at 9:39 a.m. and mentioned:
'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.'

A later Reuters news article on the same day elaborated:
'The reappearance of a software glitch that was first seen in April was behind a nearly three hour outage on Wednesday on Germany's electronic trading platform Xetra, the exchange operator Deutsche Boerse said.The issue resulted from a problem with third-party software and has been fixed, Deutsche Boerse said. 'The system is now running stably and we expect it to remain so,' Deutsche Boerse said on Wednesday. The technical snag on Wednesday follows one of the exchange operator's longest outages in April when the Frankfurt stock market was halted for more than four hours. Chief Executive Theodor Weimer said after the April blackout that the stock exchange had taken precautions to avoid such a breakdown in the future.'

A Bloomberg news article from 1 July 2020 cites a Eurex spokesman as follows:
'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.'

A Financial Times article from 1 July 2020 states:
'A series of high-profile outages in the second half of 2020 has put the spotlight on operators of the financial infrastructure that underlies global markets. [..] The glitches have underscored global authorities' mounting concerns that the reliance across markets on technology and automation to buy and sell assets at the blink of an eye is creating a risk to the financial system. [..] The matter has taken on more urgency over the past few months. Germany's main market, Deutsche

Börse's Xetra in Frankfurt, was hit by repeated technical failures this year that took out share trading across several European countries.'

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.'*

B.3 News Reports on Previous Eurex Outages

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 im-

pact.

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, including 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.4 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.[35]

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.

[35] 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: 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.

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. 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.[36]

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 A15 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).

Figure A7 confirms this point graphically. In all but one case, the EGB trading volume was much smaller than usual, often effectively zero, on the spot market during the outage. Trading only picked up once the futures market was back online.

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 A16. 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.

[36] 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 was too short-lived and too early in the day to observe any effect on the spot 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 A15: Effect of Previous Eurex Outages on Cash Trading Volume. 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.

Figure A8 confirms this visually. Every time Eurex has been offline, liquidity on MTS has been much lower than usual. Figure A9 shows the order book depth on MTS at the country-level. It confirms that liquidity drops for all countries. The only minor exception are Italian bonds, where liquidity deteriorates, but does not evaporate entirely. Figure A10, lastly, looks at the different maturity segments. Again in line with our previous findings, the short end of the yield curve is usually less affected by Eurex outages than the medium to long end.

	(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 A16: 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).

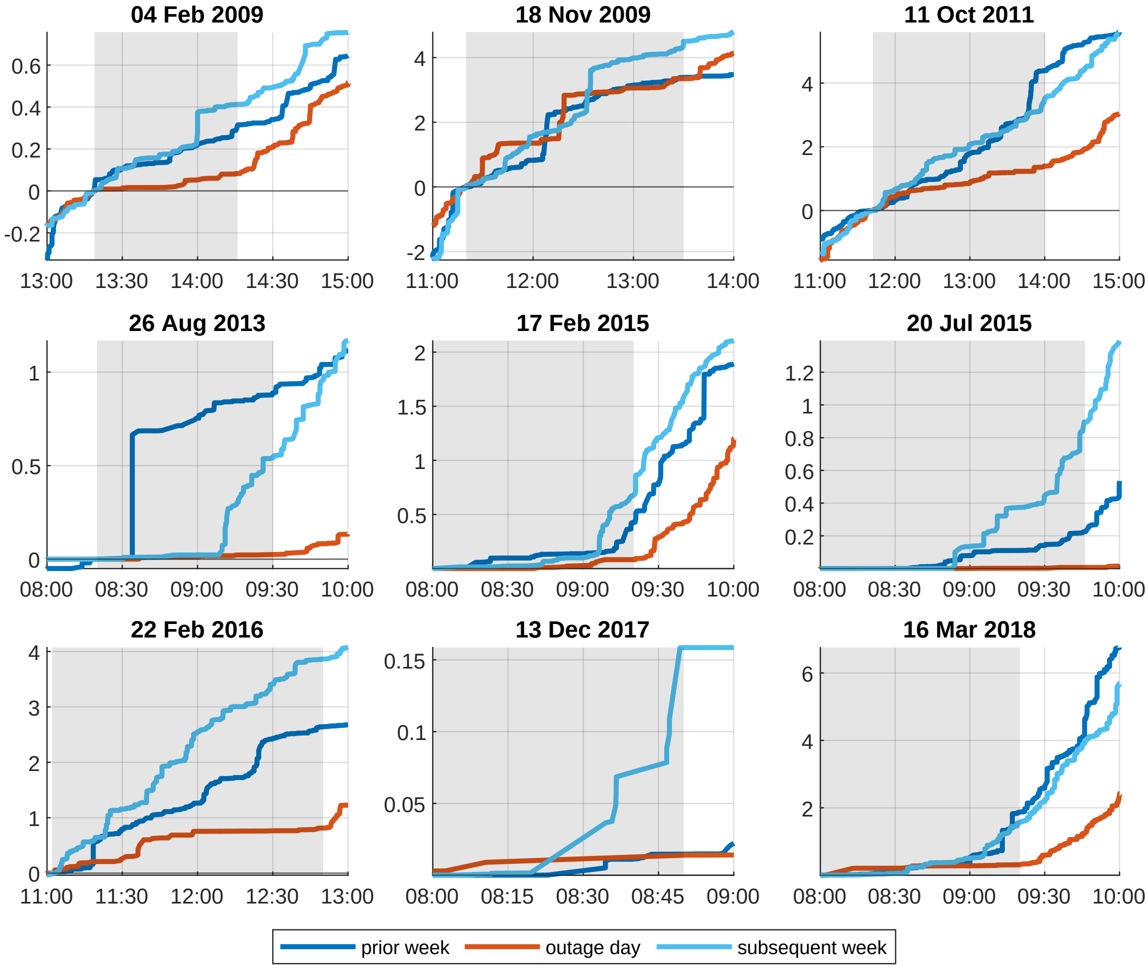


Figure A7: Cumulative EGB Trading Volume during previous Eurex Outages. This figure shows the cumulative trading volume (in billion €) in German, French, Italian and Spanish bonds. Note that the underlying 'Bafin' dataset almost exclusively covers trades in German bonds, see Section C.1 for details. Red lines refer to the outage day, dark and light blue lines refer to the previous and subsequent week. The grey areas mark the exact outage times on Eurex, which we verified using transactions data on Bund futures.

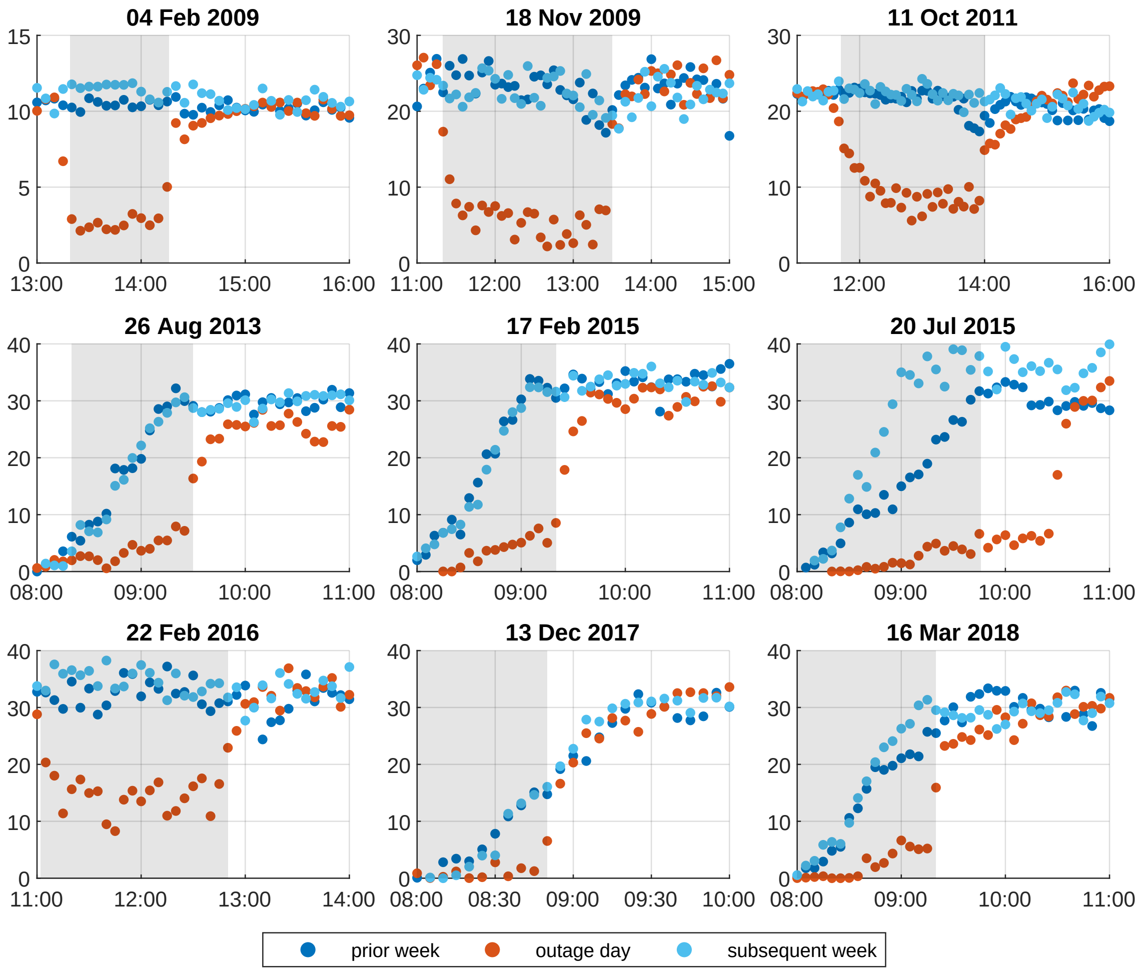


Figure A8: Total Order Book Depth on MTS during previous Eurex Outages. This figure shows the total quoted volume (in billion €) for all German, French, Italian and Spanish bonds across all three levels and both sides of the order book, at 5-minute snapshots. Each panel refers to a Eurex outage between 2008 and 2020, grey areas mark the exact intraday times of the outages. Red dots refer to outage days, dark and light blue dots to the previous and subsequent week.

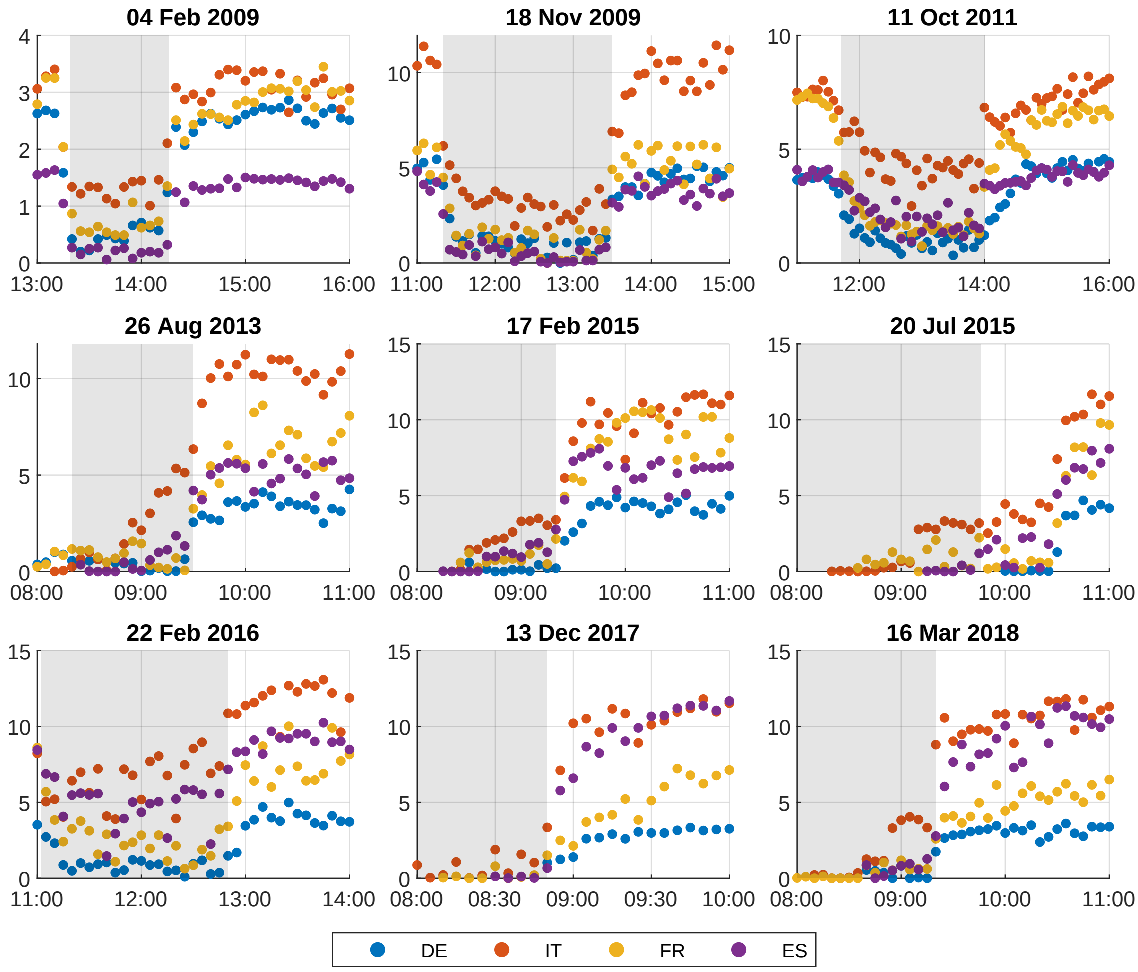


Figure A9: Total Order Book Depth on MTS at the Country-Level. This figure shows the total quoted volume (in billion €) for German, French, Italian or Spanish bonds, across all three levels and both sides of the order book, at 5-minute snapshots. See previous figure for details.

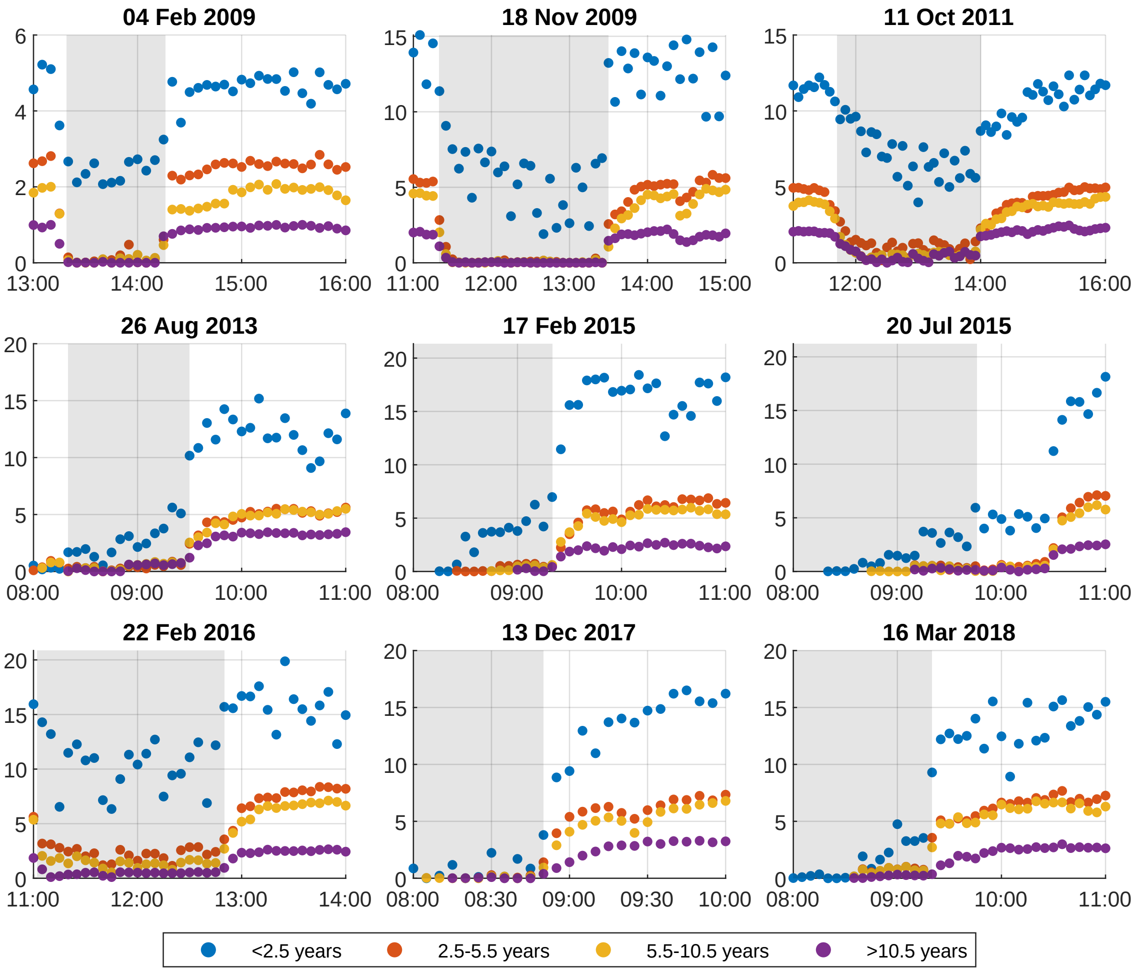


Figure A10: Total Order Book Depth on MTS across Maturity Buckets. This figure shows the total quoted volume (in billion €) for all German, French, Italian and Spanish bonds, across all three levels and both sides of the order book, at 5-minute snapshots, broken down by the remaining maturity of the bonds (less than two years, two to five years, and more than five years). See previous figure for details.

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 A17 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 A17: 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.[37] Figure A11 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.

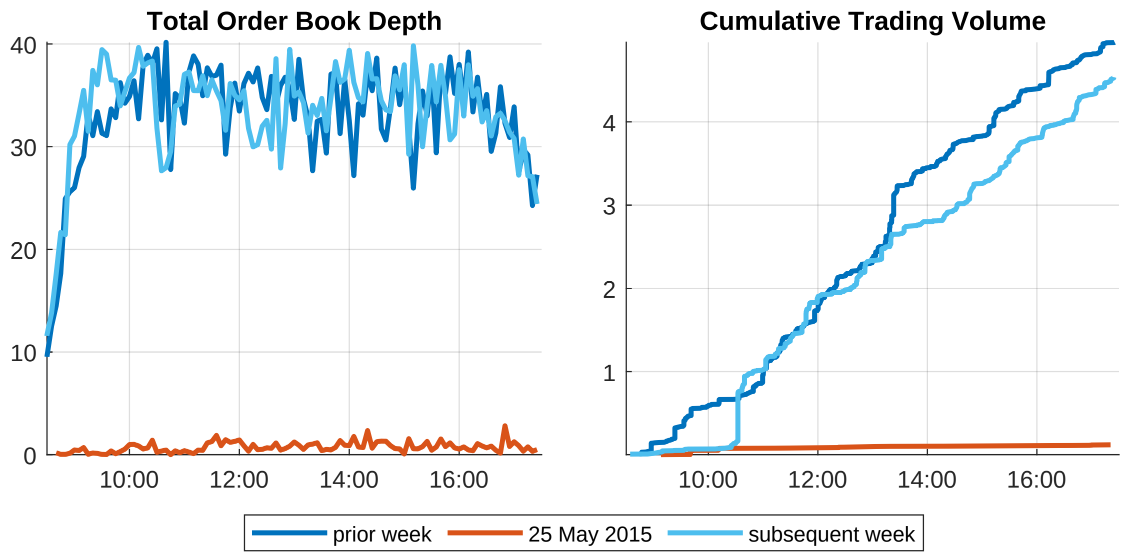


Figure A11: MTS Inactivity on Eurex Holiday. The left panel shows the total order book depth on MTS (in billion €), across all German, French, Italian and Spanish bonds and all market segments, in 5-minute snapshots. The right panel shows the total cumulative trading volume, in billion €. Red lines refer to 25 May 2015 (when Eurex was closed due to a holiday), dark and light blue lines refer to the previous and subsequent week.

[37] 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 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.2 documents that the liquidity dry-up on MTS was widespread and affected virtually all bonds.

Appendix D.3 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.4 contains ISIN-level regression results for the effect of Eurex outages on trading volumes and order book liquidity of cash bonds.

Appendix D.5 provides robustness checks regarding the effect of Eurex outages on indicative EGB quotes on the cash market.

D.1 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.[38] How did the swap market react to the Eurex outages? Below, we study short-term and long-term swaps separately, because they are used for very different purposes.

Short-term interest rate swaps are typically used to manage short-term liquidity needs or to take advantage of arbitrage opportunities in money markets. We focus on overnight index swaps that exchange fixed-rate interest payments over three, six or twelve months for floating-rate interest payments based on the daily euro short-term rate (€STR). €STR captures the average borrowing costs of euro area banks in the wholesale euro unsecured overnight market.

Figure A12 shows how these short-term swaps behaved during the Eurex outages, based on Bloomberg data.[39] At first glance, these rates exhibit their usual variability, i.e. they did not become stale during the Eurex outage (in contrast to the longer-term bond yields on Bloomberg, see Section 3.2.2). This might not come as a surprise, since these short-term swaps mainly reflect the expected path of overnight rates, which are closely linked to the ECB's policy rates, and for which the ECB provided extensive forward guidance at the time.[40] Hence, our results suggest that price discovery at the very short end of the yield curve does not hinge on bond futures.

At longer maturities, swaps are typically used to hedge duration risk. Figure A13 shows that these longer-term swap rates are affected by the outage on Eurex. While 2-year swaps still look fine, quotes for 5-year and 10-year swaps disappear on Bloomberg. Figure A14 confirms that the bid-ask spreads for these longer-dated swaps were also higher than usual during the outage, if quotes were available at all. We confirm these results using interest rate swap data from an interdealer broker. In particular, Compagnie Financière Tradition, a listed company

[38] See Dalla Fontana, Holz auf der Heide, Pelizzon, and Scheicher (2019) and Boudiaf, Frieden, and Scheicher (2024) for a detailed anatomy of the euro area interest rate swap market.

[39] These results are based on the pricing source 'BGNL', i.e. indicative quotes from Bloomberg London.

[40] Up until the December meeting, each ECB press release in 2020 contained the following paragraph: *'The interest rate on the main refinancing operations and the interest rates on the marginal lending facility and the deposit facility will remain unchanged at 0.00%, 0.25% and -0.50% respectively. The Governing Council expects the key ECB interest rates to remain at their present or lower levels until it has seen the inflation outlook robustly converge to a level sufficiently close to, but below, 2% within its projection horizon, and such convergence has been consistently reflected in underlying inflation dynamics.'* In line with this forward guidance, the daily €STR rate barely moved. Between April and July 2020, it fluctuated between -.53 and -.56 percent.

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 A15 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.

If bond futures and long-term swaps were equally viable hedging instruments, one might have expected that trading migrates from futures to swaps during the Eurex outage. We find the opposite. The long-term interest rate swap market breaks down the moment bond futures become unavailable. 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 are unwilling to act as intermediaries on the swap market, leading to the evaporation of quotes we observe. But this brings us back to where we started: why are bond futures the dominant hedging instrument in the first place? In our view, the root cause 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 the cross-asset learning model of Cespa and Foucault, 2014).

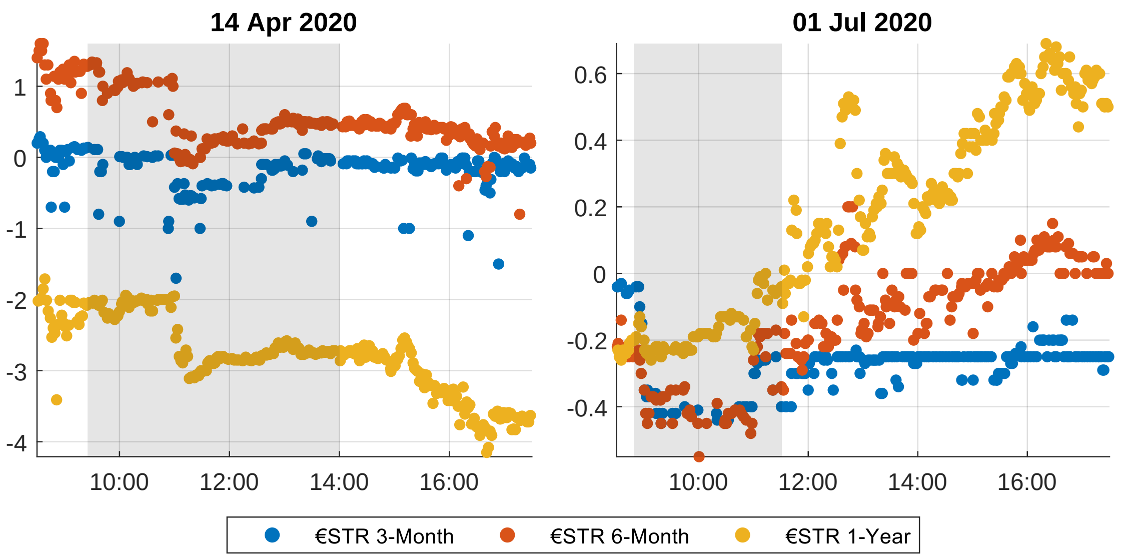


Figure A12: Short-Term €STR Swap Rates on Bloomberg. This figure shows cumulative rate changes (in basis points, normalized to zero at 8:00 a.m.) for overnight index swaps of different tenors based on the euro short-term rate (€STR).

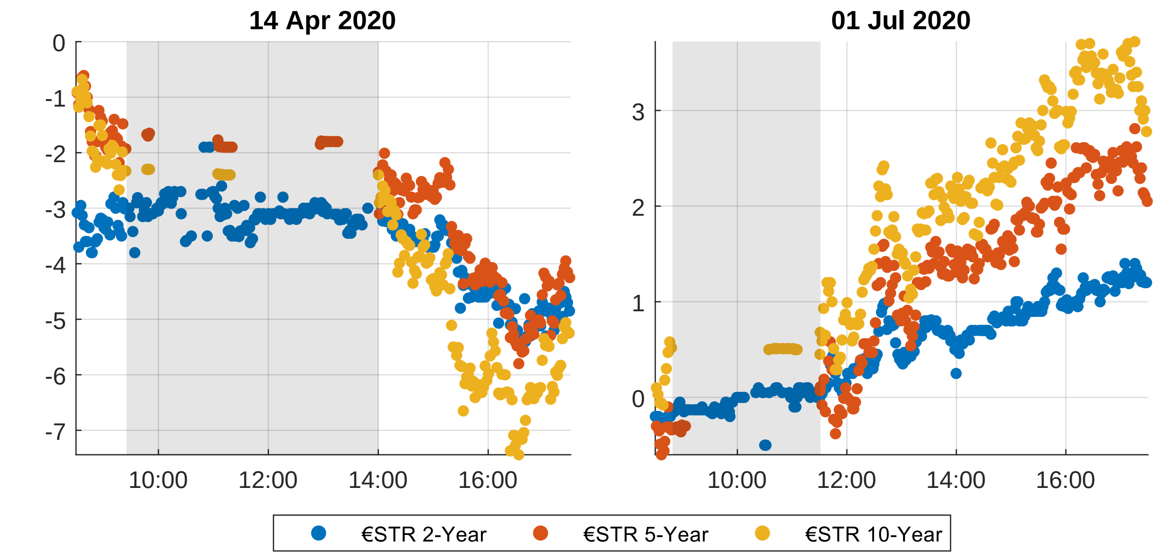


Figure A13: Longer-Term €STR Swap Rates on Bloomberg. See previous figure for details.

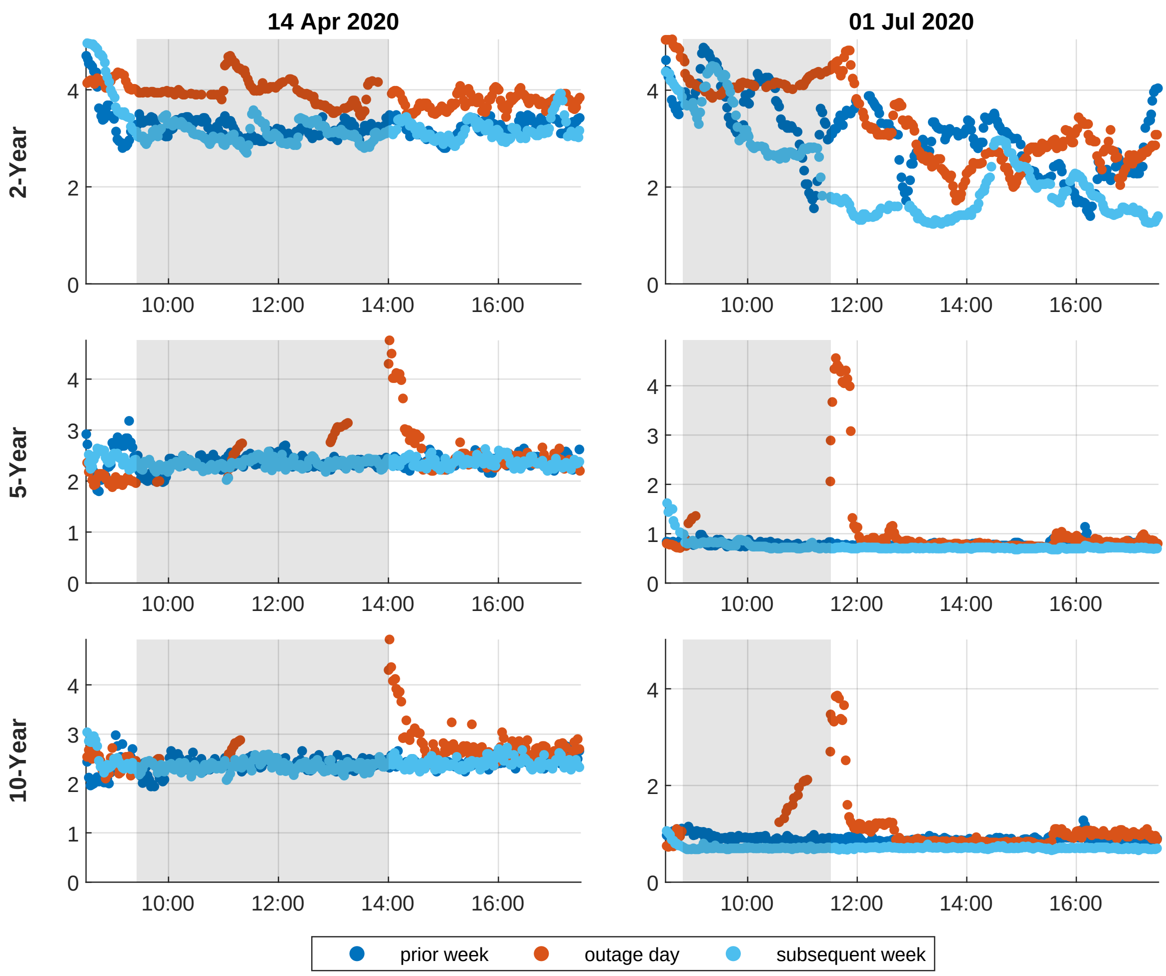


Figure A14: Bid-Ask Spread of €STR Swap Rates on Bloomberg. This figure shows the bid-ask spread (in basis points) for overnight index swaps of different tenors based on the euro short-term rate (€STR). Red lines refer to outage days, dark and light blue lines refer to the previous and subsequent week.

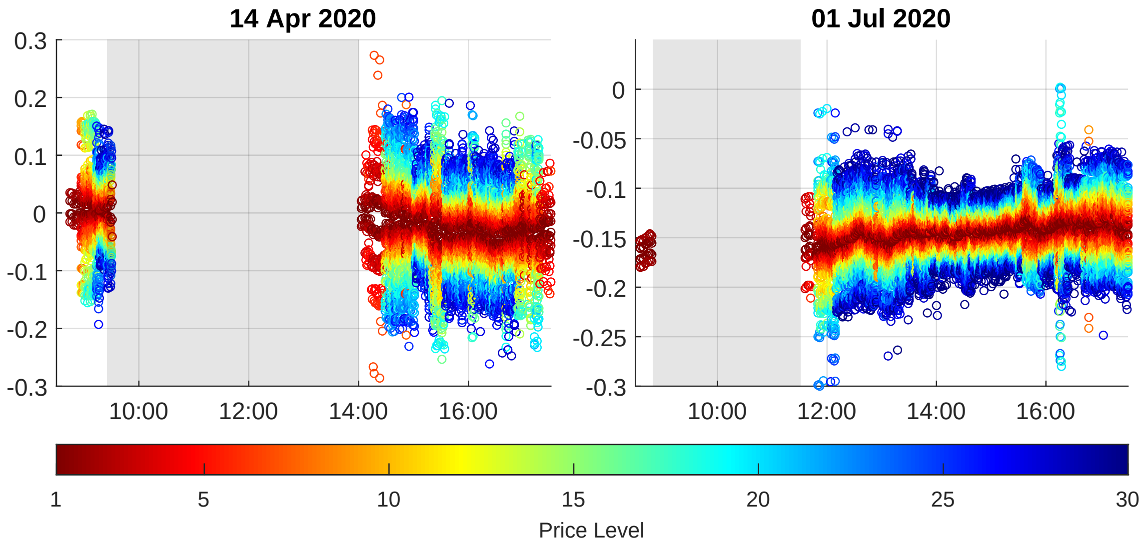


Figure A15: Bid and Ask Quotes for 10y/6m Euribor Swaps on Trad-X. The figure shows bid and ask quotes across different order book levels.

D.2 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 A16 replicates this figure at the country-level.

Figure A17 confirms that for these bonds, most mid prices disappear entirely. If the bonds are quoted at all, then at huge bid-ask spreads, see Figure A18 (note the log-scale).

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 A19 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. Figure A20 shows that the liquidity drops in all bonds that were deliverable into the 10-year future contract. In fact, our results hold for the entire universe of bonds. Figure A21 documents a sharp decline in liquidity across countries and Figure A22 across maturities. Figure A23, lastly, shows that the number of bonds that were quoted at all dropped dramatically in all countries.

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 A24 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'.

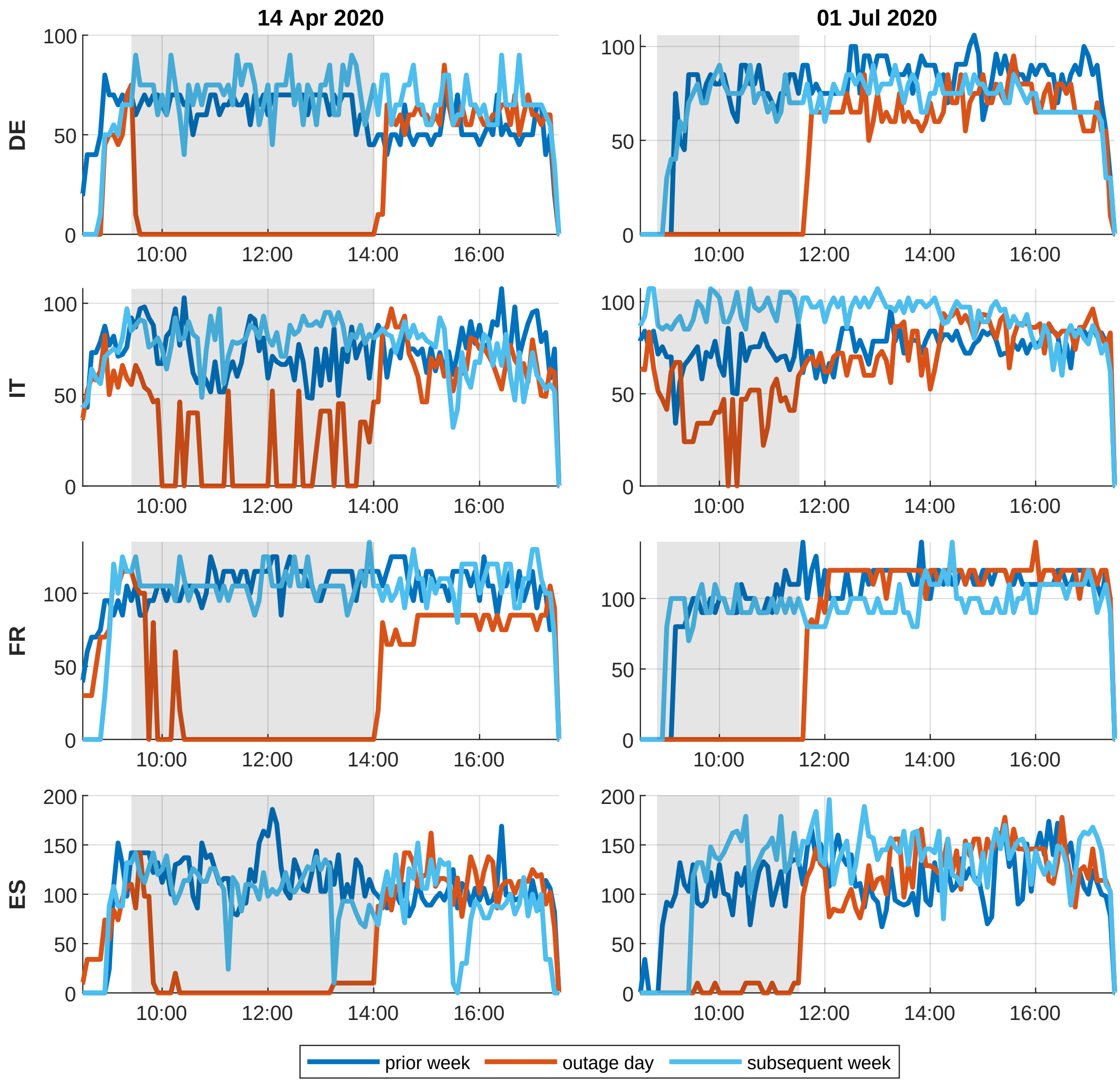


Figure A16: Order Book Depth on MTS. This figure shows the total quoted volume for 10-year CTD bonds (in million €) across all three levels and both sides of the order book, at 5-minute snapshots. See Figure A17 for details.

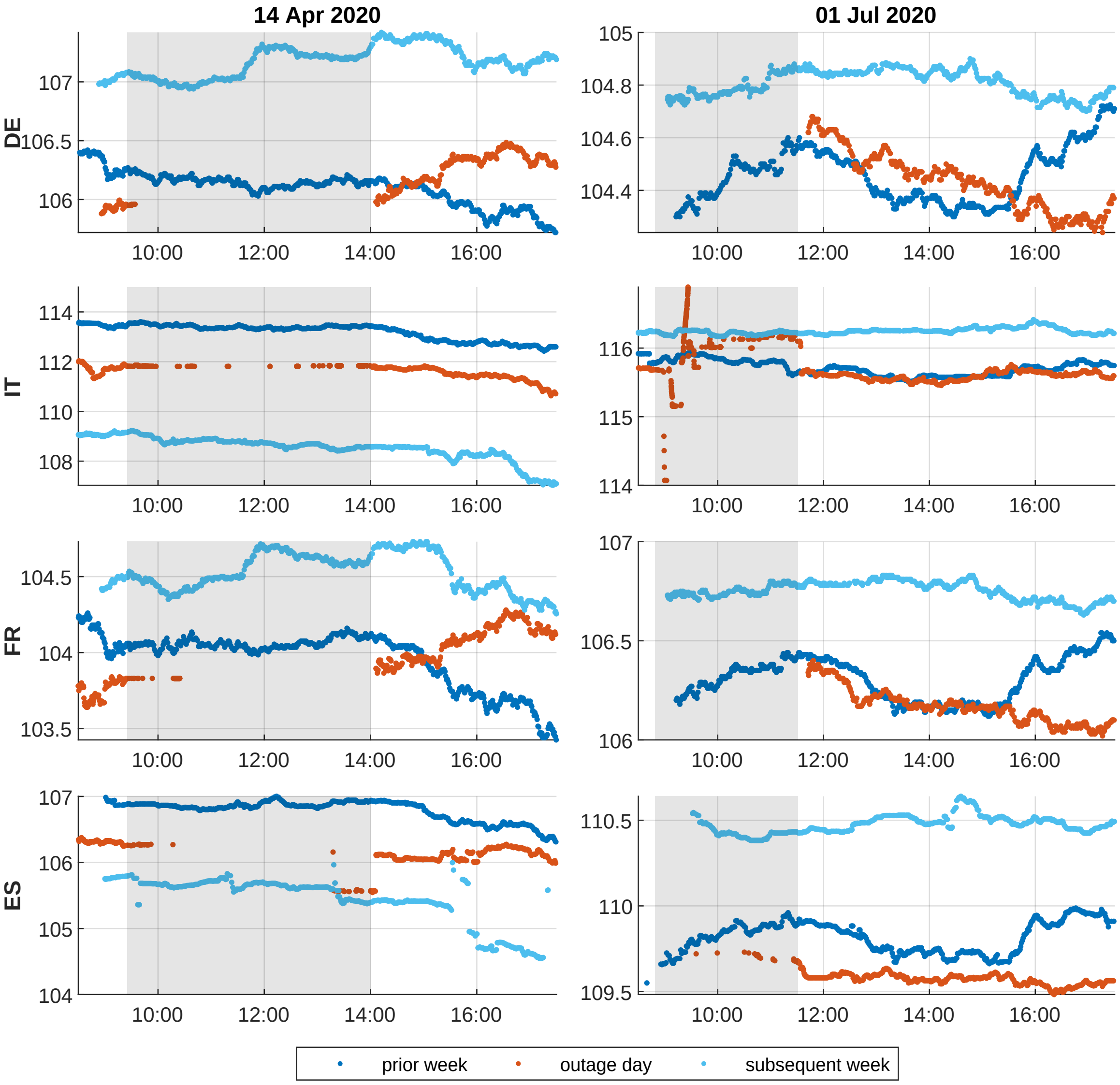


Figure A17: Mid prices on MTS. This figure shows the average of the best bid and ask quote for the cheapest-to-deliver bond underlying the 10-year bond future on Eurex. Red dots refer to outage days, dark and light blue dots to the previous and subsequent week.

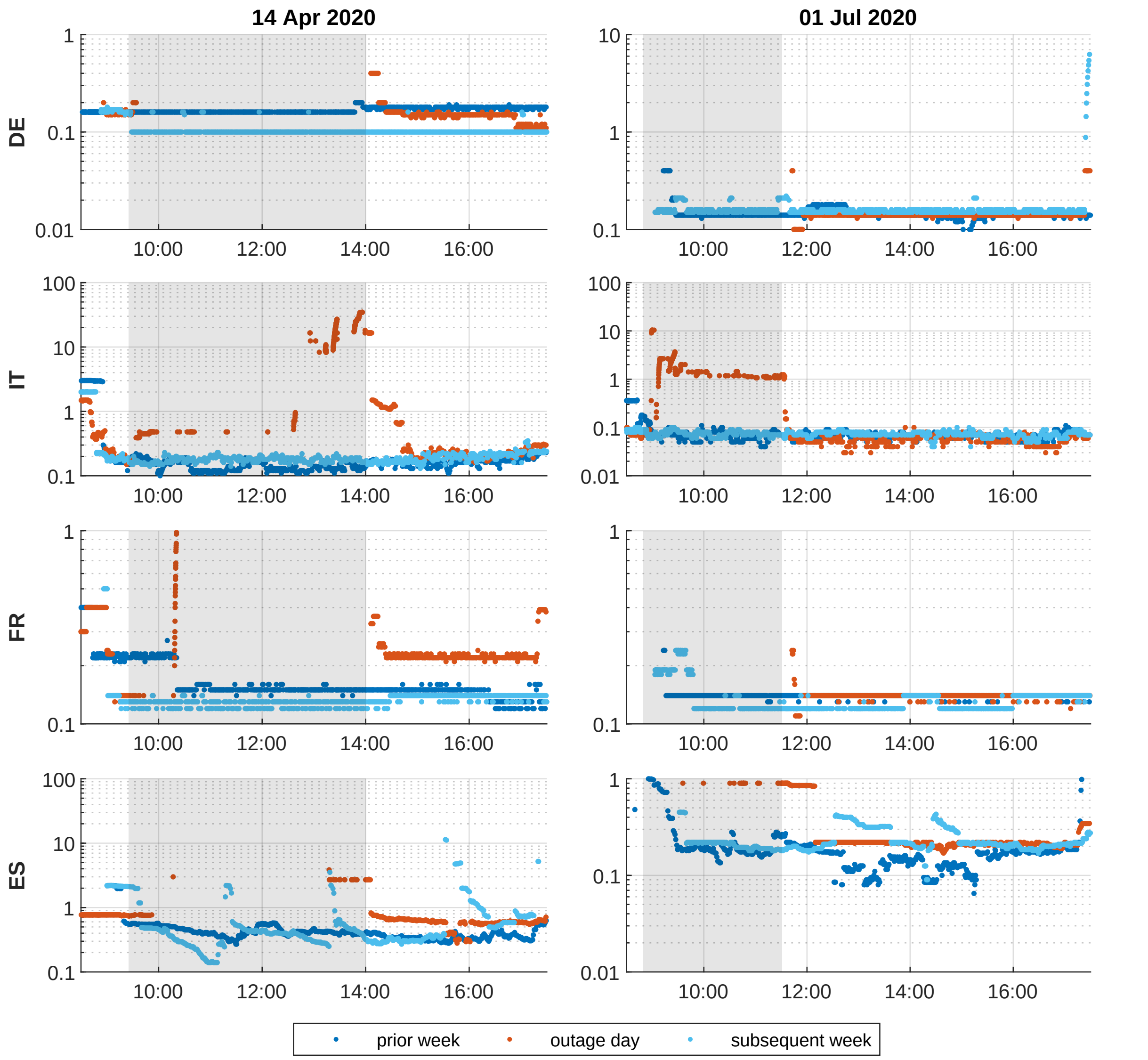


Figure A18: Bid-Ask Spreads on MTS. This figure shows the difference between the best ask and best bid price in Euro for 10-year CTD bonds (on a log scale). See Figure A17 for details.

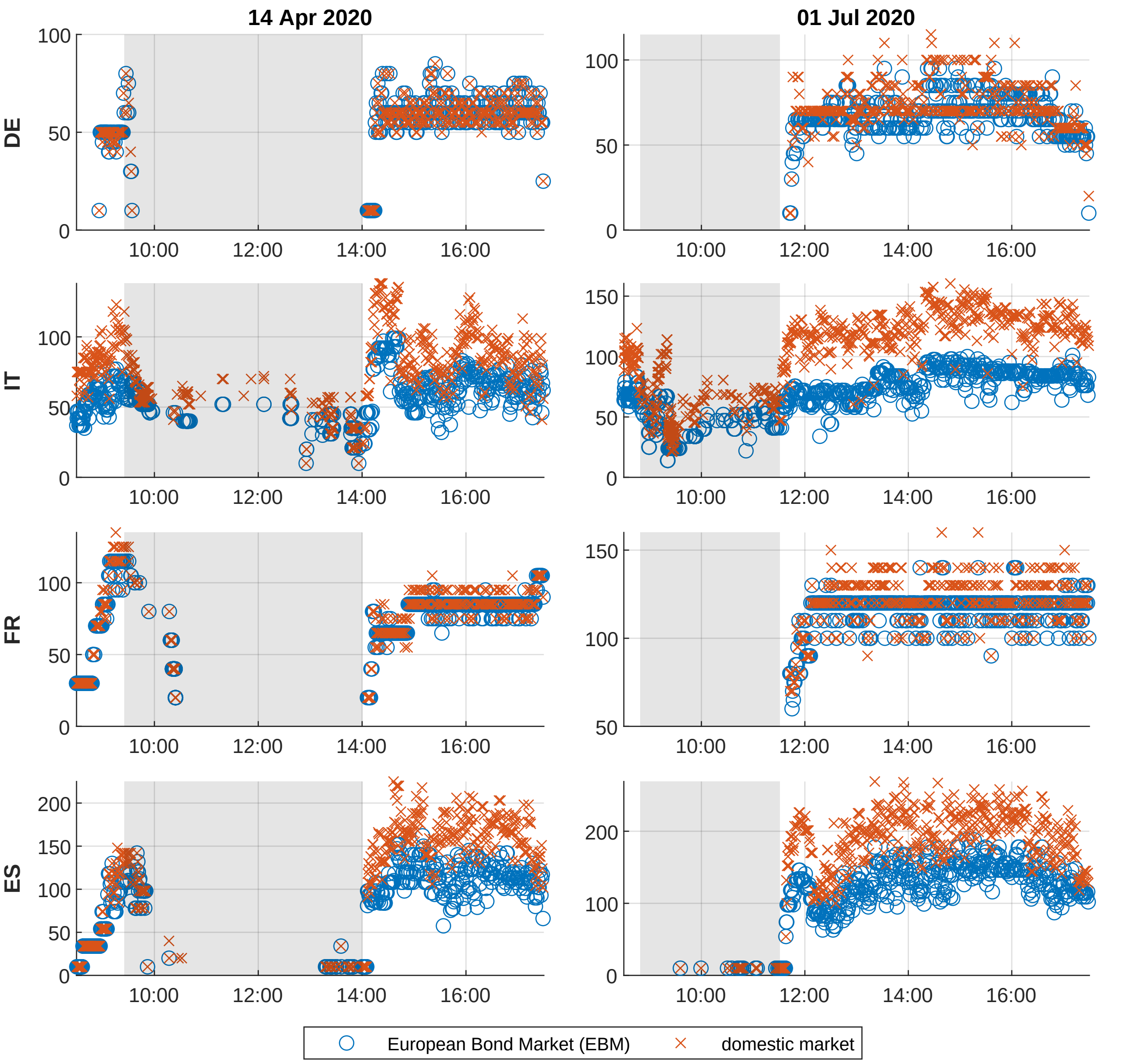


Figure A19: Order Book Depth of CTD bond on different MTS market segments. This figure shows the total quoted volume (in million €) across all three levels and both sides of the order book, for the cheapest-to-deliver bond underlying the 10-year future. Blue circles refer to the 'European Bond Market' segment (as in the main text), red crosses refers to the domestic market segment.

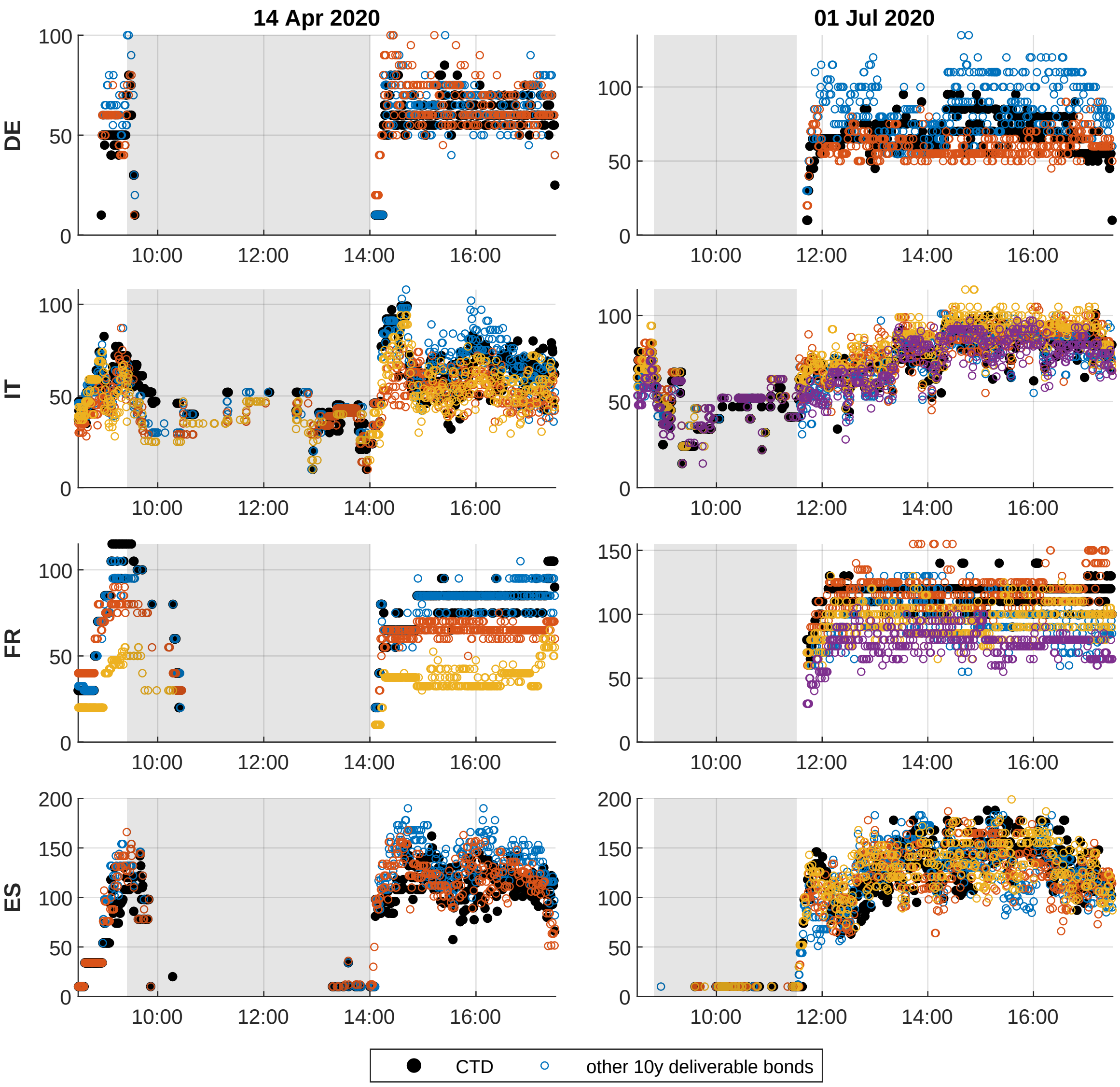


Figure A20: Order Book Depth of 10-year deliverable Bonds on MTS. This figure shows the total quoted volume (in million €) across all three levels and both sides of the order book. Black dots refer to the cheapest-to-deliver bond (as in the main text). Coloured circles refer to all other bonds that are deliverable into the 10-year future contract (one colour per ISIN).

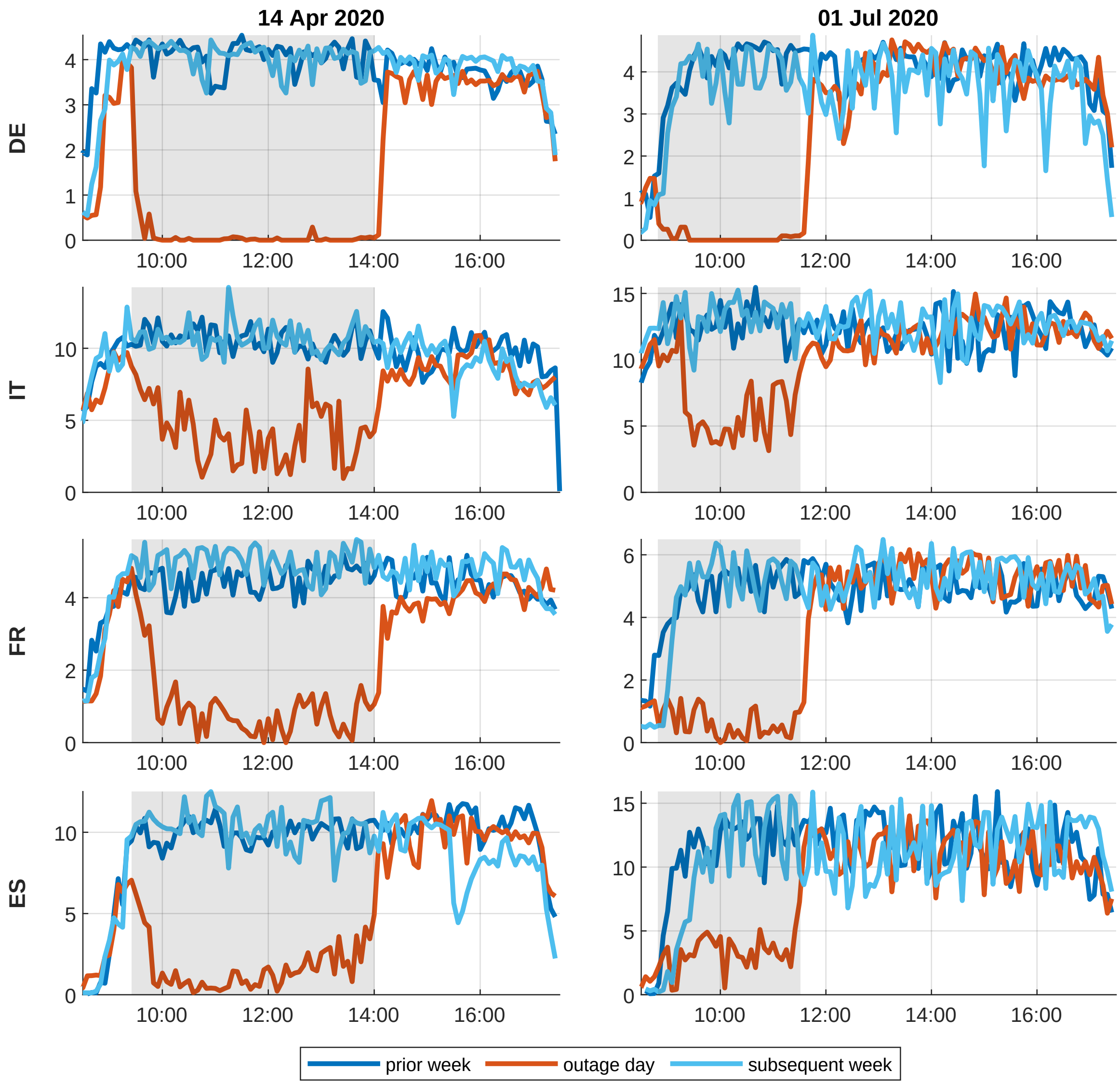


Figure A21: Total Order Book Depth on MTS across Countries. This figure shows the total quoted volume (in billion €) for German, French, Italian and Spanish bonds across all three levels and both sides of the order book, at 5-minute snapshots.

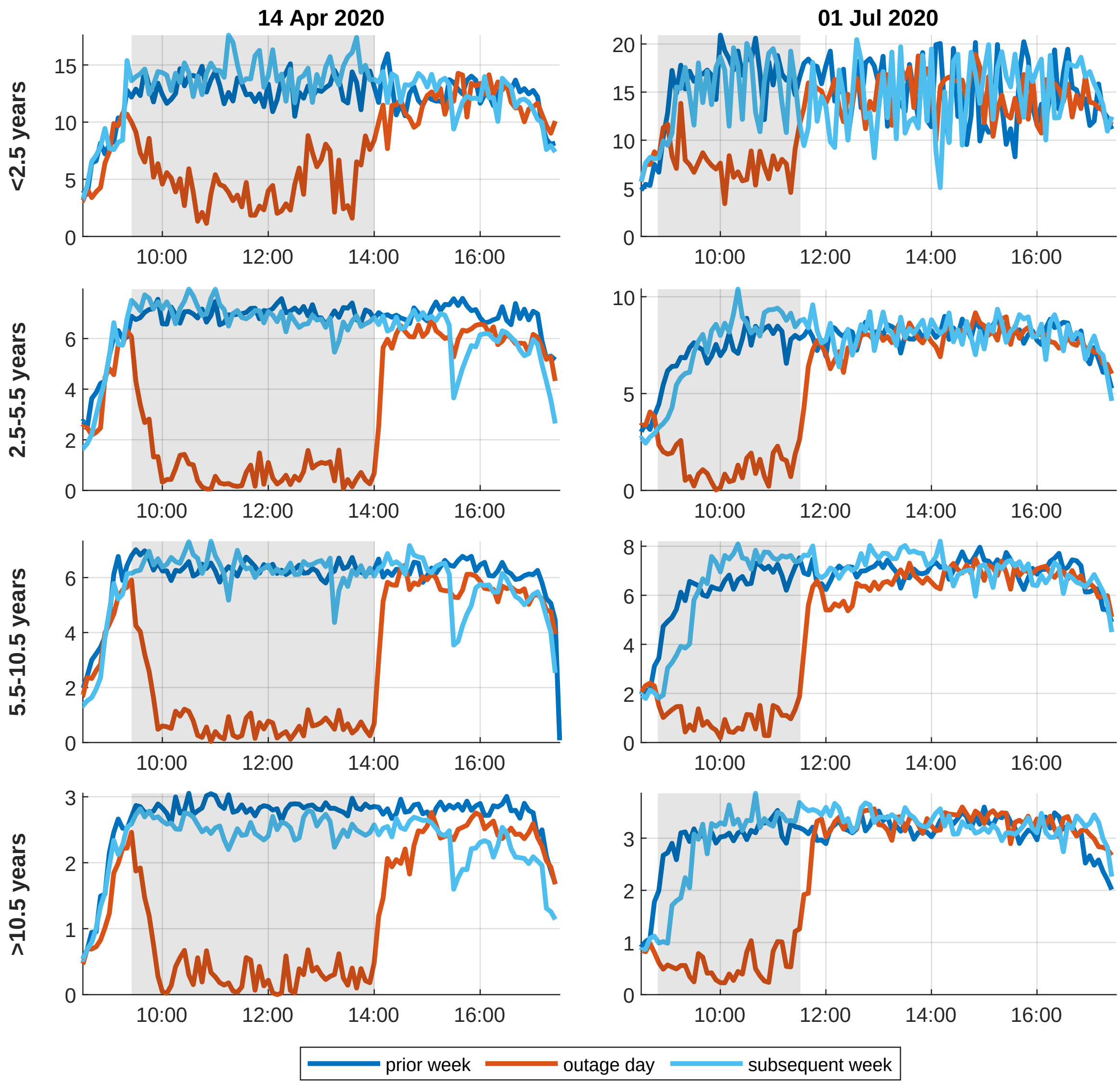


Figure A22: Total Order Book Depth on MTS across Maturity Buckets. This figure shows the total quoted volume (in billion €) for all German, French, Italian and Spanish bonds across all three levels and both sides of the order book, at 5-minute snapshots, broken down by the remaining maturity of the bonds (less than 2.5 years, 2.5 to 5.5 years, 5.5 to 10.5 years, and more than 10.5 years).

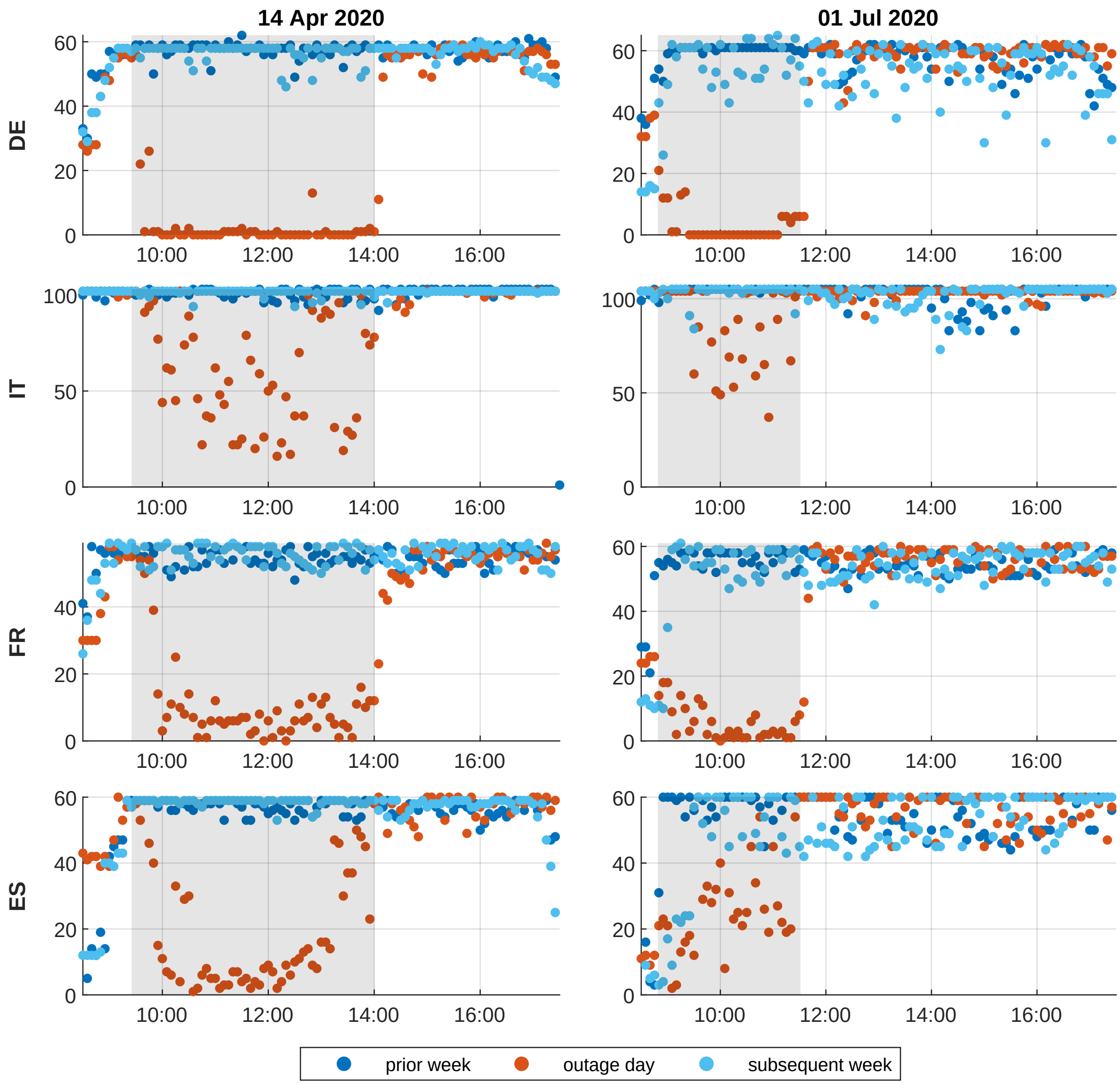


Figure A23: Number of ISINs quoted on MTS. This figure shows the number of quoted ISINs per country, in 5-minute intervals.

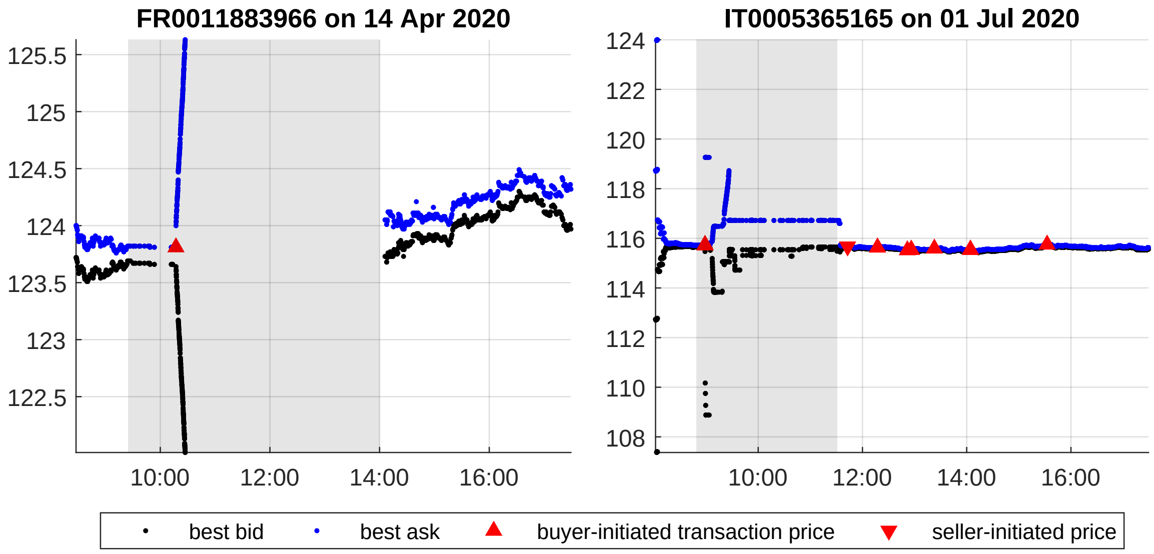


Figure A24: Quotes and Prices of Transactions on MTS during Eurex Outage. This figure shows the only two trades in 10-year bonds that were deliverable into a 10-year futures contract.

D.3 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 A25 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.

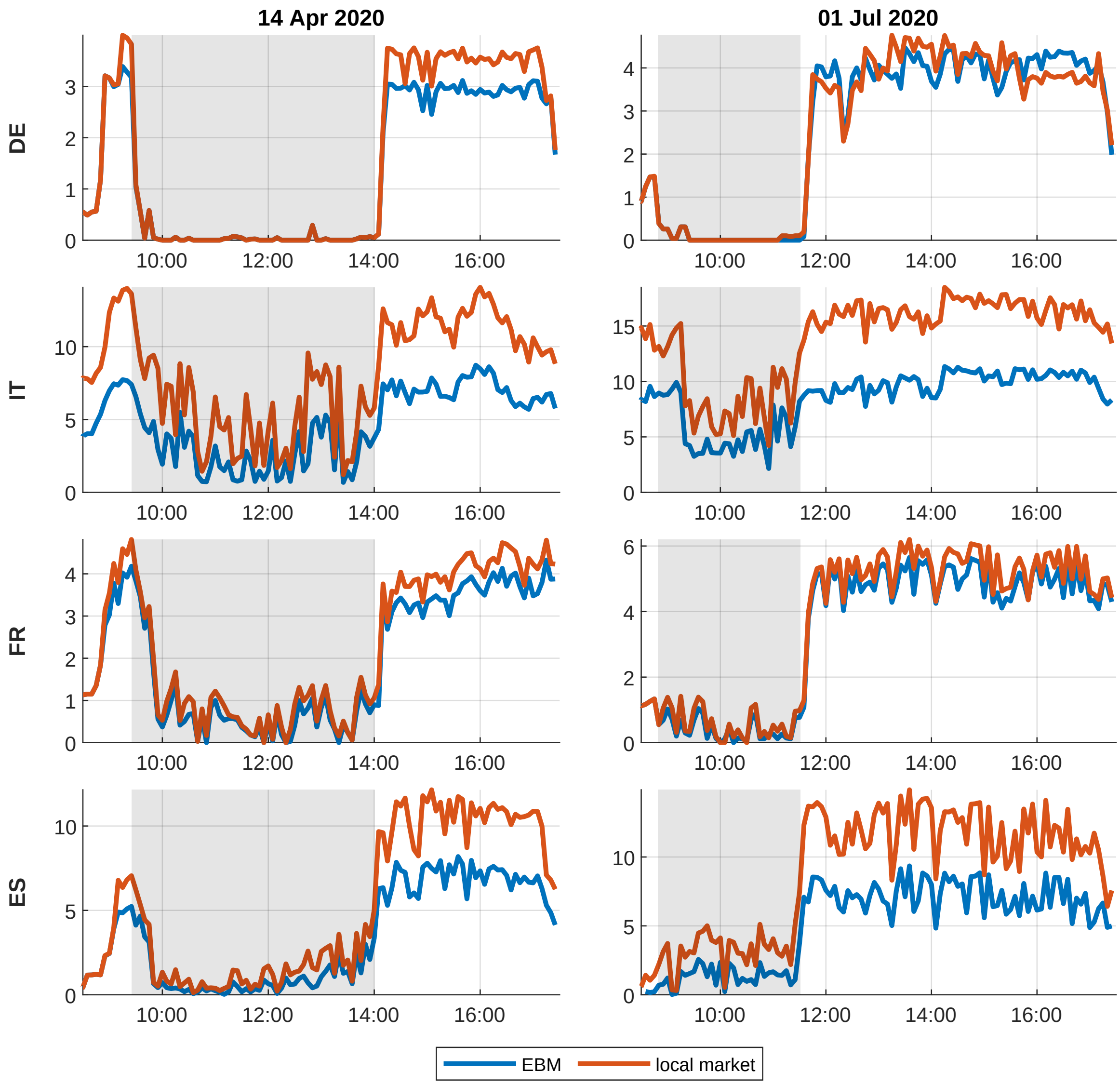


Figure A25: Order Book Depth across different Market Segments on MTS. This figure shows the total quoted volume (in million €) across all three levels and both sides of the order book, at 5-minute snapshots, for all bonds of a given country. Blue lines refer to the 'European Bond Market' segment (as in the main text), red lines refers to the respective domestic market segment.

Hence, Table A18 reports results from another dummy regression, this time run separately for each country, namely:

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

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 A18: 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.4 Bond-Level Regression Results

D.4.1 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:

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

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.[41]

	(1)	(2)
Outage	-3.14** [0.91]	-3.65** [1.06]
CTD		2.43*** [0.34]
OTR		0.73* [0.33]
Zero Coupon		-1.10*** [0.13]
log(Years to Maturity)		1.51*** [0.17]
log(Years since Issuance)		-1.13*** [0.08]
Outage × CTD		-1.32 [0.67]
Outage × OTR		-1.48** [0.47]
Outage × Zero Coupon		0.68* [0.32]
Outage × log(Years to Maturity)		0.08 [0.14]
Outage × log(Years since Issuance)		0.31 [0.32]
FE Day	✓	✓
FE Time	✓	✓
FE ISIN	✓	
FE Country		✓
FE Maturity Bucket		✓
Observations	10752	10752
Adjusted R^2	0.285	0.238

Table A19: 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 A19 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

[41] 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.

fall particularly sharply and for zero coupon bonds, where trading volumes are comparatively robust.

D.4.2 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:

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

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 A20 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 A20: 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.5 Indicative Quotes

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

Figure A26 confirms that the result holds for all countries: the number of quote updates drops dramatically during the Eurex outages. Figure A27 plots the bid yield of 10-year bonds quoted for each country. We see that yields stay virtually constant while Eurex is offline. By all appearances, these prices are stale.

For Bloomberg, Figure A28 confirms that 10-year EGB yields stay virtually constant during the Eurex outages. Figure A29 shows yield changes for German bonds of different maturity. Again, the yields shown on Bloomberg terminals seem to be stale, irrespective of the maturity.

For Refinitiv, Figure A30 shows that the number of newly submitted quotes drops dramatically during the Eurex outage. The only minor exception are Spanish bonds.

For the interdealer broker TPICAP, which publishes indicative prices for EGBs to intermediate trades between two dealers, Figure A31 shows that these quotes vanish almost entirely during the Eurex outage. Note that this figure is based on all EGBs across all maturities, in contrast to Figure A26 which is based only on quote updates in the 10-year CTD bond.

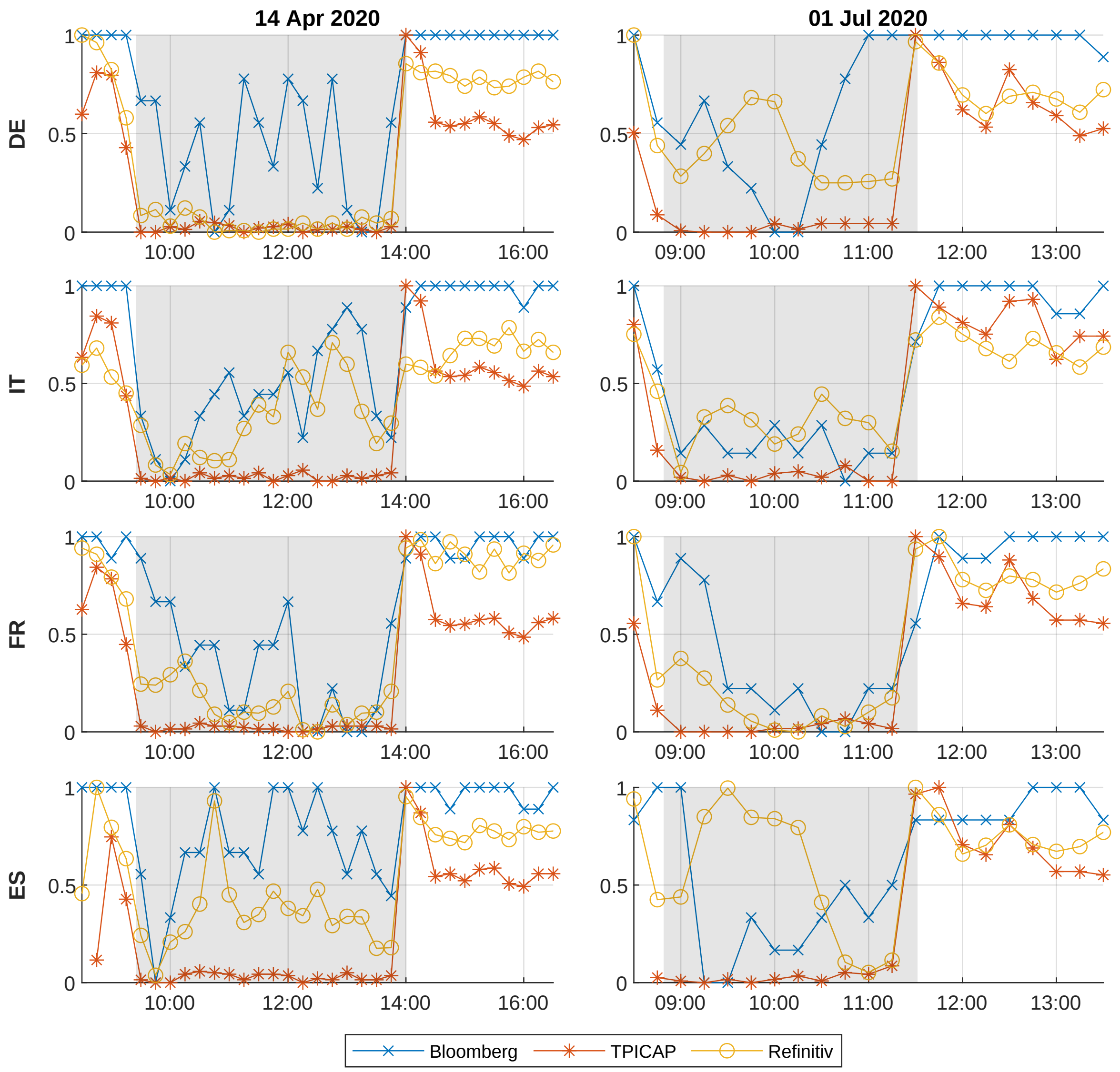


Figure A26: Quote Update Frequency for 10-Year Government Bonds on Different Platforms. Bloomberg and TPICAP data refer to quote updates in the cheapest-to-deliver bond, Refinitiv data to quote updates in the on-the-run ('benchmark') bond. For Bloomberg, we approximate the number of new quotes as the 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.

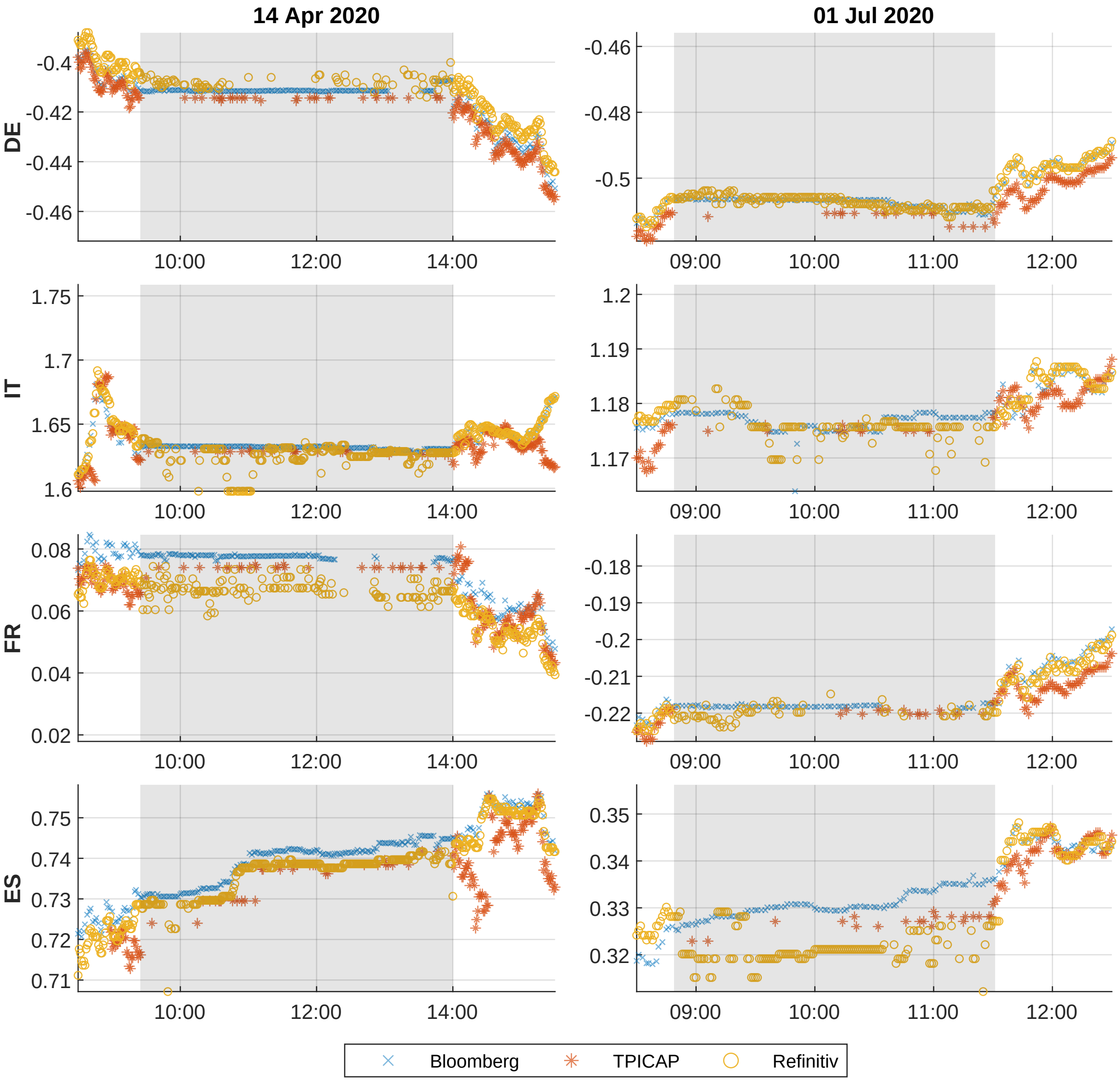


Figure A27: Quoted Bid Yield of 10-Year Government Bonds on Different Platforms. Bloomberg and TPICAP data refer to the cheapest-to-deliver bond, at minutely snapshots. Refinitiv data refers to the on-the-run ('benchmark') bond, at minutely snapshots and as the median value across all available 'pricing 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.

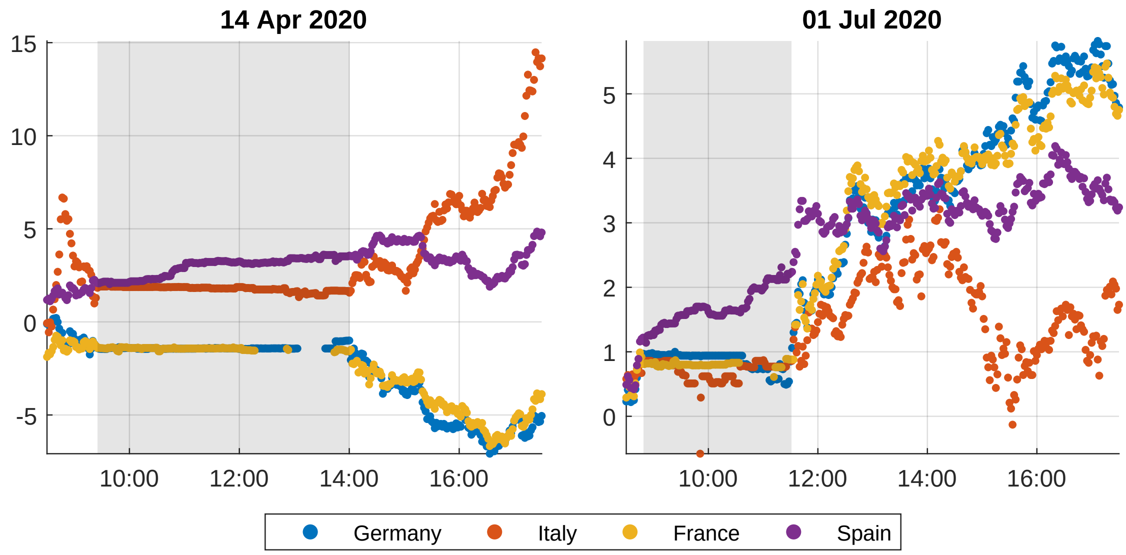


Figure A28: Yield Changes of 10-Year CTD Bonds on Bloomberg. This figure shows cumulative yield changes (in basis points, normalized to zero at 8:00 a.m.) for 10-year CTD bonds from Bloomberg.

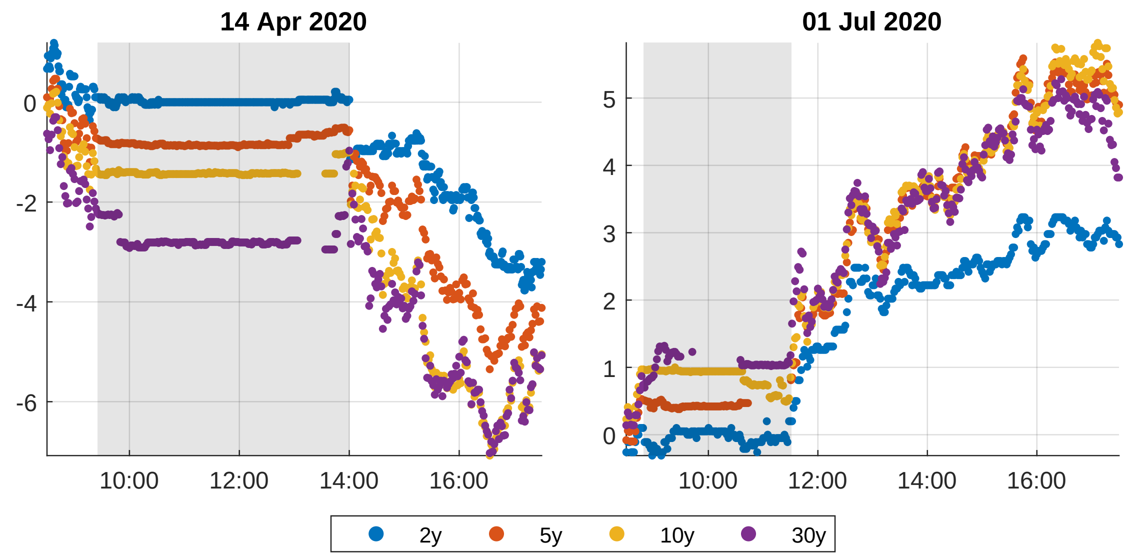


Figure A29: Yield Changes of German CTD Bonds on Bloomberg. This figure shows cumulative yield changes (in basis points, normalized to zero at 8:00 a.m.) for German CTD bonds of different maturity (2y refers to the FGBS future, 5y to FGBM, 10y to FGBL, 30y to FGBX).

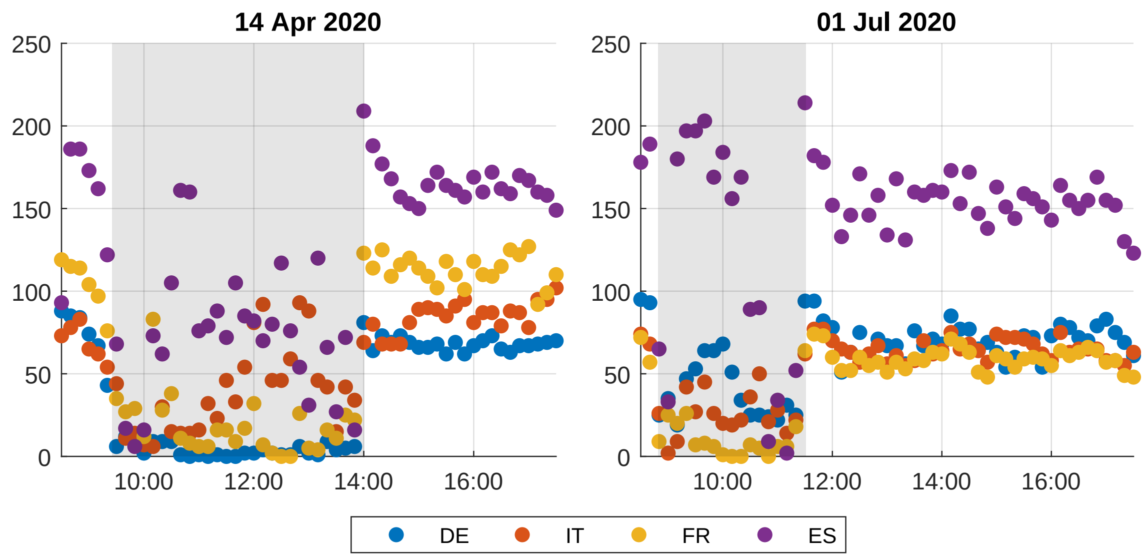


Figure A30: Number of Real-Time Feed Updates on Eikon. This figure shows the number of new bid and ask quotes submitted on Eikon in 10-minute intervals.

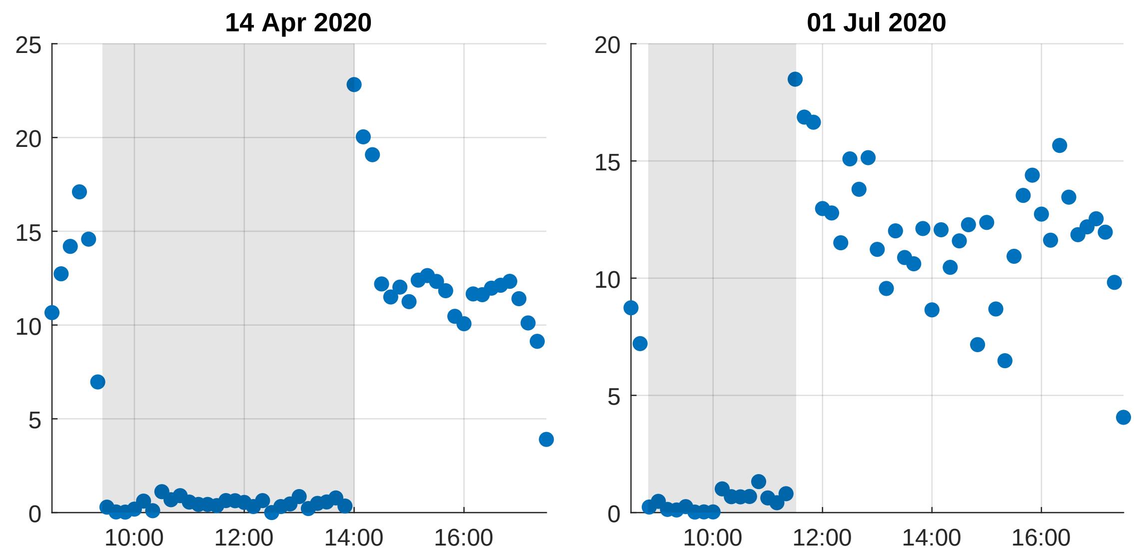


Figure A31: Number of Submitted Quotes on TPICAP. This figure shows the number of new bid and ask quotes (in thousands) for euro area sovereign bonds submitted on TPICAP, in 10-minute intervals.

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 7 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 A21 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 A22 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 A23 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.

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 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 more granular order book data. In particular, Figure A32 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 A33.

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 A21 and Table 7). Looking at individual countries, Table A22 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 A34 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 A35 shows that the lower liquidity was restricted to Italian bonds.

	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]
Adjusted R^2	0.582	0.665	0.586	0.826	0.537
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]
Adjusted R^2	0.519	0.352	0.499	0.899	0.417
IT Bonds	-2.34	-0.64	1.39	-0.97	-0.45
	[1.04]	[0.73]	[1.15]	[0.64]	[0.94]
Adjusted R^2	0.547	0.894	0.650	0.760	0.470
FR Bonds	-2.00	-8.31*	-1.72	-3.42	-2.82***
	[0.95]	[2.52]	[1.12]	[1.31]	[0.86]
Adjusted R^2	0.330	0.415	0.064	0.276	0.156
ES Bonds	-0.63	0.30	-1.88	-4.45**	-1.49**
	[0.29]	[1.74]	[1.46]	[0.98]	[0.67]
Adjusted R^2	0.104	0.421	0.443	0.238	0.274

Table A21: 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.

E.3 CME Outage

Recall that Figure 10 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 A36 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.

	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]
Adjusted R^2	0.134	0.025	0.128	0.218	0.054	0.797
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]
Adjusted R^2	0.133	0.053	0.125	0.218	-0.009	0.777
IT Futures	0.13	0.83**	-0.56		-0.41	-0.11
	[0.07]	[0.09]	[0.70]		[0.34]	[0.24]
Adjusted R^2	0.083	0.061	0.126	.	0.059	0.843
FR Futures		-0.94	-0.74		-0.46	-0.37*
		[0.33]	[0.54]		[0.50]	[0.21]
Adjusted R^2	.	0.022	0.124	.	0.072	0.873
ES Futures					-0.11	-0.01
					[0.12]	[0.01]
Adjusted R^2	.	.	.	.	-0.033	0.154

Table A22: 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.

	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]
Adjusted R^2	0.132	0.071	0.153	0.202	-0.010	0.732
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]
Adjusted R^2	0.049	0.247	0.181	0.209	0.085	0.669
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]
Adjusted R^2	0.077	0.030	0.089	0.055	0.092	0.276
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]
Adjusted R^2	0.081	-0.039	0.036	0.131	-0.020	0.436
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]
Adjusted R^2	0.018	-0.063	0.043	0.191	0.042	0.169
Observations	464	153	540	132	152	1441

Table A23: Effect of Cash Venue Outages on 10y German FGBL Future. See Table 7 for a description of the different dependent variables (rows). All regressions include time-fixed effects.

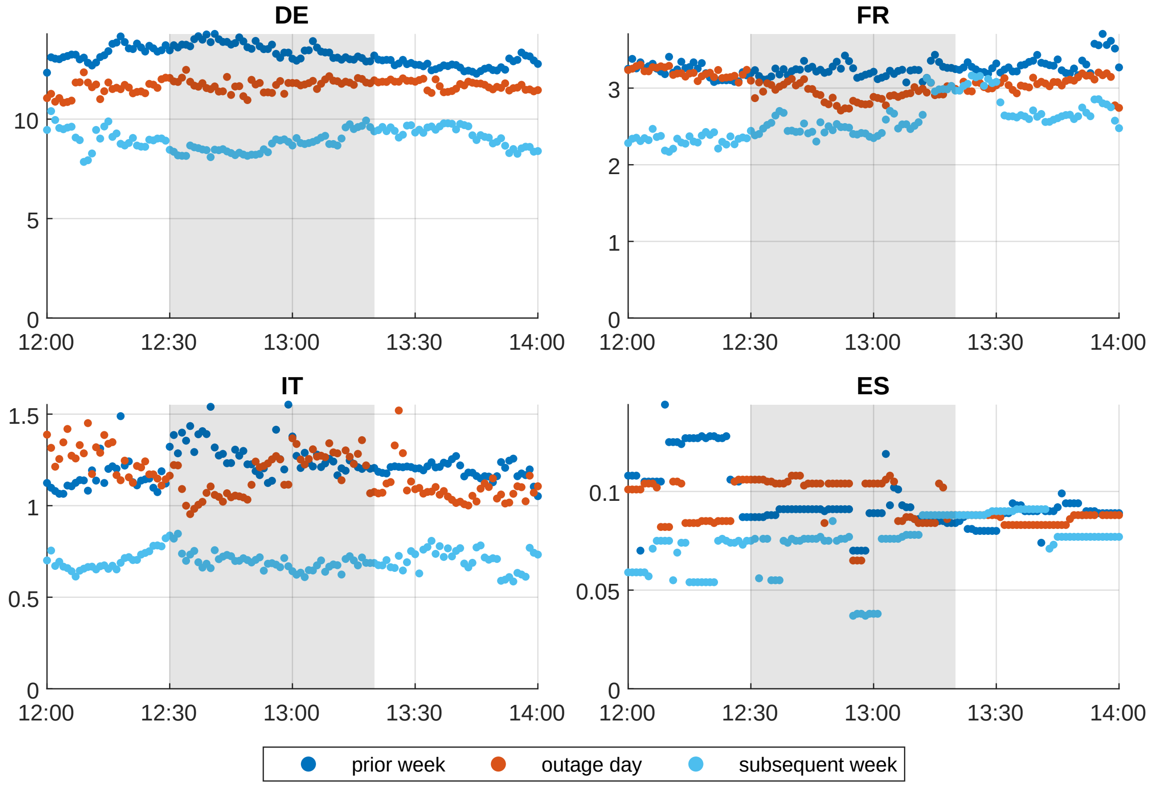


Figure A32: Order Book Depth of 10-year Bond Futures during suspected MTS Outage on 26 July 2019. This figure shows the total number of contracts (in thousands) quoted at the first fifteen levels on both sides of the order book, at minutely snapshots. Red dots refer to the suspected MTS outage day on 26 July 2019, dark and light blue dots refer to the previous and subsequent week.

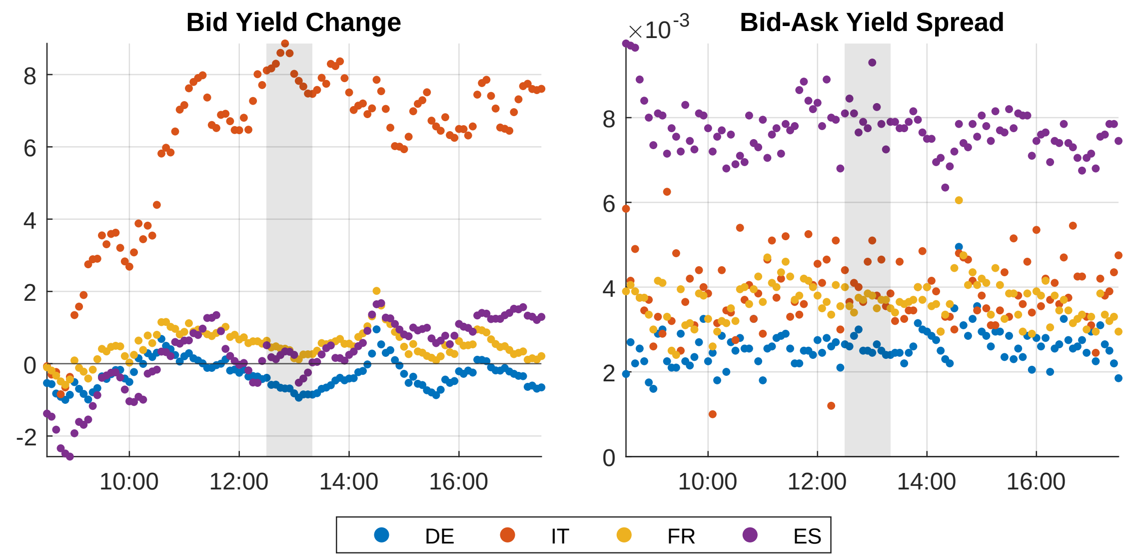


Figure A33: Indicative Quotes on Bloomberg on 26 July 2019. The left panel shows bid yield changes (in basis points since 8:00 a.m.), the right panel shows bid-ask yield spreads (in basis points). All data refers to 10-year cheapest-to-deliver bonds. The grey areas mark the times of the suspected MTS outage.

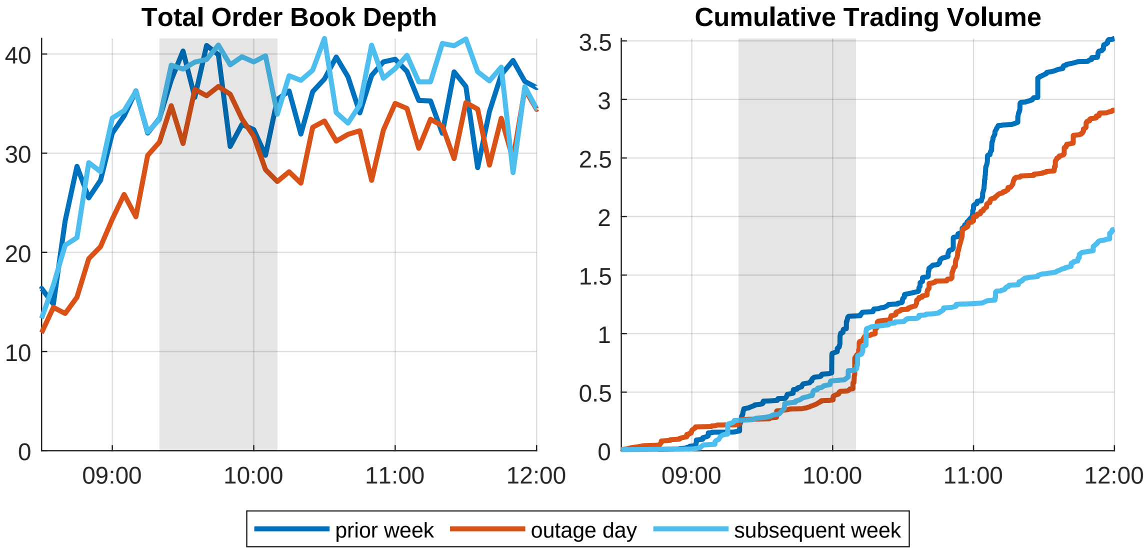


Figure A34: MTS Order Book Depth and Trading Volume during Bloomberg Outage. The left panel shows the total order book depth at 5-minute snapshots (in billion €), the right panel shows the cumulative trading volume (in billion €) in all German, French, Italian and Spanish sovereign bonds on MTS.

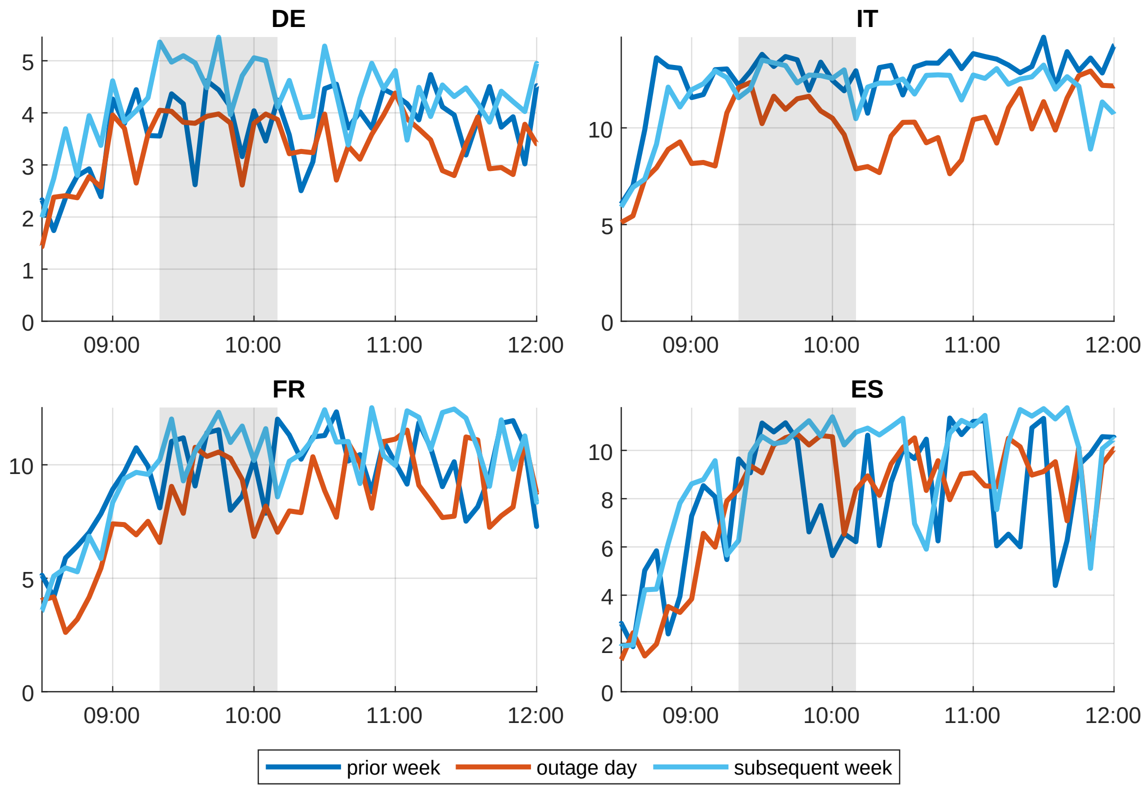


Figure A35: MTS Order Book Depth during Bloomberg Outage across Countries. This figure shows the total order book depth for German, French, Italian and Spanish sovereign bonds on MTS, at 5-minute snapshots (in billion €).

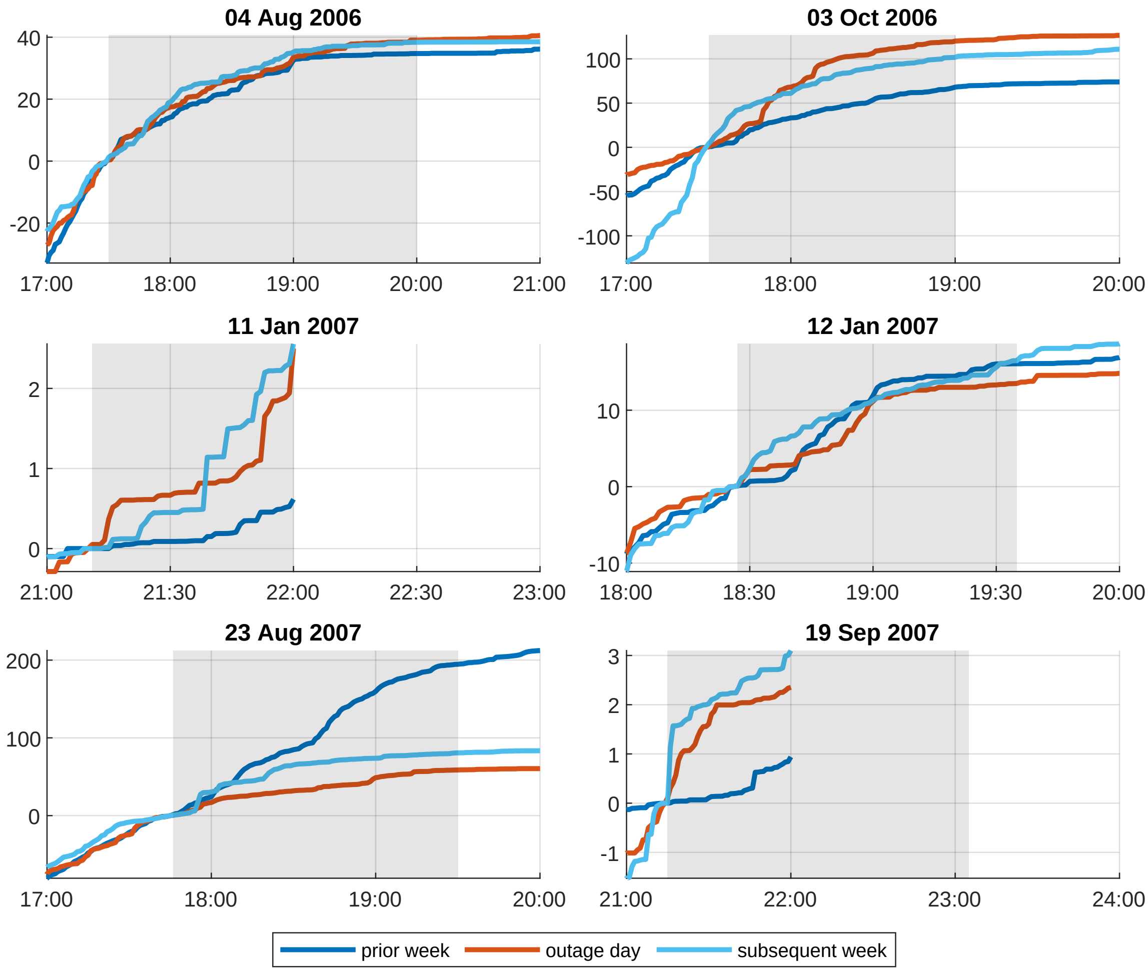


Figure A36: German Bund Future Trading Volume during CBOT Outages. This figure shows the cumulative trading volume of 10-year German bond futures around CBOT outages (in thousands of contracts, normalized to zero at the intraday time of the outage). Red lines refer to the outage day, dark and light blue 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.

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Mark Kerssenfischer

European Central Bank, Frankfurt am Main, Germany; Deutsche Bundesbank, Frankfurt am Main, Germany;
email: mark.kerssenfischer@bundesbank.de

Caspar Helmus

Deutsche Bundesbank, Frankfurt am Main, Germany; email: caspar.helmus@bundesbank.de

Postal address 60640 Frankfurt am Main, Germany
Telephone +49 69 1344 0
Website www.ecb.europa.eu

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