Outages in Sovereign Bond Markets

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Abstract

We use market outages as natural experiments to provide new evidence on how sovereign bond markets function. First, we document the vital role of bond futures in the euro area. When the Eurex futures exchange is down, trading activity on the cash market declines, liquidity evaporates, and transaction prices in risk-free bonds deviate strongly from fundamental values. Second, looking at the other direction, we show that outages on cash trading platforms have much smaller effects, suggesting that price formation and liquidity provision is more of a one-way street from the futures to the cash market. Third and lastly, we check for but do not find evidence for transatlantic spillovers. Outages of the European futures exchange Eurex have little impact on CME, the main US futures exchange, and vice versa.

Keywords: Market microstructure, natural experiment, government bonds, bond futures, liquidity.

JEL classification: G12, G14, G23

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1 Introduction

Risk-free interest rates build the foundation of all asset pricing and a large literature has made considerable progress understanding *why* interest rates change.[1] This paper tackles a closely related question, namely *where* and *how* price formation takes place, i.e. on what trading venues and via which financial instruments. To do so, we exploit market outages as natural experiments. These outages were unanticipated and for all intents and purposes exogenous. Hence, how the different trading venues, instruments, and market participants reacted to these rare outages is highly informative about how the sovereign bond market works in normal times.

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 (MTS, Bondvision, Tradeweb), a broker (TPICAP), and indicative quote providers (Bloomberg, Refinitiv). Thanks to the clear and 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 focus on *trading volumes*, *market liquidity*, and *pricing errors*.

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) and it is true across all major cash market segments (over-the-counter, electronic trading venues, exchanges). 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

[1]The two major drivers of interest rates identified in the literature are news and flows. Regarding the effect of 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 (2022). On the effect of 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 C contains further narrative evidence on the outages.

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). The exact calculation methods behind these quotes are not disclosed, but our results suggest that bond future prices are a vital input.

Pricing errors on the cash bond market spike when the futures market exchange is down. Focusing on German bonds as the risk-free benchmark asset for the euro area, we show that the remaining transactions that did take place on the spot market during the Eurex 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 during 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 results suggest that bond futures are vital for the euro area fixed-income market to function smoothly. This conclusion is based on the most recent Eurex outages in 2020, because we have the best data for this period, but those two outages have not been without precedent. Hence, to provide robustness checks of our results, we exploit twelve previous outages on Eurex between 2009 and 2018. We confirm that these previous outages also cause trading volumes on the cash market to decline and liquidity on MTS to evaporate. Importantly, two of the twelve 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 MTS less than system-wide outages, not only for German but for all bonds, and particularly for bonds whose maturity is close to the still available bond futures. This suggests that German futures are used to provide liquidity in all European government bonds, in line with their benchmark status.

Having established the dramatic effects of futures market outages on the cash market for European government bonds, we next study outages on two major cash trading platforms, namely MTS and Bloomberg. We find much smaller effects of these outages, not only on the futures market, but also across cash market platforms. We start with a suspected outage of MTS on 26 July 2019, when trading and quoting activity was lower than usual for several hours and broke down entirely for almost one hour. This outage has no discernable impact, neither on the liquidity of bond futures traded on Eurex, nor on indicative quotes of government bonds on Bloomberg. We proceed with the outage of Bloomberg on 17 April 2015, when traders worldwide were not able to access their Bloomberg terminals for about two hours. The outage reduces trading volumes on the cash market significantly, which is in line with the fact that Bloomberg is a major trading platform for European government bonds, particularly at the time of the outage in 2015. The outage also reduces the order book depth on MTS somewhat, but only for Italian bonds. Regarding the futures market, lastly, we do not observe any obvious decrease in aggregate trading volumes. Taken together, we document very asymmetric effects of outages. Price discovery and liquidity provision seems to be a one-way street from the futures to the cash market.

Lastly, we test for spillovers between outages on Eurex and outages on the main US futures exchange, the Chicago Mercantile Exchange (CME) and its predecessor Chicago Board of Trade (CBOT). Rather surprisingly, we find little evidence for spillovers in either direction. Outages in Europe have little impact on the US and vice versa. In particular, the order book depth of US Treasury futures on CME does not decrease when Eurex goes down. Looking at the other direction, we exploit an outage on CME on 26 February 2019 and six older outages on CBOT 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 spillovers documented for asset price movements, see e.g. Boehm and Kroner (2023).

Contribution to Literature

Our results contribute to different strands of the literature. We discuss the most important ones below.

Liquidity Spillovers

Our paper sheds light on competing theories of liquidity spillovers. In models of *cross-asset arbitrage* (see Gromb and Vayanos, 2010, for a survey), arbitrageurs such as high-frequency traders exploit mispricings of similar securities across different exchanges. 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) 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 Cespa and Foucault (2014), who present a model for liquidity spillovers based on *cross-asset learning*. The key idea is that liquidity providers use some particularly informative asset prices to price and provide liquidity in other assets. Applied to our case of euro area government bonds, bond futures are used to price and provide liquidity in cash bonds.

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 (2023) 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 (2023) 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. Welfare calculations should take this point into account. Centralizing the OTC market would probably have additional benefits, if it leads to more liquidity and better price discovery. This is in line with Kutai, Nathan, and Wittwer (2023), who document that the

[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.

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.

Price Discovery on Future vs. Cash Market

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) for US Treasuries, Upper and Werner (2007) for German bonds and Jappelli, Lucke, and Pelizzon (2022) for German, French and Italian bonds. Our results are in line with this evidence but suggest 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 properly. Without bond futures, liquidity for cash bonds evaporates and market participants commit large pricing errors along the risk-free yield curve.

Dominant vs. Satellite Markets

Our paper also speaks to the literature on dominant vs. satellite markets, which usually looks at stocks traded on multiple exchanges (cross-listed instruments). A main finding of this literature is that price discovery occurs mostly on the primary stock exchange, see e.g. Hasbrouck (1995). Guillaumie, Loiacono, Winkler, and Kern (2020) further show that when a stock stops trading on the dominant exchange (due to a circuit-breaker event), then the trading activity and liquidity for this stock decreases drastically on all other exchanges. Hagströmer and Menkveld (2023) show that on-exchange trades in UK stocks are an order of magnitude more informative than off-exchange trades. Our results are similar. 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.

Cyber Risk and Market Infrastructure

Event 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.

We show that the European futures exchange Eurex is of systemic importance for the fixed-income market. When Eurex goes down, investors reduce their trading activity, liquidity providers exit the market, and transaction prices deviate from fundamentals.

Fortunately, past outages 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.

2 European Government Bond Market Structure

We study euro area government bonds (EGBs) of the four largest member states: Germany, France, Italy and Spain. They are also the only countries with corresponding fixed income futures. The futures market 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. Because of their benchmark status in the euro area fixed income markets, futures on German bonds dominate trading with roughly 82% of the total in 2022. Italian (9%), French (9%) and Spanish (<1%) futures are much less relevant, see Appendix A.2.

By contrast, the spot market for EGBs is much more fragmented and opaque. There are hundreds of individual bonds outstanding at any point in time and these can be traded on very different venues.[5] 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. mostly 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 and they remain common since bonds are less standardized and generally traded less

[5]The 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) from 2021 provides a detailed overview of the European government bond market, including the market shares of different trading platforms across different market segments. The European Commission approved this merger only after the London Stock Exchange Group sold off its MTS platform to Euronext (see European Commission press release).

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 an intermediary (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.[6] This way, the two counterparties do not have to reveal their identity to each other. Compared to on-exchange trades, both 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.[7] 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. On Bloomberg, market participants typically express their trading interest by voice over the phone, or using the terminals' chat functionality. Yet another trading venue are single-dealer platforms. On these platforms, large dealer banks act as a central counterparty for trades initiated by their clients.[8] 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 the MTS platform, i.e. electronically, multilaterally and 'on-exchange', whereas German bonds are traded more bilaterally and by voice on the OTC market. To capture this heterogeneous bond market as much as possible, we combine a number of different data sources. Appendix A.2 provides an overview of the EGB spot market. The following subsections briefly describe the various data sources we exploit.

[6] In their application, which is based on the 'Bafin' dataset mentioned in Section 2.2, they focus on dealer-to-dealer trades in German bonds, where they can identify both sides of the trade. In this data subset, interdeaeler broker are involved in roughly 80% of trading volume. In relation to the entire trading in German bonds, however, interdeaeler brokers account for roughly 10% of volume.

[7] A recent ESMA Consultation Paper provides a concise overview of European trading venues.

[8] In terms of regulation, MiFID II Art. 4(1)(20)-(24) differentiates three types of trading venues: regulated markets, multilateral trading facilities (MTF) and organised trading facilities (OTF). Single-dealer platforms are called 'systemic 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'. Such trades are considered a particular form of OTC trading and in practice, systematic internalisers are usually large banks. The 'SI' status comes with extra regulatory responsibilities, e.g. an obligation to report trades through an Approved Publication Arrangement (APA).

2.1 Futures Market Data

For bond futures, we exploit three different datasets. First, 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. Both datasets come directly from Eurex. Third and lastly, we have non-anonymous investor-level data on bond future transactions, going back to 2008. These data come from the European Market Infrastructure Regulation (EMIR) dataset since 2019 and prior to that from its predecessor ('Bafin' dataset, see next section).

2.2 Cash Market Data

For EGB transactions on the cash market, we start with two regulatory datasets. First, the 'MiFIR' dataset, which contains information on all bond transactions since 2019 and which is collected under the MiFID II regulation. Second, the 'Bafin' dataset, which is in some sense the predecessor of the former dataset and which covers the 2008-2017 sample. For a detailed description of this latter dataset, see de Roure et al. (2019), Gündüz, Ottonello, Pelizzon, Schneider, and Subrahmanyam (2023), and the Bundesbank website. For each transaction, these datasets contain the price, size, time, the involved counterparties, as well as the venue on which the trade was executed.

An important caveat for our purposes is that the regulatory datasets only include trades in which at least one counterparty had a reporting obligation to Bafin, which usually means that it is domiciled in Germany or that a German security was traded. This is why trades in German bonds are overrepresented. Consequently, to offset this limitation we complement the regulatory dataset by data sourced directly from trading platforms that cover bonds also for French, Italian and Spanish government bonds, namely MTS, MTS BondVision, TPICAP, and Tradeweb. In contrast to the regulatory data, these datasets are anonymous, i.e. they do not contain information about the involved counterparties.

Besides the transaction data, we also use quote data. In particular, we have the entire central limit order book data, i.e. executable quotes and volumes, from MTS. In addition, we use indicate quote data from Bloomberg, Refinitiv and TPICAP.

Appendix A.4 provides a detailed breakdown of our data sources for the six most important days in our sample (the two Eurex outage days and the respective control days).

3 Eurex Outages as Natural Experiments

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 volume 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.[9]

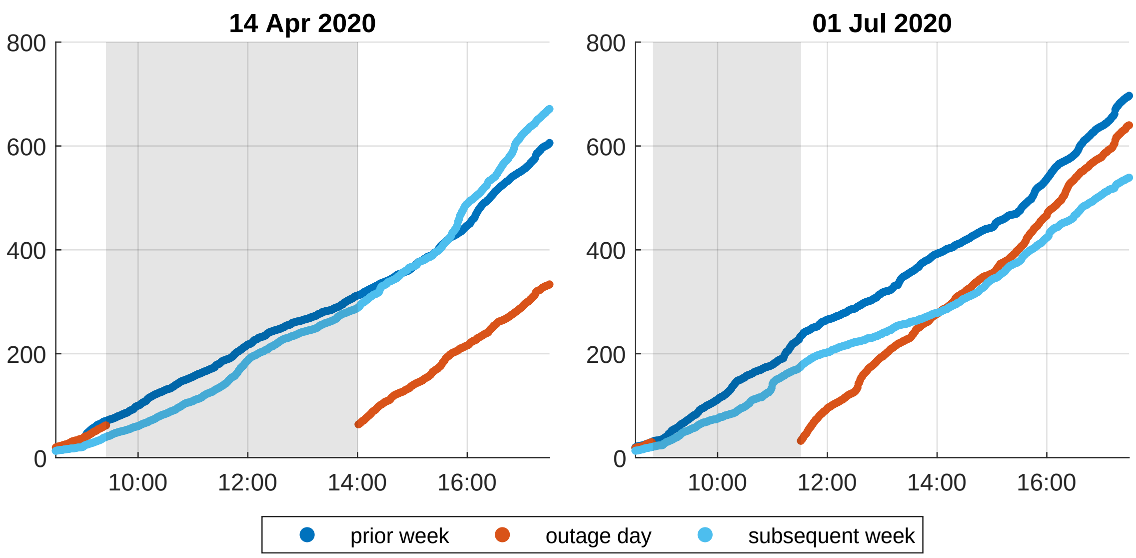

Figure 1: Cumulative Trading Volume of 10-year Bond Futures. This figure shows the cumulative number of traded contracts (in thousands). Red dots refer to the outage day, dark and light blue dots refer to the previous and subsequent week.

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).

[9] Appendix B.1 provides country-level results.

3.1 Trading Activity on Cash Market

How did the Eurex outage affect trading in EGBs on the cash market? To answer this question, we combine data from various sources to cover as many transactions as possible, see Section 2.2 for details.

Based on this extensive dataset, Figure 2 shows that trading volumes on the cash market are much lower while Eurex is offline.

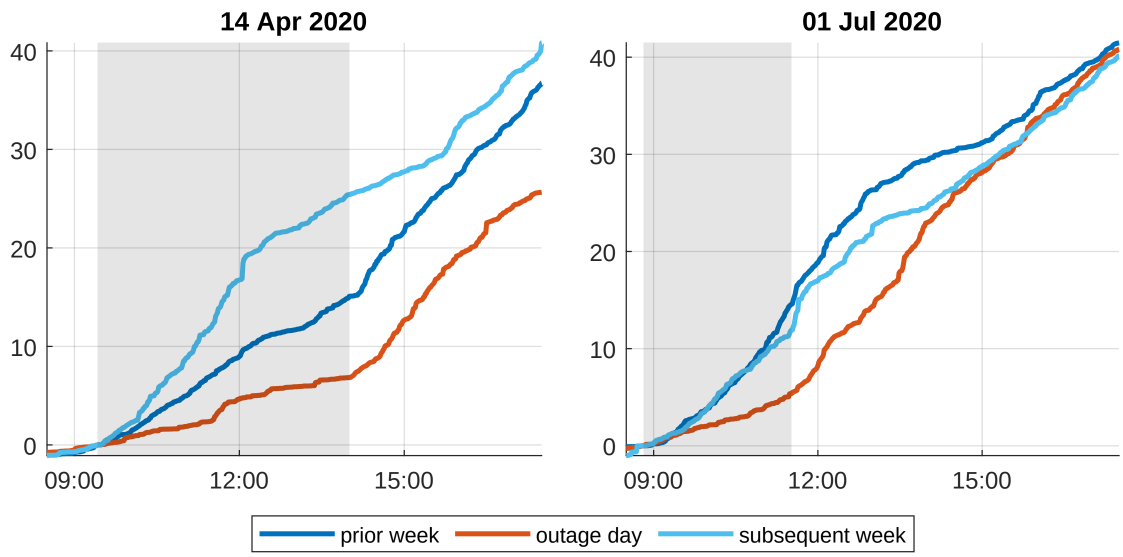

Figure 2: Cash Market Trading Volume in EGBs. This figure shows the cumulative trading volume on the cash market in all German, French, Italian and Spanish sovereign bonds (in billions of Euro, normalized to zero at the intraday time of the outage). Red dots refer to outage days, dark and light blue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

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 of country c's bonds in 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 16 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.[10]

Table 1 reports the results. Model (1) confirms that trading volumes on the cash market decrease dramatically during the futures market outages. Model (2) shows that

[10]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, see Appendix A.3 for details. Appendix B.5 reports results for similar regressions as in Equation 1 but at the individual bond level. Trading volumes fall particularly sharply for on-the-run bonds and slightly less for zero coupon bonds.

trading activity in longer-term bonds drops disproportionately and model (3) shows that all four euro area countries are affected similarly by the outage.

	(1) Aggregate	(2) Maturities	(3) Countries
Outage	-2.66*** [0.30]	-0.96** [0.32]	-2.45*** [0.20]
2.5-5.5y		-1.04** [0.33]	
5.5-10.5y		-0.01 [0.35]	
>10.5y		-1.32** [0.45]	
Outage × 2.5-5.5y		-2.12*** [0.34]	
Outage × 5.5-10.5y		-2.14** [0.56]	
Outage × >10.5y		-2.55** [0.90]	
ES			-3.22*** [0.36]
FR			-3.35*** [0.44]
IT			-0.85** [0.24]
Outage × ES			0.09 [0.49]
Outage × FR			-0.54 [0.75]
Outage × IT			-0.41 [0.38]
FE Day	✓	✓	✓
FE Time	✓	✓	✓
FE Country	✓	✓	
FE Maturity Bucket	✓		✓
Observations	1536	1536	1536
Adjusted R^2	0.333	0.340	0.332

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 30-minute intervals. Model (1) refers to the aggregate transaction volume in all bonds, model (2) to the transaction volume across maturity buckets, and model (3) to the volume across countries. 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). *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

An 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 longer maturities. Hence, market participants become reluctant to trade long-term bonds.[11]

[11] This mechanism differs slightly from a simple duration risk explanation. Section B.2 in the Appendix shows that interest rate swaps provided a reliable indicator of 'fair' short-term rates during the Eurex outages. Hence, it seems unlikely that longer-term bonds were traded less frequently just because their prices are more sensitive to changes in the short rate.

3.2 Liquidity on Cash Market

3.2.1 Executable Quotes

MTS is the dominant electronic trading platform 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. So did trading transition from Eurex to MTS? 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 3 shows that trading in these bonds effectively freezes on MTS during the Eurex blackout. Roughly three minutes after Eurex went down on 14 April 2020, virtually all quotes vanish from the MTS platform, 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, the first 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 future 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 banks 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 futures prices as a reference point, market functioning on the spot market is severely impaired.

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

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

where $OBdepth_{cmt}$ is the order book depth (in €) of all bonds of country c and maturity

[12] See Appendix A.3 for the ISIN of each CTD bond. Appendix B.3 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.

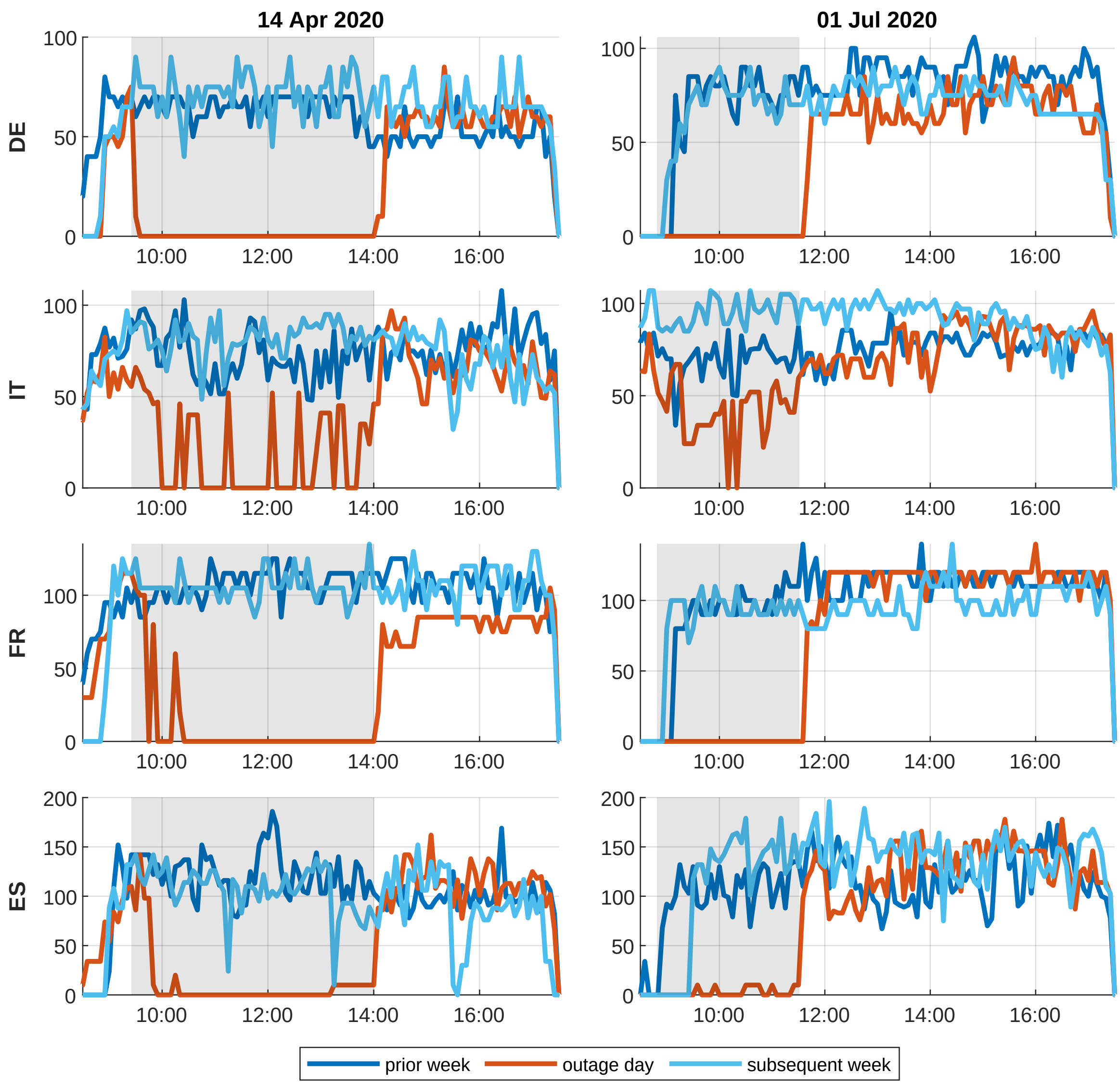

Figure 3: Order Book Depth on MTS. This figure shows the total quoted volume for 10-year CTD bonds (in million €) across all three levels and both sides of the order book, at 5-minute snapshots. See Figure A12 for details.

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 by $exp(-10.86) - 1 \approx 100\%$ when Eurex goes down, i.e. liquidity

[14] Appendix B.5 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 bonds and zero coupon bonds. The same is true for bonds with a longer time since issuance and a longer time to maturity.

essentially evaporates, see model (1). Model (2) shows that bonds with longer maturity are affected more than short-term bonds, i.e. those with less than two and a half years to maturity.

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.2 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 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]	-4.95*** [0.21]	-18.03*** [0.43]
2.5-5.5y		-0.62*** [0.13]	
5.5-10.5y		-0.70*** [0.11]	
>10.5y		-1.84*** [0.18]	
Outage × 2.5-5.5y		-8.50*** [0.32]	
Outage × 5.5-10.5y		-7.73*** [0.61]	
Outage × >10.5y		-7.40*** [0.72]	
ES			0.17 [0.24]
FR			0.44*** [0.08]
IT			1.42*** [0.23]
Outage × ES			8.57** [2.46]
Outage × FR			3.87*** [0.07]
Outage × IT			16.24*** [0.91]
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 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). *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

3.2.2 Indicative Quotes

Apart from the executable quotes on MTS, there are several providers of indicative quotes for EGBs. How did these quotes react to the futures market outage? 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. For instance, Schestag, Schuster, and Uhrig-Homburg (2016) 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. Lastly, we have quotes from the interdealer broker TPICAP. 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 indicative bid yields for 10-year EGBs on the two outage days across all three data sources. For maximum comparability, we again focus on the CTD bond underlying the 10-year bond future.[15] We see that yields stay virtually constant while Eurex is offline. By all appearances, these prices are stale. In line with this, Figure 5 shows that the number of new quotes drops dramatically during the Eurex outages.[16]

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.

[15] The Refinitiv (Eikon) data instead refers to 10-year 'benchmark' (on-the-run) bonds, i.e. ticker codes DE10YT, FR10YT, IT10YT and ES10YT for Germany, France, Italy and Spain, respectively.

[16] For TPICAP and Refinitiv we can compute the exact number of new quotes per bond. For Bloomberg, we approximate the number of new quotes as tick-by-tick price changes.

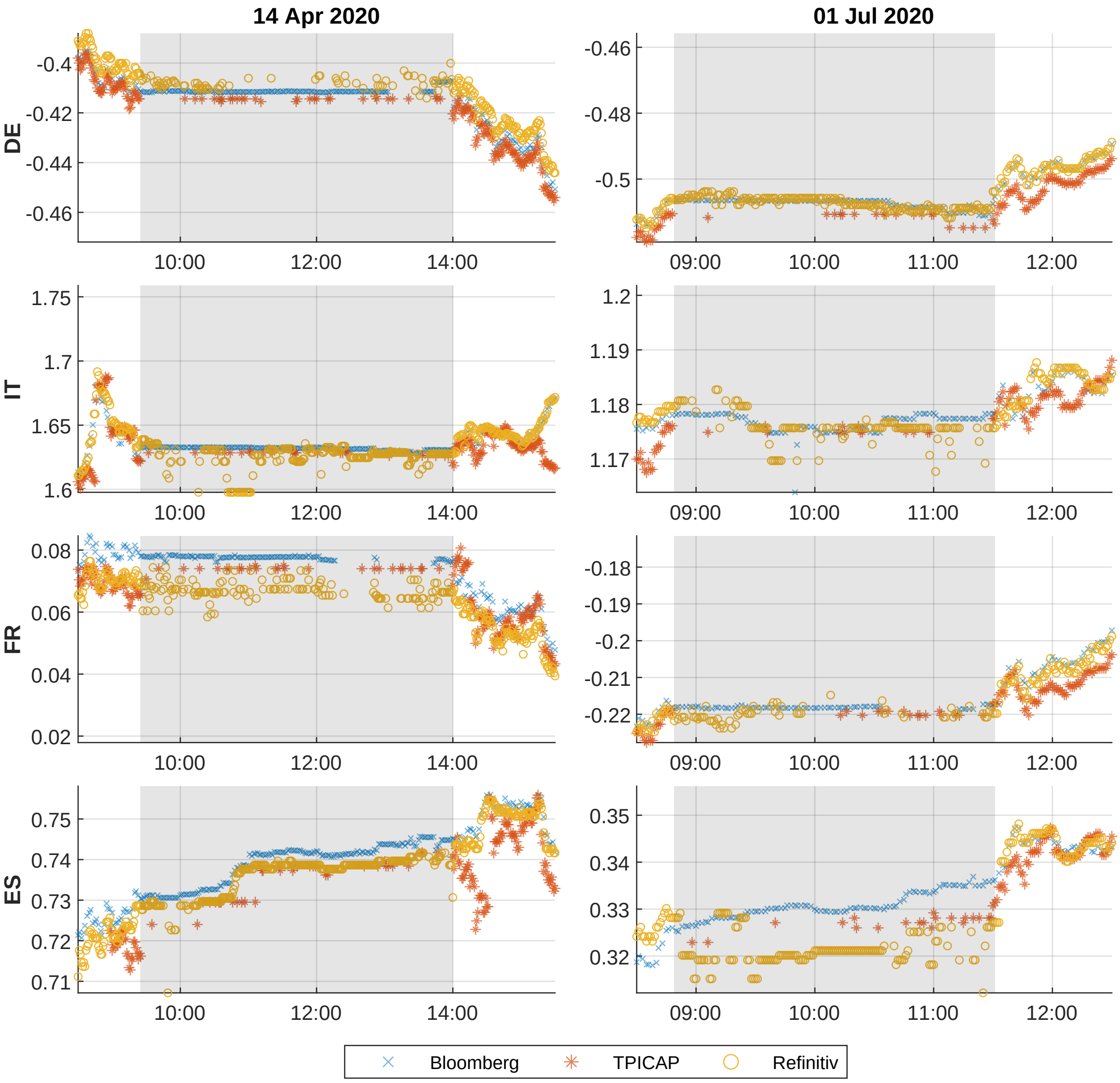

Figure 4: Quoted Bid Yield of 10-Year Government Bonds on Different Platforms. Bloomberg and TP-ICAP data refer to the cheapest-to-deliver bond, at minutely snapshots. Refinitiv data refers to the on-the-run ('benchmark') bond, at minutely snaphots and as the median value across all available 'pricing 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 on Bloomberg/TPICAP).

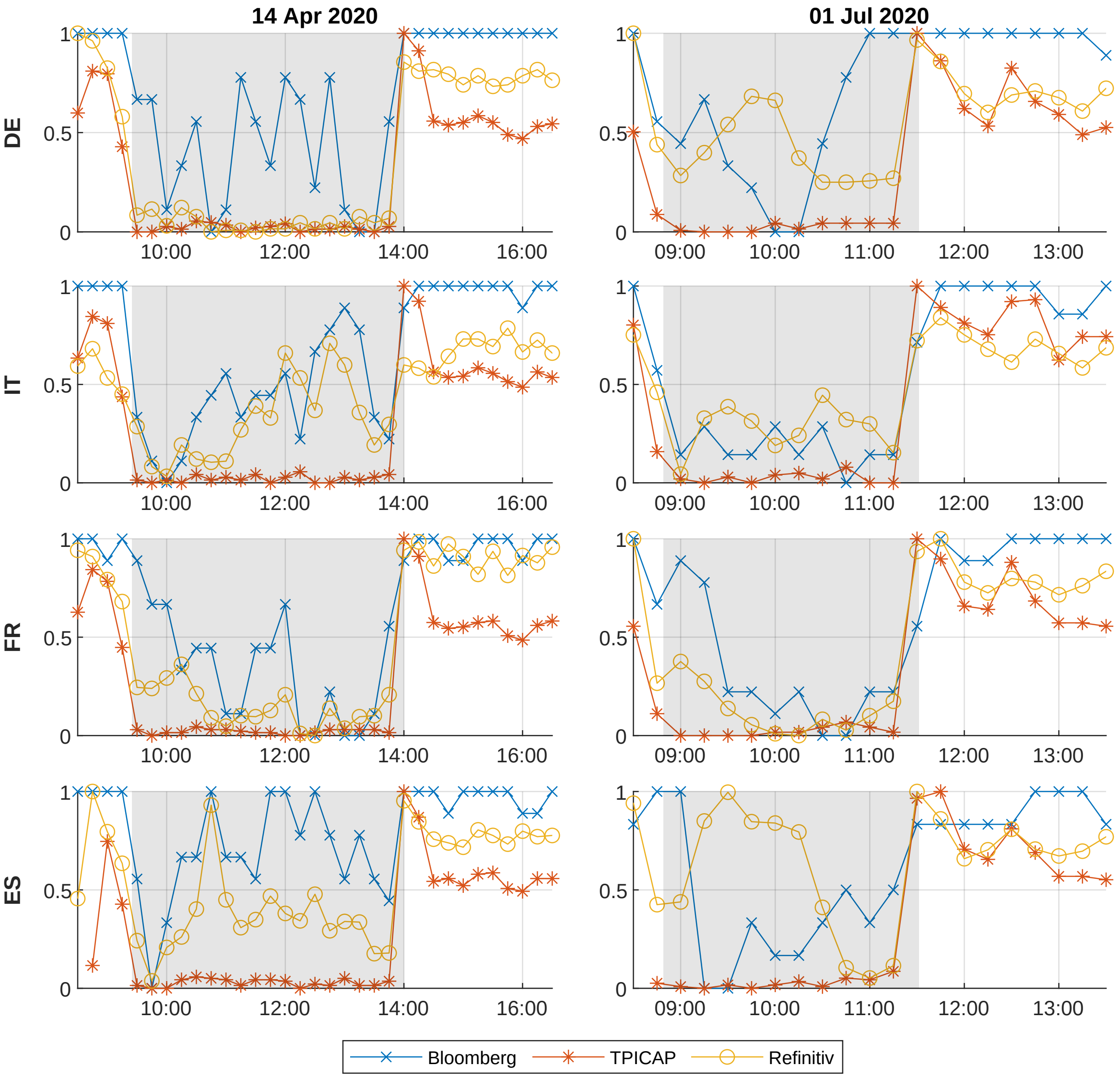

Figure 5: Quote Update Frequency for 10-Year Government Bonds on Different Platforms. Bloomberg and TPICAP data refer to quote updates in the cheapest-to-deliver bond, Refinitiv data to quote updates in the on-the-run ('benchmark') bond. For Bloomberg, we approximate the number of new quotes as the number 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.

3.3 Pricing on Cash Market

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 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 6 shows the results. 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. 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.

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

[18]For simplicity, we restrict this analysis to plain vanilla German government bonds with a remaining maturity of one to ten years, see Appendi A.4.

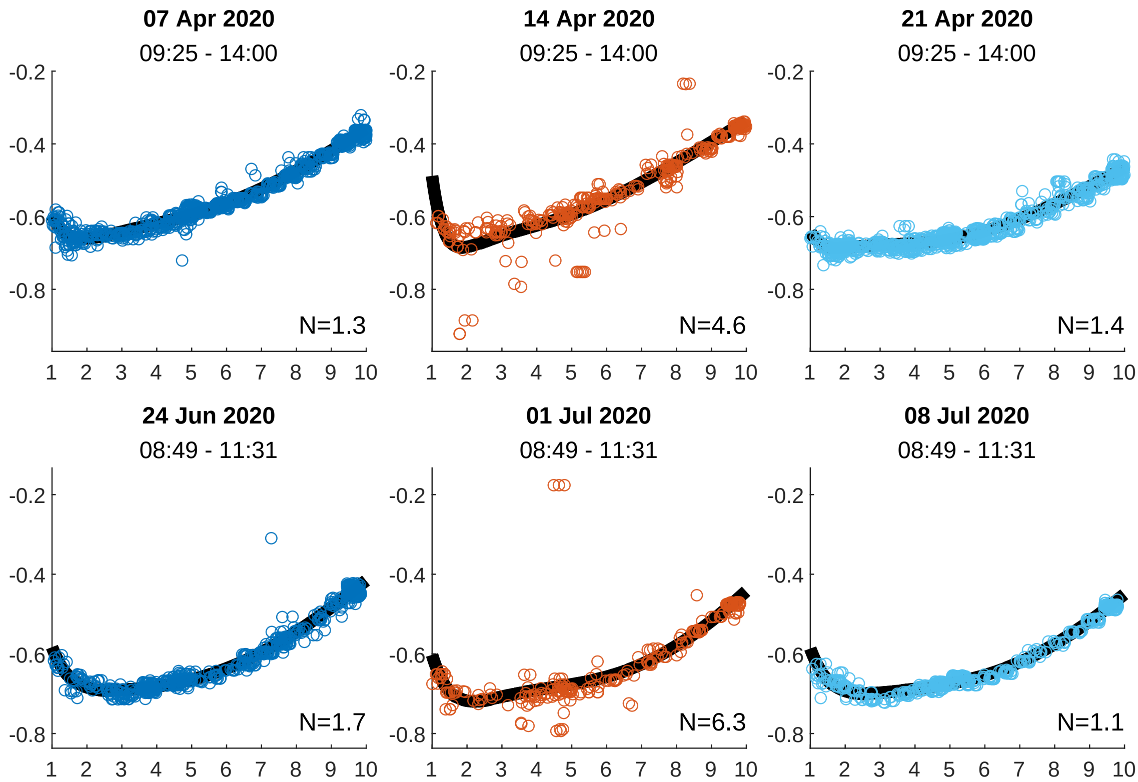

Figure 6: German Yields and Fitted Yield Curves. Circles show the implied yield of transactions in German bonds during selected intraday windows. Red circles refer to the two Eurex outage days (middle column), dark and light blue circles refer to the same intraday window in the previous and subsequent 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 is the root mean squared pricing error in each window, which is the noise measure proposed by Hu et al. (2013).

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 7 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, which moves yields and mechanically increases 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.

One remaining possibility is that the pricing errors in German bonds were higher

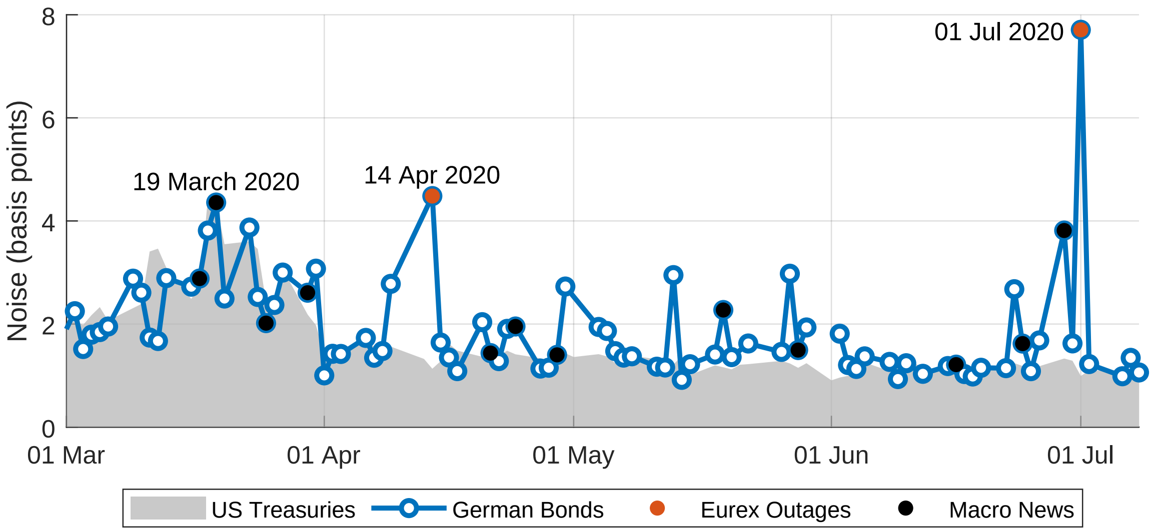

Figure 7: Yield Curve Noise during 2020. The grey area is the US Treasury noise measure published by Hu et al. (2013). It refers to the root mean squared pricing error, based on the cross-section of end-of-day bond prices from the CRSP database and using the Svensson (1994) method to fit yield curves. The blue line applies the same methodology to German government bonds, as in Figure 6. 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, and 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.

throughout the two outage days, for reasons other than the Eurex outages. Figure 8 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 outage and quickly recedes once Eurex is back online.

Next, we relate the pricing error of each transaction to bond and trade characteristics. In particular, we focus on the same set of transactions as shown in Figure 6, 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 3 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.

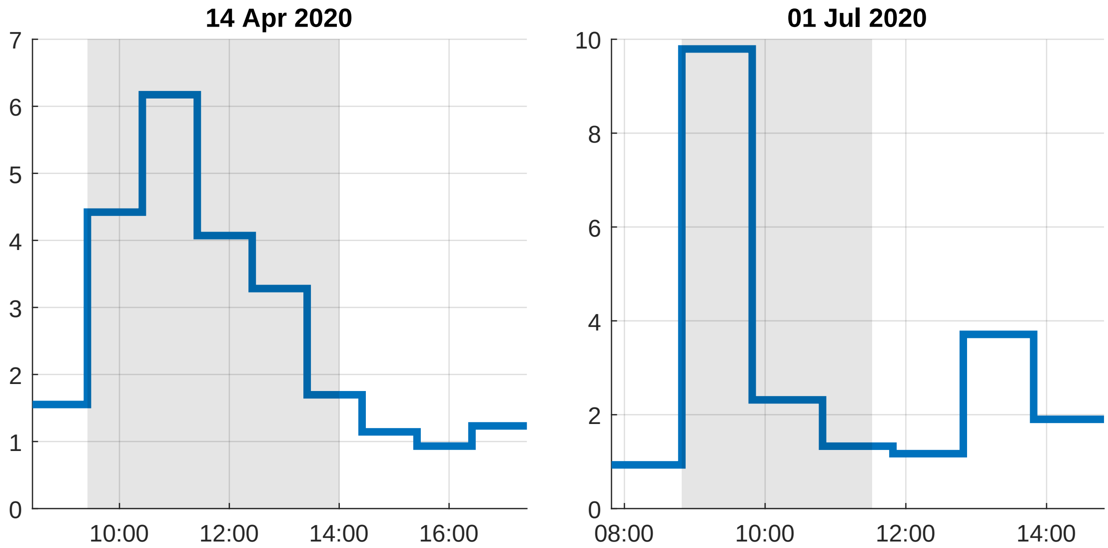

Figure 8: German Yield Curve Noise on Eurex Outage Days. This figure shows the noise measure proposed by Hu et al. (2013) on the two Eurex outage days, from one hour before the outage till four hours after the outage. For each one hour window, we fit a Svensson (1994) curve to the observed market yields and compute the root mean squared pricing errors. Grey areas mark the outage periods on Eurex.

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. 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 use bond futures to price the risk-free yield curve.

Overall, our results suggest that a smooth functioning of the fixed-income market in the euro area depends on an active futures market.

	(1)	(2)	(3)
Outage	1.23*** [0.12]	1.13*** [0.14]	-3.14*** [0.52]
log(Volume)		-0.14 [0.08]	-0.03** [0.01]
CTD		-0.39* [0.17]	-0.26** [0.07]
OTR		0.19 [0.16]	0.21** [0.06]
Zero Coupon		0.04 [0.28]	0.09 [0.10]
Years since Issuance		0.06* [0.03]	0.05 [0.03]
Years to Maturity		-0.08 [0.04]	-0.03 [0.04]
Outage × log(Volume)			-0.69*** [0.04]
Outage × CTD			-0.90* [0.36]
Outage × OTR			-0.59 [0.39]
Outage × Zero Coupon			-0.04 [0.70]
Outage × Years since Issuance			0.02 [0.03]
Outage × Years to Maturity			-0.14** [0.05]
Constant	0.99*** [0.07]	0.31 [0.50]	0.70* [0.34]
FE Minute	✓	✓	✓
FE ISIN	✓		
Observations	3362	3362	3362
Adjusted R^2	0.113	0.123	0.220

Table 3: 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 6, 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. *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

4 Previous Eurex Outages

The previous section suggests that market functioning for euro area sovereign bonds heavily depends on the futures market, but the evidence is based on just two Eurex outages in 2020. This section provides further evidence based on previous outages on Eurex.[19]

4.1 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 A.1.[20]

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 2.2) 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 eight outage days plus the same day in the preceding and subsequent week, i.e. 24 days in total. Each day, we have 15 intraday observations (from 08:00 a.m. to 3:00 p.m.).[21] Table 4 reports the results. In line with our previous finding, trading volumes on the cash market drop significantly when the futures market suffers an outage (model 1) and compared to short-term bonds, longer-term bonds are particularly affected (though there is no differential effect for bonds with more than 10.5 years to maturity).

How about MTS? Did Eurex outages always lead to an evaporation of liquidity on MTS, as we have shown for the two 2020 outages in Section 3.2? Yes, as shown in Table 5. 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

[19] We put particular emphasis on the 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.4.

[20] 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. Appendix B.8 confirms the regression results reported below graphically.

[21] We omit the outage on 16 March 2018 since the 'Bafin' data ends in 2017.

	(1) Aggregate	(2) Maturities
Outage	-1.46*** [0.41]	-0.40 [0.76]
Outage $\times$ $2.5 - 5.5$ years		-1.75** [0.77]
Outage $\times$ $5.5 - 10.5$ years		-3.77*** [0.72]
Outage $\times$ > 10.5 years		1.29 [1.94]
FE Day	✓	✓
FE Time	✓	✓
FE Maturity Bucket	✓	
Observations	1440	1440
Adjusted R^2	0.456	0.459

Table 4: 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. *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

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.

	(1) Aggregate	(2) Maturities	(3) Countries
Outage	-10.73*** [0.93]	-4.08*** [1.11]	-13.23*** [0.61]
2.5-5.5y		-0.63*** [0.10]	
5.5-10.5y		-0.77*** [0.10]	
>10.5y		-1.90*** [0.08]	
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]	
ES			-0.17 [0.12]
FR			0.56*** [0.07]
IT			1.22*** [0.11]
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 5: 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). *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

4.2 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 A.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) led 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 6 shows the results. The first two of the above predictions are clearly confirmed by the data. The partial outages have i) substantially smaller effects on the liquidity on MTS than system-wide outages, and this is ii) particularly true for bonds with 2.5-10.5 years to maturity. Prediction iii), that German bonds should be less affected, is only true when comparing system-wide with partial Eurex outages, but it is not true when comparing the different countries during the partial outages.

Recall that system-wide outages affect Germany significantly more than all other countries, see model (3) in Table 6. Model (4) shows that these differences are much less pronounced for the partial Eurex outages. The liquidity in French bonds, e.g., drops just as much as those in German bonds during the partial outages. But even during these partial outages, the liquidity in German bonds drops significantly more than in Italian (and to a lesser extent Spanish) bonds, even though some German bond futures were still available for trading on Eurex while all Italian and Spanish futures were unavailable.

Overall, these partial outages confirm that German bond futures are a benchmark used to price any EGB bonds on the cash market. This is why the overall liquidity on MTS drops less when less of these benchmark instruments suffer an outage, and it drops less in those maturity segments where these benchmark instruments are still available.

	Maturity Buckets		Countries	
	(1) System-Wide	(2) Partial	(3) System-Wide	(4) Partial
Outage	-4.95***	-2.89*	-18.03***	-7.12***
	[0.21]	[1.18]	[0.43]	[0.60]
Outage × 2.5-5.5y	-8.50***	-3.20		
	[0.32]	[1.88]		
Outage × 5.5-10.5y	-7.73***	-3.82*		
	[0.61]	[1.52]		
Outage × >10.5y	-7.40***	-4.80***		
	[0.72]	[0.48]		
Outage × ES			8.57**	2.53*
			[2.46]	[1.19]
Outage × FR			3.87***	-1.16
			[0.07]	[0.75]
Outage × IT			16.24***	3.76***
			[0.91]	[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 6: 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. For brevity, the table shows estimates only for the outage dummy and interaction terms. *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

4.3 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.[22] Figure 9 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 even quote EGBs without an active futures market.

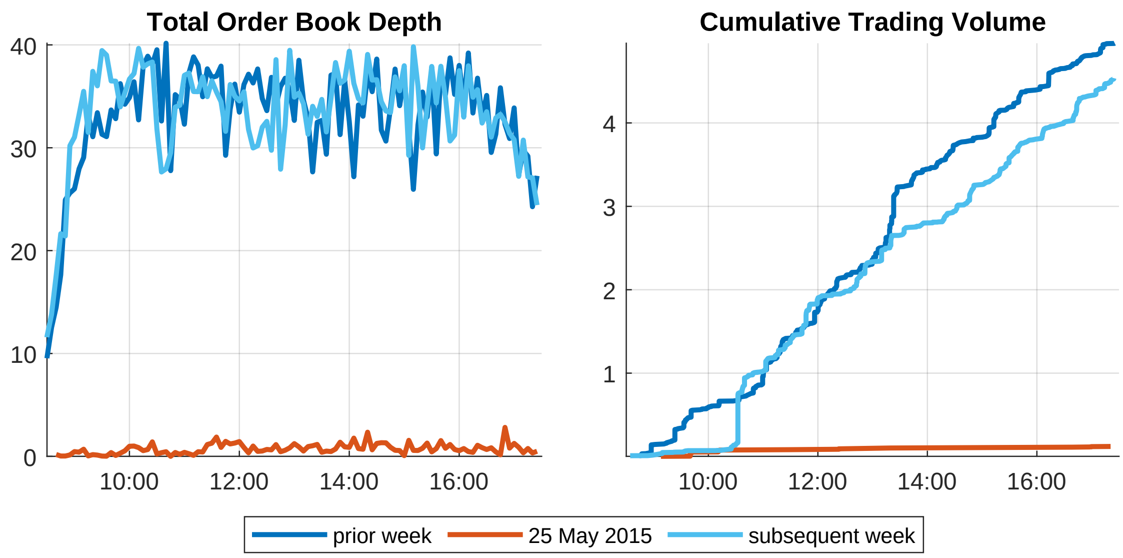

Figure 9: MTS Inactivity on Eurex Holiday 25 May 2015. The left panel shows the total order book depth on MTS (in billion €), across all German, French, Italian and Spanish bonds and all market segments, in 5-minute snapshots. The right panel shows the total cumulated trading volume, in billion €. Red 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.

[22] 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.'

5 Evidence from Outages on Other Markets

The previous sections show that the cash market for euro area sovereign bonds depends heavily on an active futures market. What about the other way around? Section 5.1 and Section 5.2 exploit outages on two cash market trading platforms to study their role for the broader fixed-income market. The question we are trying to answer is whether the market functioning of bond futures also depends on an active cash market. Section 5.3 studies transatlantic spillovers, i.e. whether outages of the European futures exchange Eurex affect market functioning on CME, the main US futures exchange, and vice versa.

5.1 MTS Outage

Section 3.2 shows that the MTS platform is dependent on Eurex: trading and quotation activity on this spot market platform stops when the futures market is down. Is there a similar dependency of Eurex on MTS?

Ideally, we would test this hypothesis using outages of MTS as natural experiments. Since we could not find newspaper reports about such outages, we do the next best thing. We manually look for non-activity periods on MTS - without knowing whether these episodes were due to technical glitches.[23] We found one potential outage on 26 July 2019. As Figure 10 shows, trading and quoting activity on MTS was lower than usual from about 10 a.m. that day, before breaking down entirely from 12:30 till 13:20. There were no quotes and no transactions in any bond. We were not able to find any relevant news during this window that could explain this breakdown. How was Eurex affected by the apparent MTS outage? Figure 11 suggests not at all. There is no discernible drop in liquidity for any of the four euro area countries with a 10-year bond future. Similarly, indicative quotes on Bloomberg do not show any obvious reaction to the MTS outage, see Figure 12. Unfortunately, we cannot check whether trading volumes on the cash market were lower than usual during the MTS outage since our regularoty transaction-level dataset is not available for 2019.

[23] We have contacted MTS and a representative confirmed that they are not aware of any outages of their platform. Regarding the suspected outages we identified, MTS could not provide an explanation.

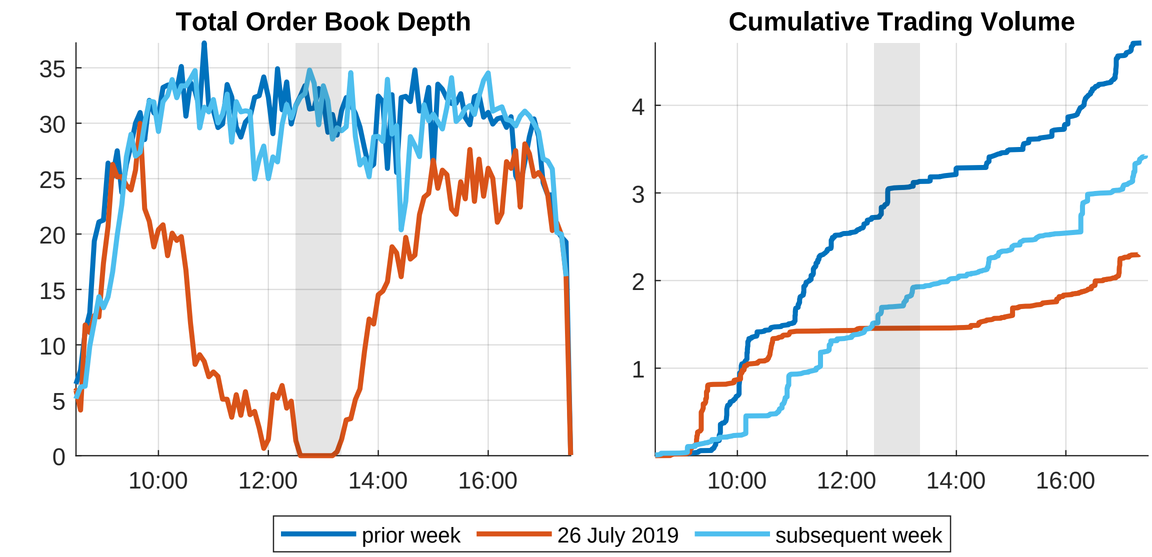

Figure 10: Trading Activity on MTS on 26 July 2019. The left panel shows the total quoted volume (in billion €), across all German, French, Italian and Spanish sovereign bonds and all market segments, in 5-minute intervals. The right panel shows the total cumulated trading volume (in billion €). Red lines refer to 27 July 2019 (the potential MTS outage day), dark and light blue lines refer to the previous and subsequent week.

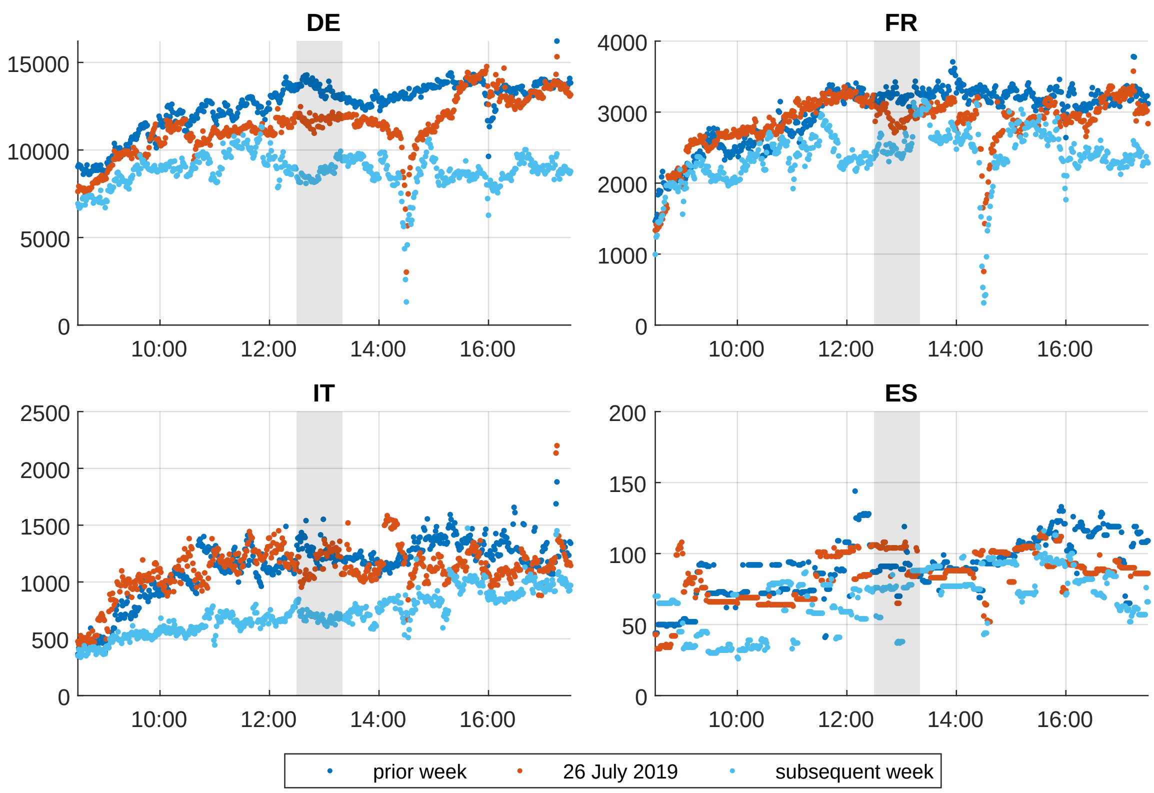

Figure 11: Order Book Depth of 10-year Bond Futures on 26 July 2019. This figure shows the total number of contracts quoted at the first fifteen levels on both sides of the order book, at minutely snapshots. Red dots refer to the potential MTS outage day, dark and light blue dots refer to the previous and subsequent week.

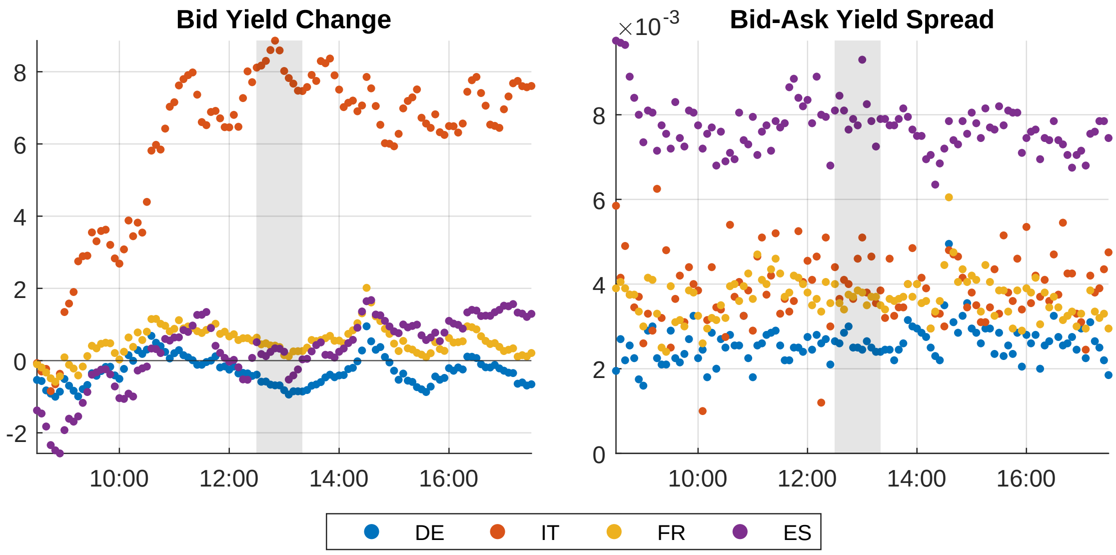

Figure 12: Indicative Quotes on Bloomberg on 26 July 2019. The left panel shows bid yield changes (in basis points since 8:00 a.m.), the right panel shows bid-ask yield spreads (in basis points). All data refers to 10-year cheapest-to-deliver bonds. The grey areas mark the times of the suspected MTS outage.

5.2 Bloomberg Outage

On Friday, 17 April 2015, Bloomberg suffered an outage from 8:20 a.m. till roughly 10:00 a.m. London time. Newspaper reports disagree on the exact duration of the outage, probably because Bloomberg terminals came back online gradually.[24] In any case, traders worldwide were not able to access their terminals temporarily.[25]

Figure 13 shows how the Bloomberg outage affected the cash and future market for European government bonds. On the cash market, effects are quite dramatic. There is virtually no trading while Bloomberg is fully offline, at least according to our transaction database. This is in line with the fact that Bloomberg is a major EGB trading platform, particularly at the time of the outage in 2015. On the futures market, we do not observe an obvious decrease in aggregate trading volumes. Looking at individual countries, however, Figure 14 shows that trading volumes did somewhat decrease in German and French bond futures. But this was 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 15 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 16 shows that the lower liquidity was restricted to Italian bonds.

Overall, we conclude that Bloomberg outages affect the European fixed-income market not nearly as much as Eurex outages.

[24] A Yahoo article mentions e.g. 'by 09:10 London time the company said that some customers had reported the terminal was back online.', a BBC News article says 'Bloomberg's trading terminals in London went down for more than two hours' and a The Globe and Mail article mentions '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'.

[25] The UK Debt Management Office postponed a Treasury bill auction of three billion British pound planned for 10:30 a.m. that day (see article on dmo.gov.uk), since these auctions are run 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 pricing discovery process (as we argue for the cancelled auction of Dutch bonds during the Eurex outage on 14 April 2020).

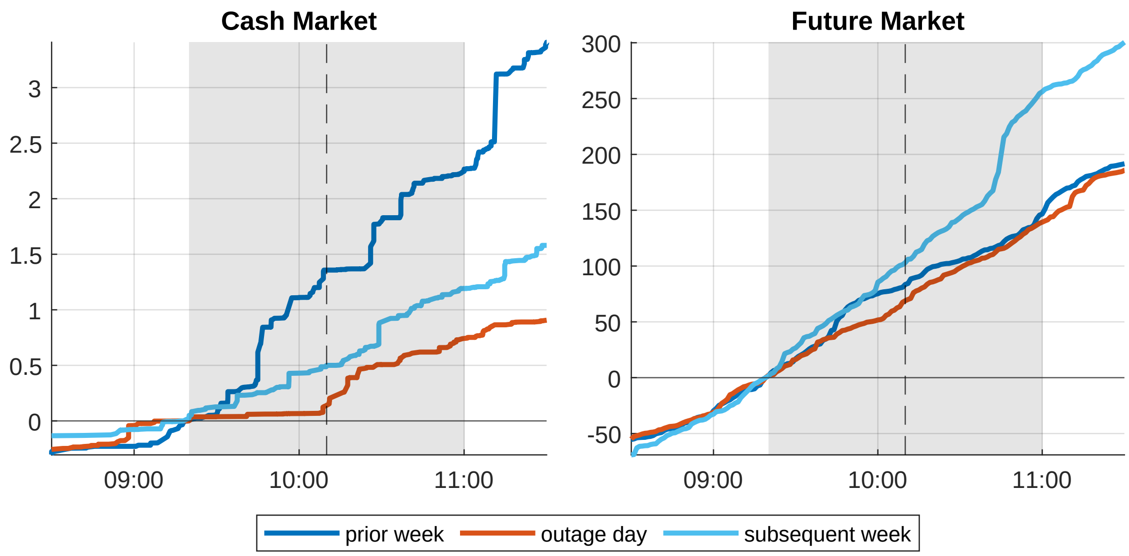

Figure 13: Trading Volumes during Bloomberg Outage. This figure shows the cumulative trading volume of German, French, Italian, and Spanish government bonds (left panel; in billion €; from the regulatory 'Bafin' transaction-level dataset, cf. Section 2.2) and bond futures (right panel; in thousands of contracts), normalized to zero at the intraday time of the outage. See Appedix A.3 for an overview of the underlying bond futures. Red lines refer to the outage day, dark and light blue lines refer to the previous and subsequent week. The grey areas mark the approximate outage times of Bloomberg. The dashed vertical line refers to 9:10 London time, when the first Bloomberg terminals were reportedly back online.

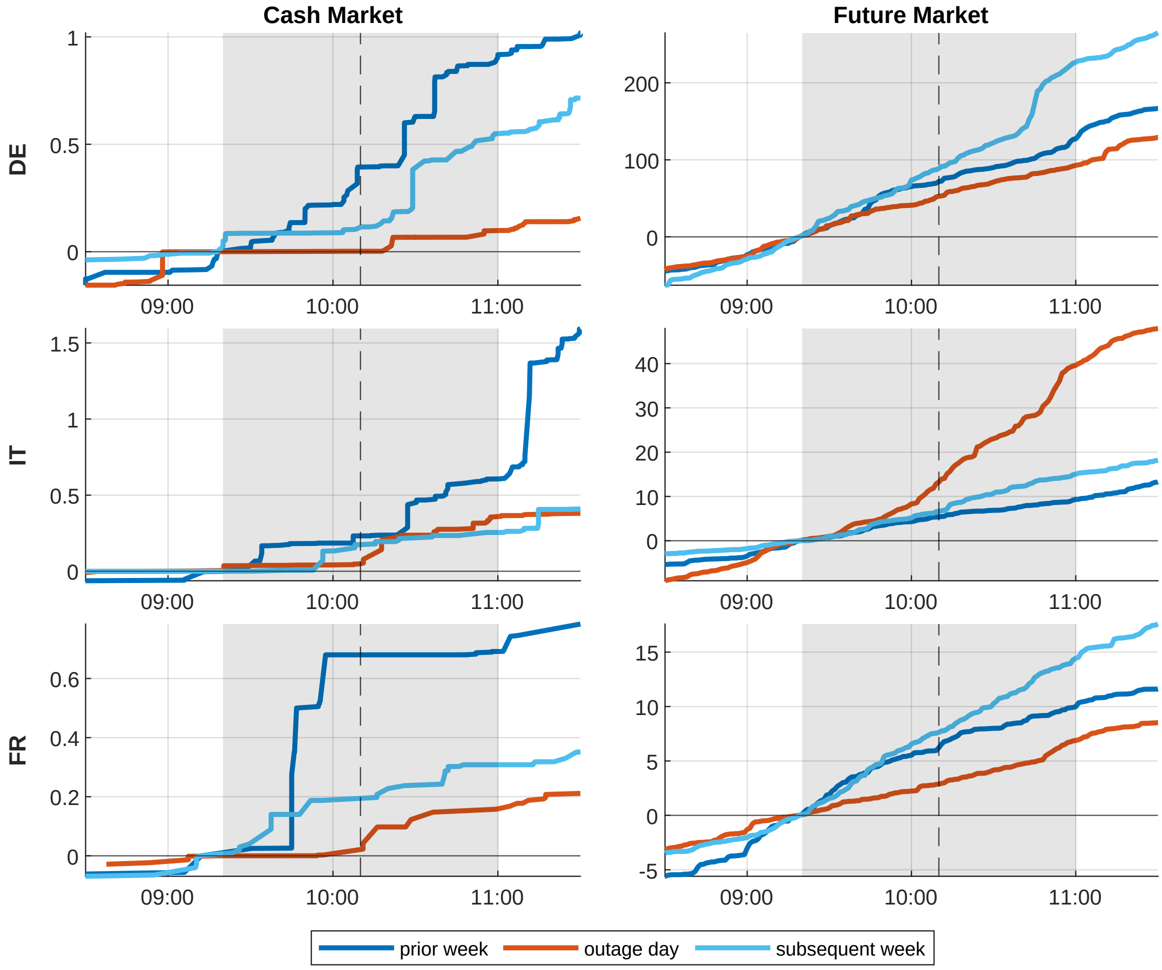

Figure 14: Trading Volumes during Bloomberg Outage across Countries. The left column shows trading volumes in cash bonds (in billion €; from the regulatory 'Bafin' transaction-level dataset, cf. Section 2.2), the right column in bond futures (in thousands of contracts), normalized to zero at the intraday time of the outage. Spain is omitted because the Spanish bond future was introduced in October 2015. See previous figure for details.

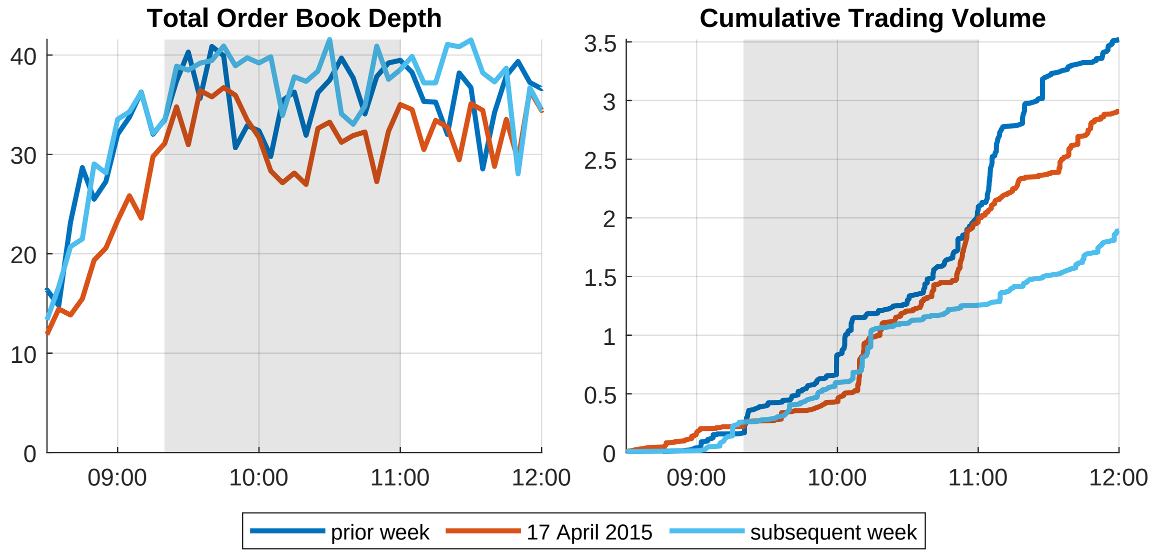

Figure 15: MTS Order Book Depth and Trading Volume during Bloomberg Outage. The left panel shows the total order book depth at 5-minute snapshots (in billion €), the right panel shows the cumulative trading volume on MTS (in billion €). Both panels cover all of German, French, Italian and Spanish sovereign bonds on MTS. See previous figure for details.

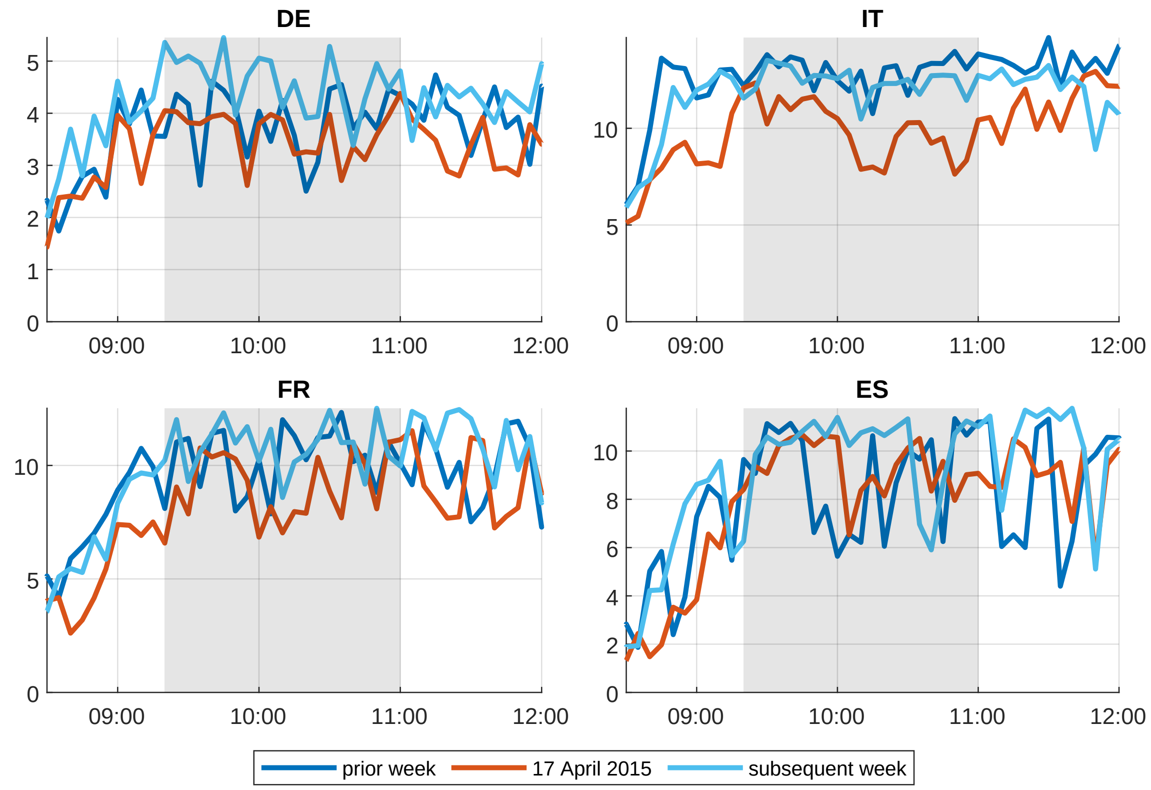

Figure 16: MTS Order Book Depth during Bloomberg Outage across Countries. This figure shows the total order book depth for German, French, Italian and Spanish sovereign bonds on MTS, at 5-minute snapshots (in billion €).

5.3 Transatlantic Spillovers

Did the Eurex outages in 2020 spill over across the Atlantic? Did they reduce the liquidity in US Treasury futures? Figure 17 refutes this conjecture based on intraday order book data from the CME. At most, there is a minor and short-lived drop in liquidity after the first Eurex outage.[26] The lack of spillovers might not be surprising, since a large literature has shown that asset price movements spill over much more from the US to other countries than the other way around, see e.g. Boehm and Kroner (2023) for recent evidence. We will now show, however, that outages of the US futures market also do not seem to affect the euro area futures market.

On 26 February 2019, the Chicago Mercantile Exchange (CME) suffered an outage. The outage started at 7:39 p.m. and lasted till 10:45 p.m. US Eastern Time (in Central European Time, this corresponds to 1:39 a.m. till 4:45 a.m. on 27 February 2019). The outage affected all markets on CME, i.e. also US Treasury futures. 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 future contract, namely the one expiring in March 2019.

The left panel in Figure 18 confirms the outage on CME. More importantly, the right panel shows that the outage barely affects the order book liquidity of German bond futures.[27] Is this a robust finding or is it driven by the timing of the outage, which occurred very early in the morning in Europe, when trading is usually very quiet?

We can answer this question by repeating the same exercise for six older outages of the US futures market that occurred between 2006-2007 (see Harding and Ma, 2010).[28] Since we do not have order book data for this early sample, we look at trading volumes instead. Figure 19 shows that our finding is indeed robust. 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.

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]Note that the temporary drop in liquidity on 1 July 2020 at 2:15 p.m. and 4:00 p.m. was due to US macroeconomic news releases.

[27]For US Treasury futures, there is a level shift in liquidity across days. This is due to the fact that the roll-over into the next-nearest future contract occurs at the end of the month prior to the expiration month. There is no such shift in Bund futures, because there the roll-over occurs just one or two days before the delivery day, i.e. usually the tenth calendar day of the expiration month.

[28]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.

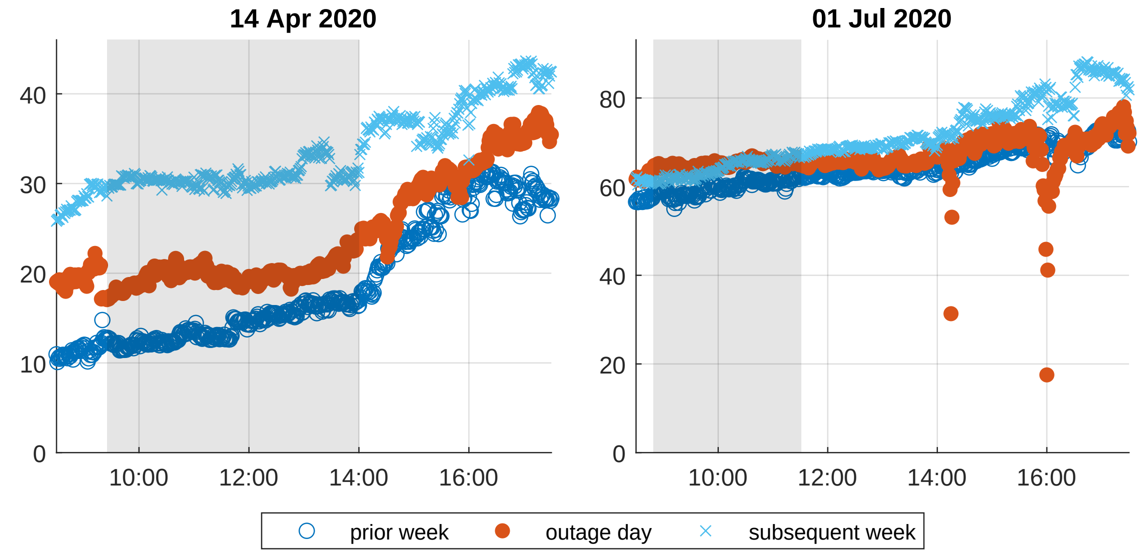

Figure 17: Order Book Depth of US Treasury Futures during Eurex outages. This figure shows the number of quoted contracts (in thousands) at the first 15 levels of both sides of the order book for 10-year Treasury futures. The grey area refers to the outage period on Eurex.

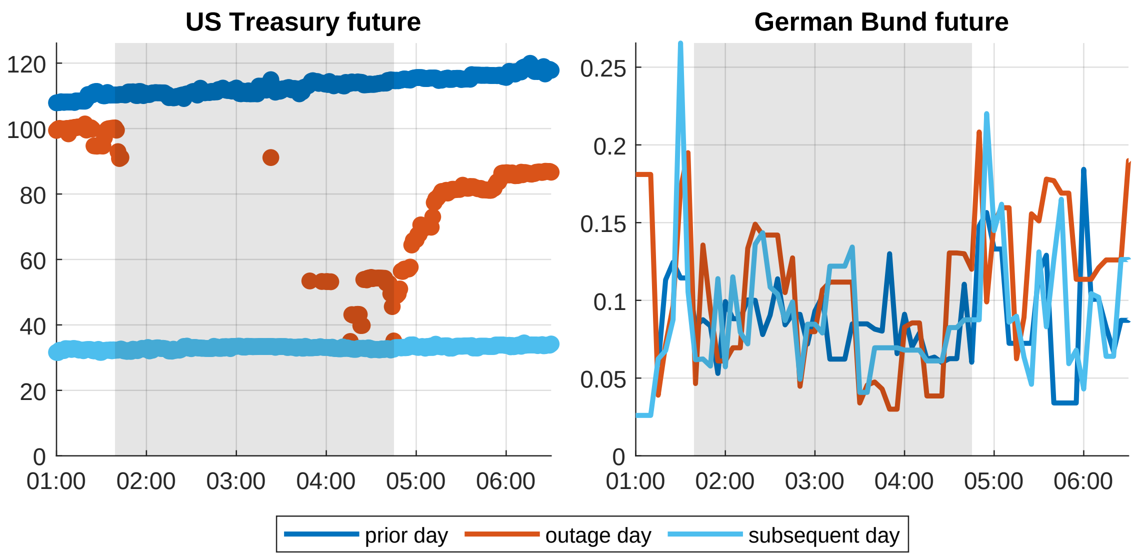

Figure 18: Order Book Depth of US and German Bond Futures during the CME Outage. This figure shows the order book depth of 10-year US Treasury and German Bund futures (both in thousands of contracts). Red lines refer to the outage day, dark and light blue lines refer to the previous and subsequent day. The grey areas mark the approximate outage times of CME. Timestamps are in CET.

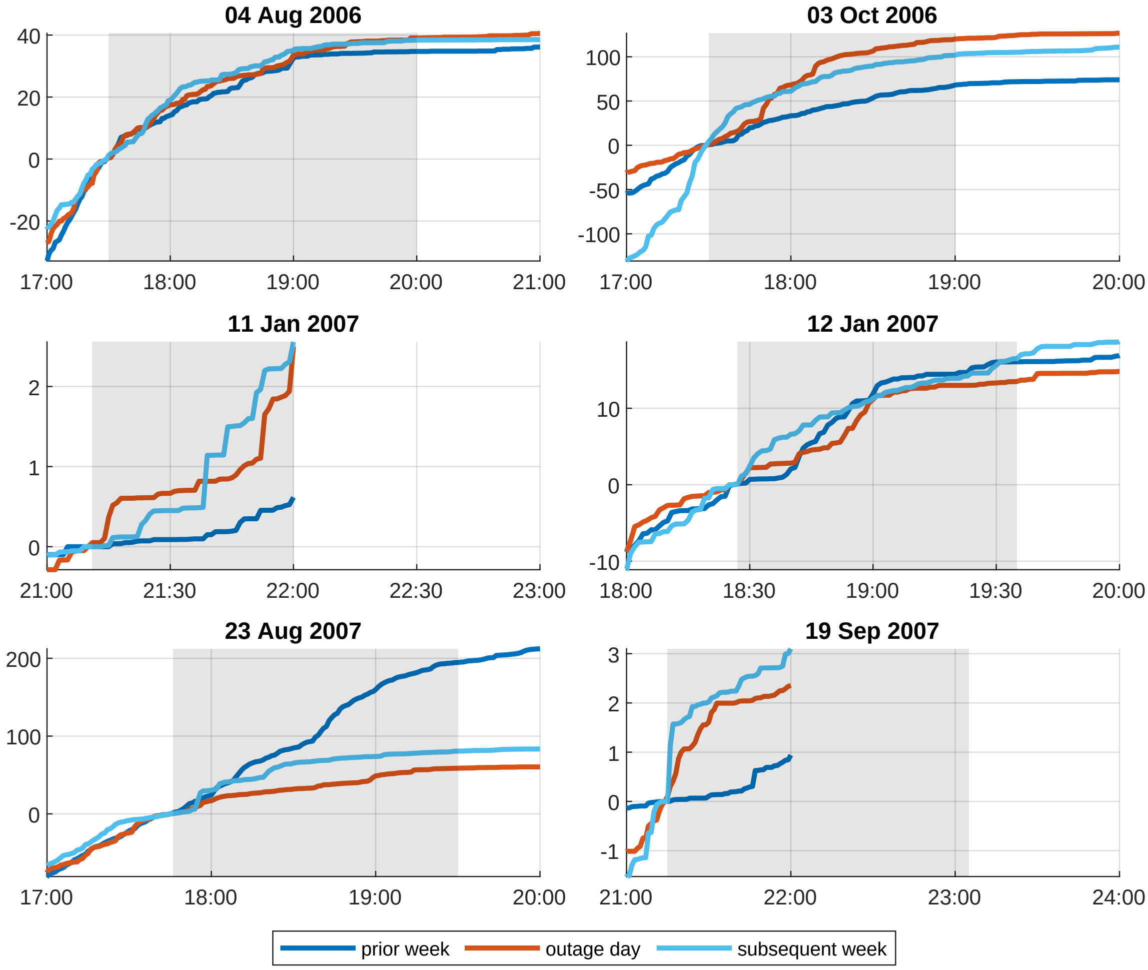

Figure 19: German Bund Future Trading Volume during CBOT Outages. This figure shows the cumulative trading volume of 10-year German bond futures around CBOT outages (in thousands of contracts, normalized to zero at the intraday time of the outage). Red lines refer to the outage day, dark and light blue 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.

6 Conclusion

Risk-free interest rates are a key building block to price any asset. We show that the pricing of these interest rates themselves depends crucially on government 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. The price formation process of German sovereign bonds, the benchmark for risk-free interest rates in the euro area, depends heavily on bond futures.

The reverse is not true. Trading in European government bond futures is comparatively robust to outages on cash trading platforms, suggesting that price formation and liquidity provision is more of a one-way street from the futures to the cash market than previously thought. Finally, we 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 centralisation. A recent proposal by the U.S. Securities and Exchange Commission e.g. aims to boost the use of central clearing for bond transactions. We show that the futures market, where trading and clearing is fully centralized on Eurex, is highly liquid and clearly dominates in price discovery. The downside is that an outage of Eurex becomes a systemic risk. The cash market, on the contrary, is fragmented across multiple trading platforms, most of which do not offer central clearing, which leads to lower liquidity and a minor role for price discovery. The upside is that the cash market is robust to an outage of any individual cash platform.

References

Allen, J. and M. Wittwer (2023). Centralizing over-the-counter markets? *Journal of Political Economy forthcoming*.

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.

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.

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).

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

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*.

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

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.

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.

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*.

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

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.

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 (2022). What moves markets? *Deutsche Bundesbank Discussion Paper No 16*.

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 (2023). Why trade over-the-counter? *Available at SSRN*.

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.

Pasquariello, P. and C. Vega (2007). Informed and strategic order flow in the bond markets. *The Review of Financial Studies 20*(6), 1975–2019.

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

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*.

Internet Appendix
for
Outages in Sovereign Bond Markets

by Mark Kerssenfischer and Caspar Helmus

(not for publication)

Appendix A provides details on the outages we study and the data we use.
Appendix B contains further results and robustness checks.
Appendix C contains narrative evidence, namely newspaper reports about the outages and selected quotes from private market participant about their views on euro area bond market functioning.

Appendix A Data Details

A.1 Overview of Market Outages

Table A1 contains a list of market outages. We study the two most recent Eurex outages in Section 3 of the paper, the previous Eurex outages in Section 4, and the outages of other platforms in Section 5.

Figure A1 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 Appendix C.2.

Figure A2 confirms the two partial outages on Eurex studied in Section 4.2 in the main text. 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.[29] On the first of these days, there were two outage periods.

Exchange/Platform	Affected Assets	Dates
Eurex	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
	some EGB futures	21 November 2016 26 May 2014
Bloomberg	EGB spot market	17 April 2015
MTS (suspected)	EGB spot market	26 July 2019
CME CBOT	US futures	26 February 2019 19 September 2007 23 August 2007 12 January 2007 11 January 2007 3 October 2006 4 August 2006

Table A1: Overview of Market Outages Studied in This Paper.

[29] Regarding the partial first outage, a Reuters news article explained: 'BTP and OAT futures were not priced in the session on Tuesday due to technical problems. This was reported by Eurex, the platform that manages exchanges on the two derivatives.' For the second outage, the only real-time confirmation we could find is on Twitter, see e.g. this Tweet.

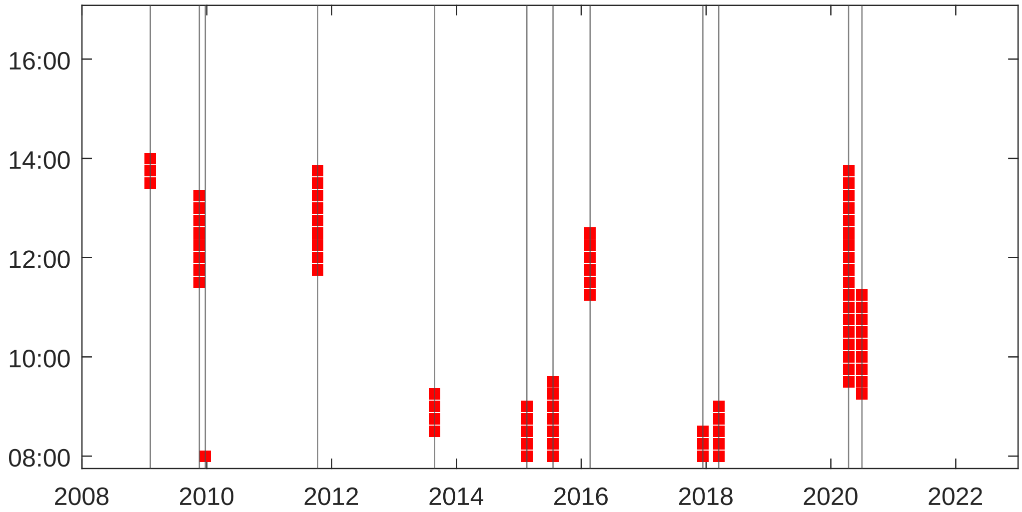

Figure A1: System-Wide Eurex Outages since 2008. For each trading day since 2008, this figure shows 15-minute intraday windows with no trading in the German 10-year bond future (FGBL). The vertical axis ranges from 8:00 a.m. to 5:00 p.m. local time. Solid vertical lines mark the twelve known outage days.

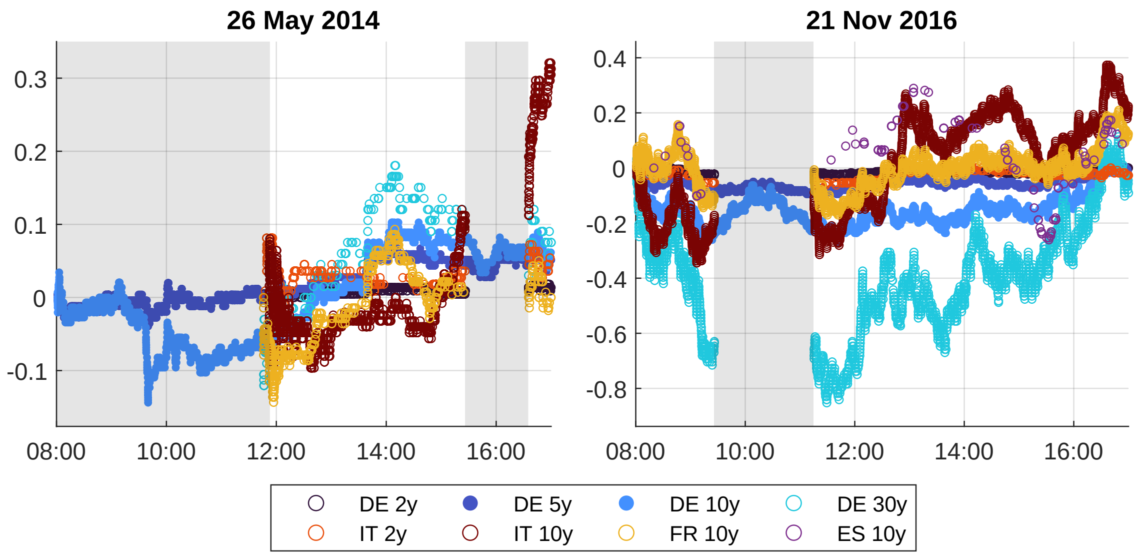

Figure A2: Partial Outages on Eurex. This figure shows intraday transaction prices of all euro area government bond futures (in percentage changes since 8:00 a.m.). The grey areas mark the outage times that affected all futures except those for 5-year and 10-year German bonds. The Spanish 10-year future was introduced in October 2015, i.e. after the 2014 outage.

A.2 Future and Cash Market

The futures market for European government bonds is fully centralized on Eurex. Table A2 gives an overview of the available bond futures and their trading volumes in 2022. For each future, three contracts with different expiring 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 all traded contracts, 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 contracts that expire in June 2020. For the July outage, we use contracts that expire in September 2020.

In comparison, the cash market for European government bonds is much more fragmented. Table A3 gives a stylized overview of the different venues cash bonds can be traded on.

Table A4 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, they are of comparable size. For Spain, where a future was introduced last, namely in October 2015, trading volumes are less than 1% of the cash market.

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.

	On-Exchange	Electronic Platforms	Over-the-Counter
Trading Protocol	Central Limit Order Book	Request for Quote	Voice, Chat
Immediacy, Centralization, and 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, ...

Table A3: Stylized Differences between Trading Venues for European Government Bonds.

Country	Future Volume (billion €)	Cash Volume (billion €)	Ratio Future/Cash
Germany	72,044	7,404	9.7
France	7,745	5,435	1.4
Italy	8,367	7,197	1.2
Spain	21	2,002	.01

Table A4: Comparison of Euro Area Government Bond Trading Volumes on the Futures and Cash Market in 2022. 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). We cross-checked these figures with data from the Government Bond Data Report from the Association for Financial Markets in Europe (AFME). For Germany, the report is 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.

A.3 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 (which have eco- and climate-friendly budget expenditures assigned to them), 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 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 A6 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 3.1, we study a fixed set of bonds, to avoid compositional effects. In particular, we start with all plain vanilla bonds that were traded at least once during the six selected days (the two outage days plus the same day in the preceding and subsequent week). Then, we drop bonds that were issued after 7 April 2020 or matured before 8 July 2020 and we drop a handful of bonds that rolled into a different maturity bucket within the above timeframe. This leaves us with 259 different bonds. Table A7 provides a breakdown by maturity bucket and the number of cheapest-to-deliver, on-the-run, and zero coupon bonds per country. Table A8 provides further summary statistics of the time to maturity, the time since issuance, and the original maturity.

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 bounds ensure that we have an on-the-run 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).

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

Table A5: 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 A6: Overview of On-the-Run Bonds. *For Spain, the 1-year on-the-run bond on 21 April 2020 was ES0L02104161 (issued on 17 April 2020).

Maturity Bucket	DE	ES	FR	IT
< 2.5 years	21	17	21	34
$2.5 - 5.5$ years	14	11	10	20
$5.5 - 10.5$ years	13	14	11	17
> 10.5 years	9	11	15	21
	DE	ES	FR	IT
CTD	4	1	1	2
	DE	ES	FR	IT
OTR	3	3	3	3
	DE	ES	FR	IT
Zero Coupon	22	11	20	15

Table A7: Number of Bonds by Type and Country. 'CTD' refers to bonds that are cheapest-to-deliver in any bond future contract traded on Eurex, 'OTR' refers to 'on-the-run' bonds, see Appendix A.3. 'Zero coupon' bonds are bonds that pay zero coupon.

	min	p50	mean	max
< 2.5 years				
Years to Maturity	0.3	0.9	1.1	2.5
Years since Issuance	0.0	1.5	3.6	28.2
Original Maturity in Years	0.0	3.0	4.6	30.0
$2.5 - 5.5$ years				
Years to Maturity	2.8	3.9	3.9	5.4
Years since Issuance	0.1	5.2	6.1	28.2
Original Maturity in Years	3.0	10.0	9.9	31.0
$5.5 - 10.5$ years				
Years to Maturity	5.9	7.9	8.0	10.3
Years since Issuance	0.0	3.2	6.2	23.2
Original Maturity in Years	7.0	10.0	14.1	31.0
> 10.5 years				
Years to Maturity	11.1	20.3	22.4	46.9
Years since Issuance	0.1	5.1	7.6	20.1
Original Maturity in Years	16.0	31.0	30.0	50.0
Total				
Years to Maturity	0.3	4.4	7.8	46.9
Years since Issuance	0.0	3.5	5.5	28.2
Original Maturity in Years	0.0	10.0	13.2	50.0

Table A8: Bond Characteristics across Maturity Buckets. Years to maturity and years since issuance are calculated as of 7 April 2020.

A.4 Cash Market Transaction Dataset

As explained in Section 2.2, we exploit multiple datasets to capture as many cash transactions in EGBs as possible. In a nutshell, we start with the regulatory 'Mifir' dataset described in Section 2.2 and add non-duplicate trades from MTS, MTS Bondvision, Tradeweb and TPICAP.[30] We define duplicates as transactions in the same ISIN, at the same price, with the same volume, and with the same secondly timestamp. For the Mifir sample, we apply some very basic filters. We drop transactions with missing or clearly erroneous prices (below €10 or above €1000), and we drop transactions that occured more than two days prior to the bond's issuance (so-called 'when-issued' transactions).

Table A9 shows the final number of transactions we use from each data source. There are big differences across countries. For instance, adding transactions from Tradeweb to the Mifir dataset gives only 3% more observations for Germany, but almost doubles the number of observations for France. Similarly, incorporating transactions from MTS and MTS Bondvision is crucial for Italy, but rather negligible for Germany.

Table A10 provides the same overview for the transaction volume. To put these numbers into perspective, they imply a daily trading volume of $148/6 \approx 25$ billion Euro in German government bonds. This is more 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) but less than the ICMA estimates for 2022 ($7,404/250 \approx 30$ billion Euro daily volume, see Table A4). One reason we might slightly overstate the trading volume is due to duplicates in the regulatory 'Mifir' dataset. For instance, a single trade might be reported independently by both counterparties, by some intermediate broker, and/or by the trading platform on which the trade occurred. Our above-mentioned filtering procedure might not capture all those duplicates because the different reporting entities might use slightly different intraday timestamps.

The last row in Table A10 provides country shares of the trading volume we capture. In our combined dataset, trades in German bonds are still overrepresented, but not nearly as much as would be the case without augmenting data sourced directly from trading platforms. German bonds account for 56% of volume in our dataset compared to a 34% cash market share in 2022 based on Table A4. The analogous figures are 9% vs. 25% for France, 27% vs. 33% for Italy, and 8% vs. 9% for Spain.

These 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.

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,

[30]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 for the last six months. Clearstream and Euroclear, the two principal clearing houses in Europe, offer data on ISIN-level trading volumes, but only at a daily frequency. Similarly, we have access to bond data from Markit, covering various data sources, but also only at a daily frequency.

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[31] 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 3906 transactions during the six selected intraday windows shown in Figure 6 and used in the regression of Table 3. Table A11 provides some descriptive statistics for these transactions.

Source	DE	FR	IT	ES	Total	in %
Mifir	22549	2076	14417	2237	41279	73
Tradeweb	625	1927	2428	1465	6445	11
MTS	39	439	5248	469	6195	11
BondVision	42	125	1802	139	2108	4
TPICAP	276	28	158	10	472	1

Table A9: Number Of Cash Transactions by Data Source and Country. All figures refer to transactions in 'plain vanilla' European government bonds on six days in 2020 (the two Eurex outage days and the respective control days), see Appendix A.3 for details.

Source	DE	FR	IT	ES	Total	in %
Mifir	147.9	15.6	32.9	15.0	211.4	78
Tradeweb	0.7	2.1	2.6	1.8	7.2	3
MTS	0.3	4.1	27.3	4.6	36.3	13
BondVision	0.1	2.0	9.0	1.2	12.3	5
TPICAP	2.6	0.8	1.0	0.1	4.5	2
Total	151.6	24.6	72.8	22.7	271.7	
in %	56	9	27	8		

Table A10: Trading Volume of Cash Transactions by Data Source and Country. All figures are in billion € and refer to transactions in 'plain vanilla' European government bonds on six days in 2020 (the two Eurex outage days and the respective control days), see Appendix A.3 for details.

[31]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				
Years to Maturity	1.00	5.36	5.77	9.86
Years since Issuance	-0.01	2.23	3.19	26.47
Coupon Rate	0.00	0.00	0.51	6.50
Yield	-0.73	-0.62	-0.59	-0.31
Yield Curve Fitting Error	-0.12	-0.00	-0.00	0.28
Outage				
Years to Maturity	1.01	5.84	6.08	9.84
Years since Issuance	0.09	2.25	3.62	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	-0.24	-0.00	-0.00	0.51
Total				
Years to Maturity	1.00	5.48	5.82	9.86
Years since Issuance	-0.01	2.25	3.26	26.47
Coupon Rate	0.00	0.00	0.53	6.50
Yield	-0.92	-0.61	-0.58	-0.18
Yield Curve Fitting Error	-0.24	-0.00	-0.00	0.51

Table A11: Descriptive Statistics for Yield Curve Fitting Sample. These statistics refer to the 3906 transactions in German sovereign bonds with 1-10 year maturity shown in Figure 6 and underlying the regression results in Table 3.

Appendix B Further Results and Robustness Checks

This section provides further evidence on the two Eurex outages in 2020 studied in Section 3 in the main text. Section B.1 looks at the role of high-frequency traders in the aftermath of the outages. Section B.2 shows that the interest rate swap market is severly affected by outages on Eurex. Section B.3 documents that the liquidity dry-up on MTS was widespread and affected virtually all bonds. Section B.4 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. Section B.6 provides robustness checks regarding the effect of Eurex outages on indicative EGB quotes on the cash market. Section B.7, shows that the decline in trading volumes we document holds across the different cash market segments. Section B.8, lastly, shows that EGB trading volumes during previous Eurex Outages were lower than usual, just like for the two outages in 2020.

B.1 HFT Activity after Eurex Outages

Figure A3 compares the cumulative trading volume in each 10-year bond future on the two outage days in 2020 with the previous and subsequent week. Each column in the figure refers to an outage day, each row to a different country.

Figure A4 plots the order book depth of 10-year bond futures on the two outage days in 2020. Note that the temporary drop in liquidity across all futures on 1 July 2020 at 2:15 p.m. and 4:00 p.m. was due to scheduled US macroeconomic news releases, namely the ADP national employment report and ISM's Purchasing Managers Index. More importantly for our purposes, however, is how market liquidity recovered after Eurex went back online. Especially for the German FGBL future on 14 April 2020, this recovery was rather slow. Thanks to a regulatory dataset (EMIR), we can provide some suggestive evidence on the reason why.

In particular, the EMIR dataset contains non-anonymous investor-level trades in futures contracts. Figure A5 and Figure A6 shows that one particular set of investors, namely algorithmic high-frequency traders (HFT), had a smaller market presence than usual in the aftermath of the 14 April 2020 outage. Hence, the reduced liquidity on that day was most likely due to the absence of those HFT firms. After the second outage on 1 July 2020, we observe an immediate recovery in market liquidity, in line with the fact that HFT firms immeditaly re-entered the market. Why the behaviour of HFT firms differs across outage days is an open question, however. One possibility is that they adjusted their algorithms after the first markt outage in April. Figure A7, lastly, shows that the sheer number of active investors is not markedly affected by the outages. The number of different investors that executed at least one trade in the FGBL future is similar pre vs. post outage and on outage vs. control days.

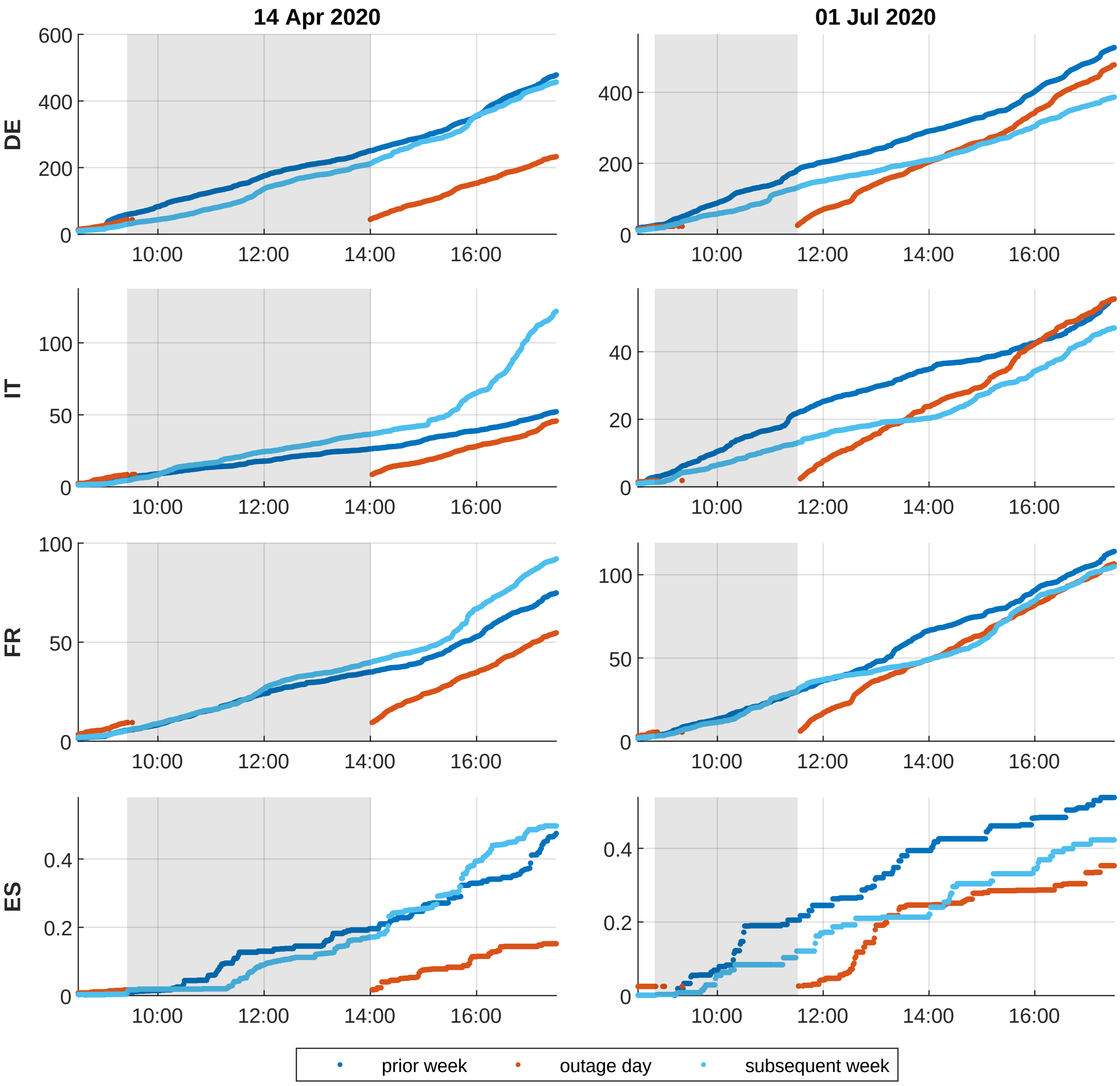

Figure A3: Cumulative Trading Volume of 10-year Bond Futures. This figure shows the cumulative number of traded contracts (in thousands) per day. Red dots refer to the outage day, dark and light blue dots refer to the previous and subsequent week.

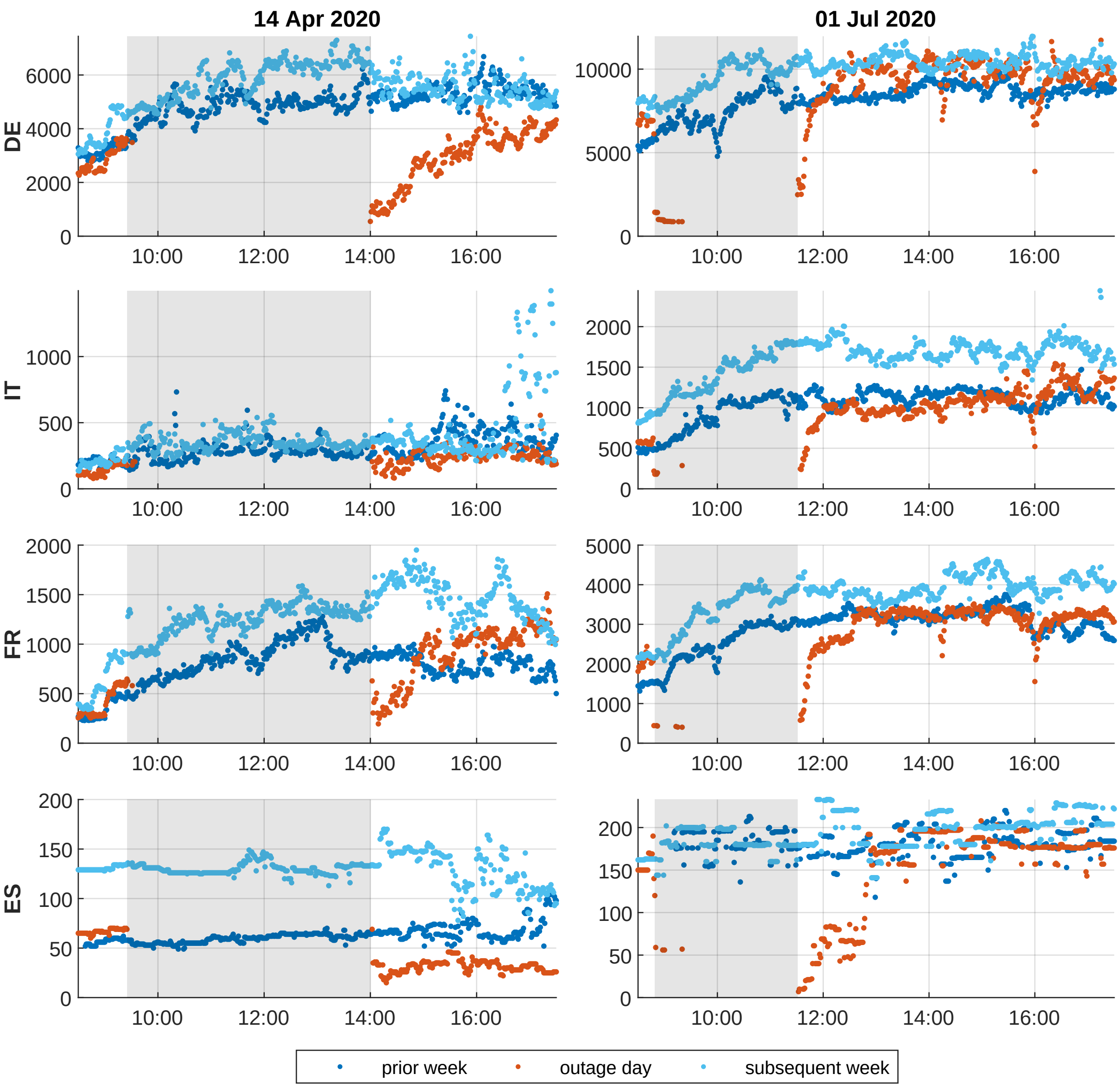

Figure A4: Order Book Depth of 10-year Bond Futures. This figure shows the total number of contracts quoted at the first fifteen levels on both sides of the order book, at minutely snapshots. Red dots refer to the outage day, dark and light blue dots refer to the previous and subsequent week.

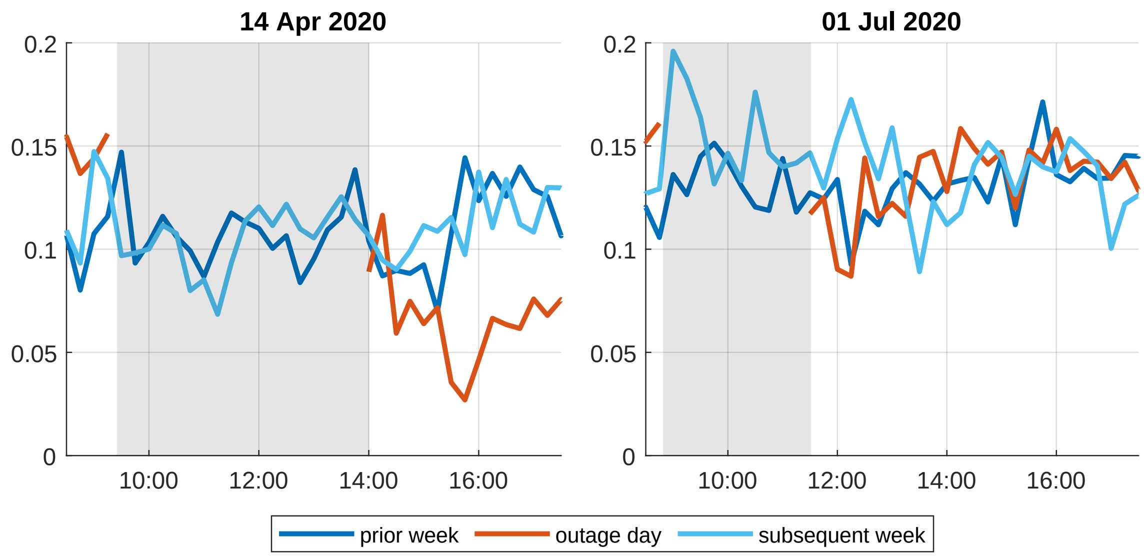

Figure A5: HFT Share of Trading Volume in 10-year Bund Futures. This figure shows the share of trading volume due to high-frequency traders, in 15-minute buckets. Red dots refer to the outage day, dark and light blue dots refer to the previous and subsequent week.

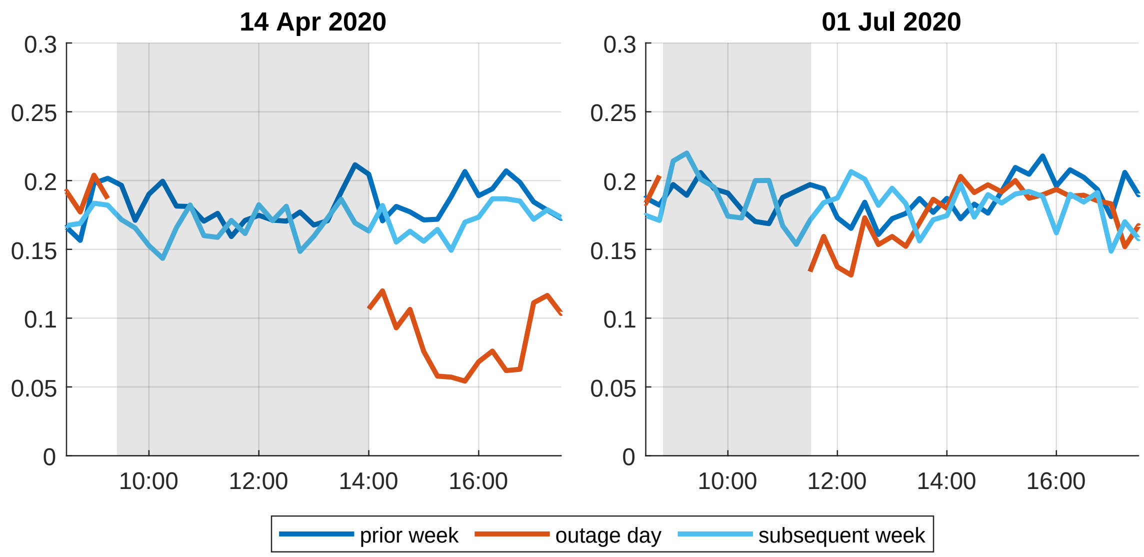

Figure A6: HFT Share of Number of Trades in 10-year Bund Futures.This figure shows the share of the number of trades due to high-frequency traders, in 15-minute buckets. Red dots refer to the outage day, dark and light blue dots refer to the previous and subsequent week.

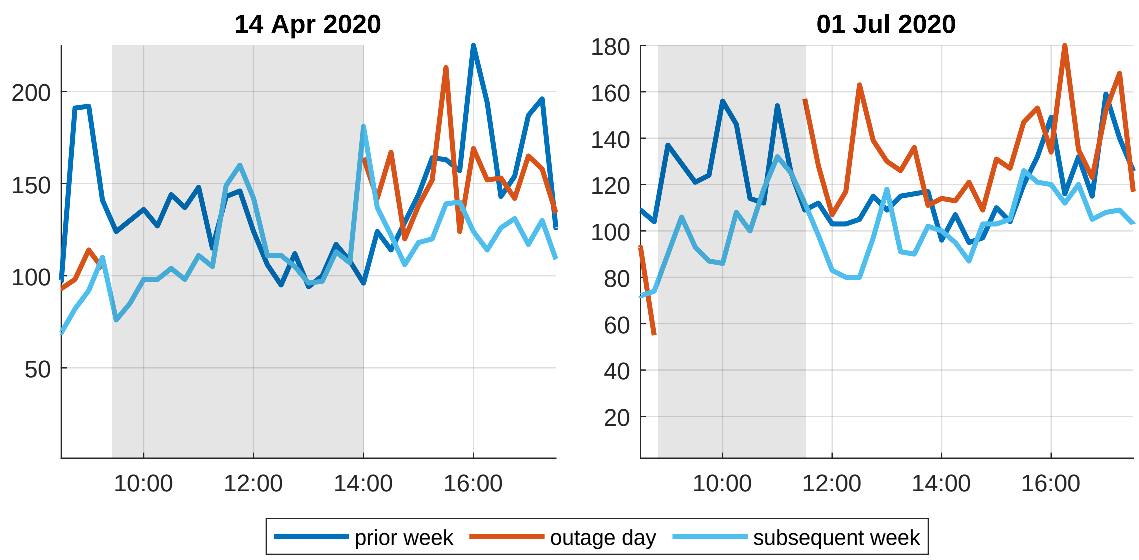

Figure A7: Number of Active Investors in 10-year Bund Futures. This figure shows the number of different investors that traded at least once in each 15-minute window. Red dots refer to the outage day, dark and light blue dots refer to the previous and subsequent week.

B.2 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.[32] 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 A8 shows how these short-term swaps behaved during the Eurex outages, based on Bloomberg data.[33] 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.[34] 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 A9 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 A10 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 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 one specific (commonly used) instrument on Trad-X, namely 10-year swaps based on the six-month Euro Interbank Offered Rate (Euribor). These derivative contracts exchange 10-year fixed-rate interest payments for six-month floating-rate interest payments. Figure A11 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.

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

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

[34] 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.

Recall that if the main function of bond futures was hedging, one might expect trading to migrate to long-term swaps while futures are unavailable. Instead, we find that the long-term interest rate swap market breaks down during the Eurex outages. This is consistent with our claim that bond futures are mainly used for price discovery or 'speculation', rather than pure hedging of existing positions in the spot market. However, these results do not rule out hedging-based explanations. Swap dealers e.g. might hedge their trades with bond futures. So if the futures market suffers an outage, these dealers might be unwilling to quote interest rate swaps, leading to the evaporation of quotes we observe.

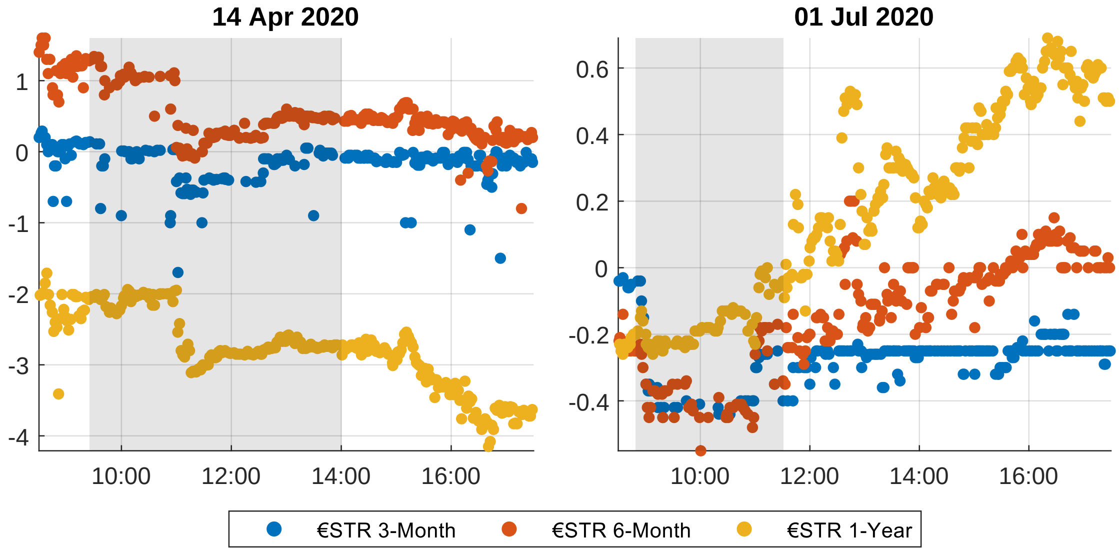

Figure A8: Short-Term €STR Swap Rates on Bloomberg. This figure shows cumulated rate changes (in basis points, normalized to zero at 8:00 a.m.) for overnight index swaps of different tenors based on the euro short-term rate (€STR).

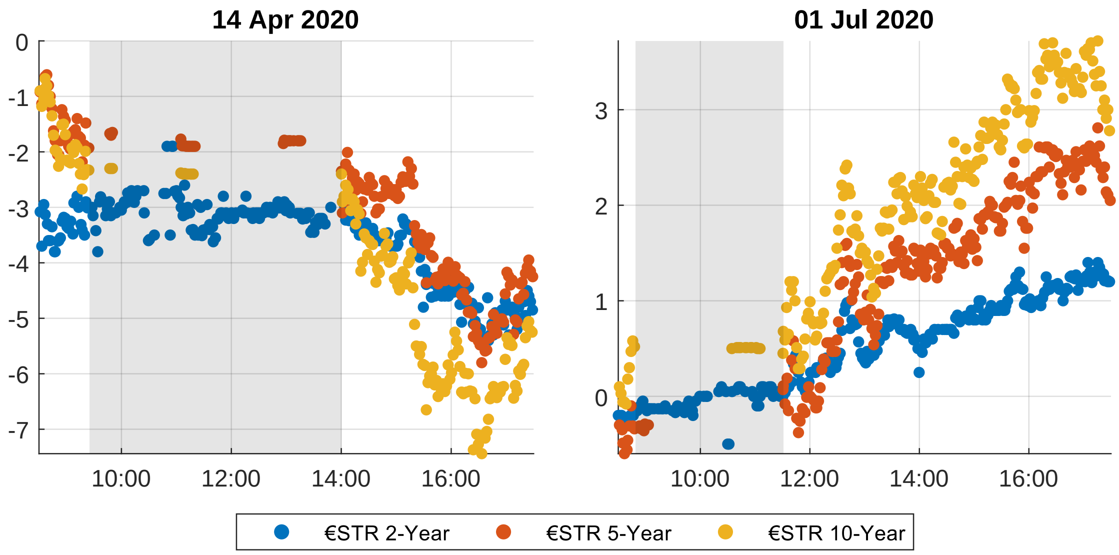

Figure A9: Longer-Term €STR Swap Rates on Bloomberg. See previous figure for details.

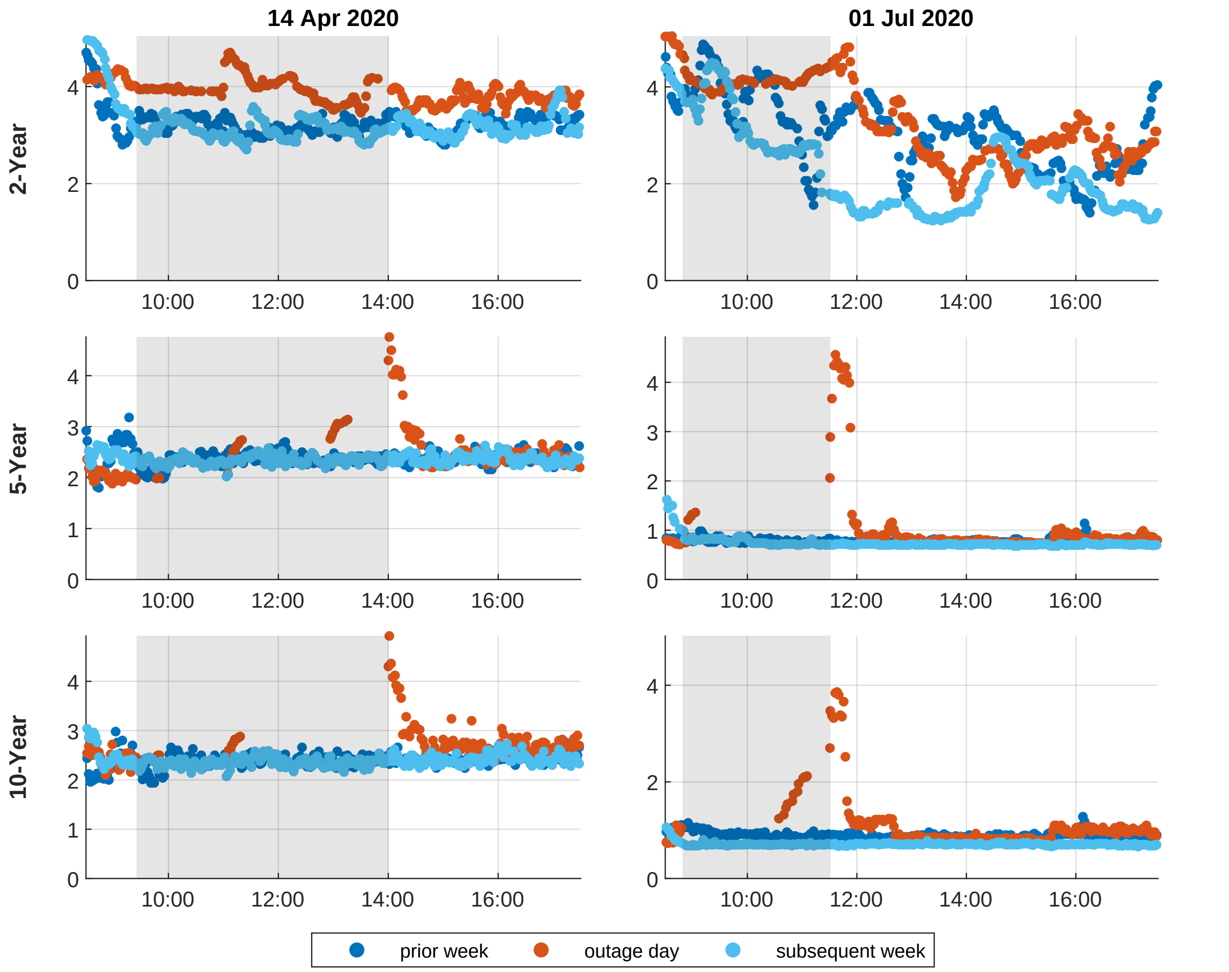

Figure A10: Bid-Ask Spread of €STR Swap Rates on Bloomberg. This figure shows the bid-ask spread (in basis points) for overnight index swaps of different tenors based on the euro short-term rate (€STR). Red lines refer to outage days, dark and light blue lines refer to the previous and subsequent week.

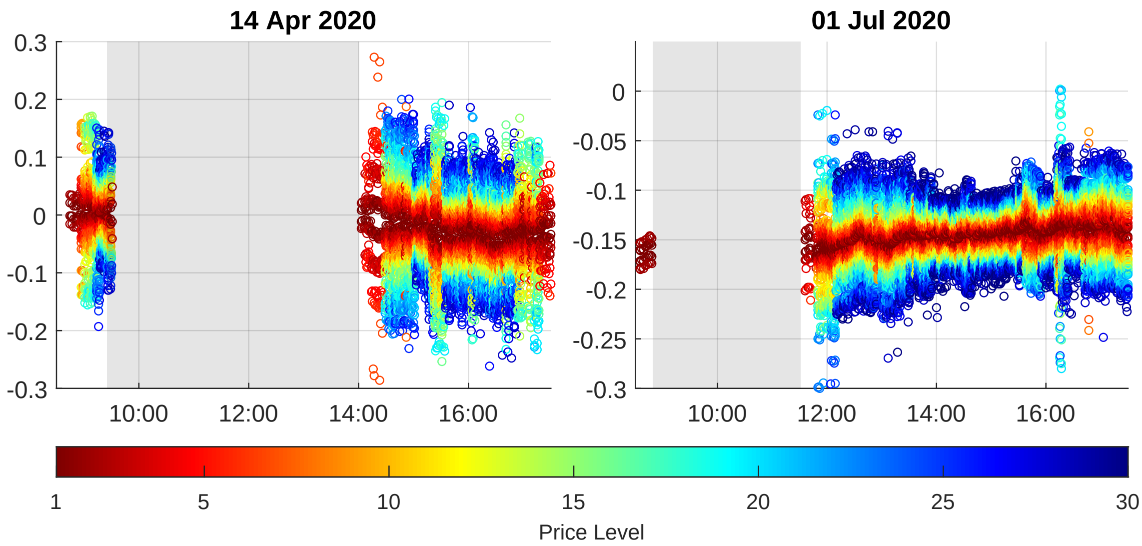

Figure A11: Bid and Ask Quotes for 10y/6m Euribor Swaps on Trad-X. The figure shows bid and ask quotes across different order book levels.

B.3 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 the 10-year bond futures evaporates on MTS when Eurex goes down. Figure A12 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 A13 (note the log-scale).

The above results are based on MTS's euro area wide 'EBM' platform (also called EuroMTS). In parallel, MTS also runs local bond market platforms (labelled 'GEM' for Germany, 'FRF' for France, 'MTS' for Italy, and 'ESP' for Spain). Figure A14 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 A15 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 A16 documents a sharp decline in liquidity across countries and Figure A17 across maturities. Figure A18, 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 e.g., i.e. bonds that were deliverable into the 10-year bond future, we only observe a single trade during each outage. Figure A19 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'.

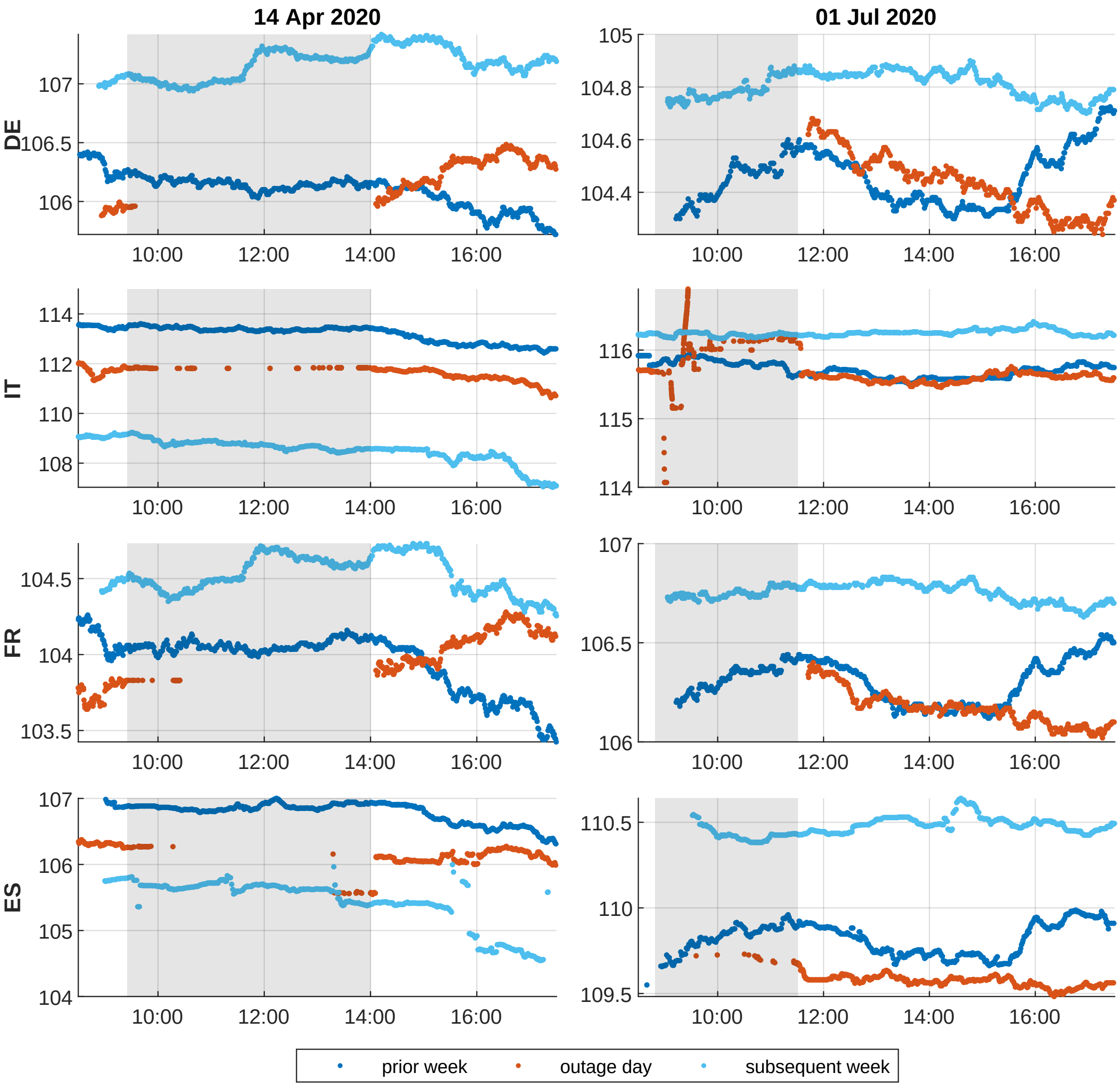

Figure A12: Mid prices on MTS. This figure shows the average of the best bid and ask quote for the cheapest-to-deliver bond underlying the 10-year bond future on Eurex. Red dots refer to outage days, dark and light blue dots to the previous and subsequent week.

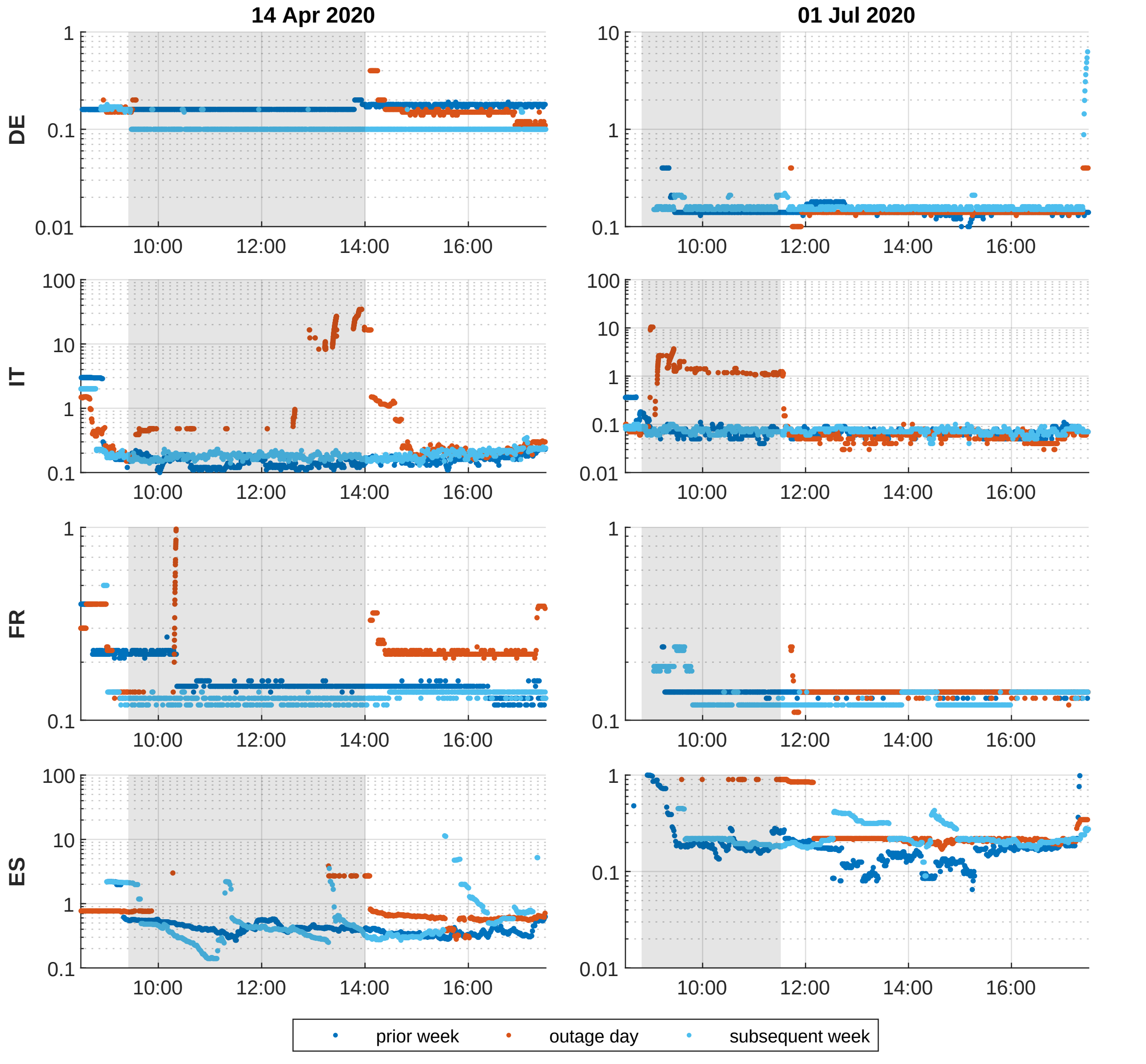

Figure A13: Bid-Ask Spreads on MTS. This figure shows the difference between the best ask and best bid price in Euro for 10-year CTD bonds (on a log scale). See Figure A12 for details.

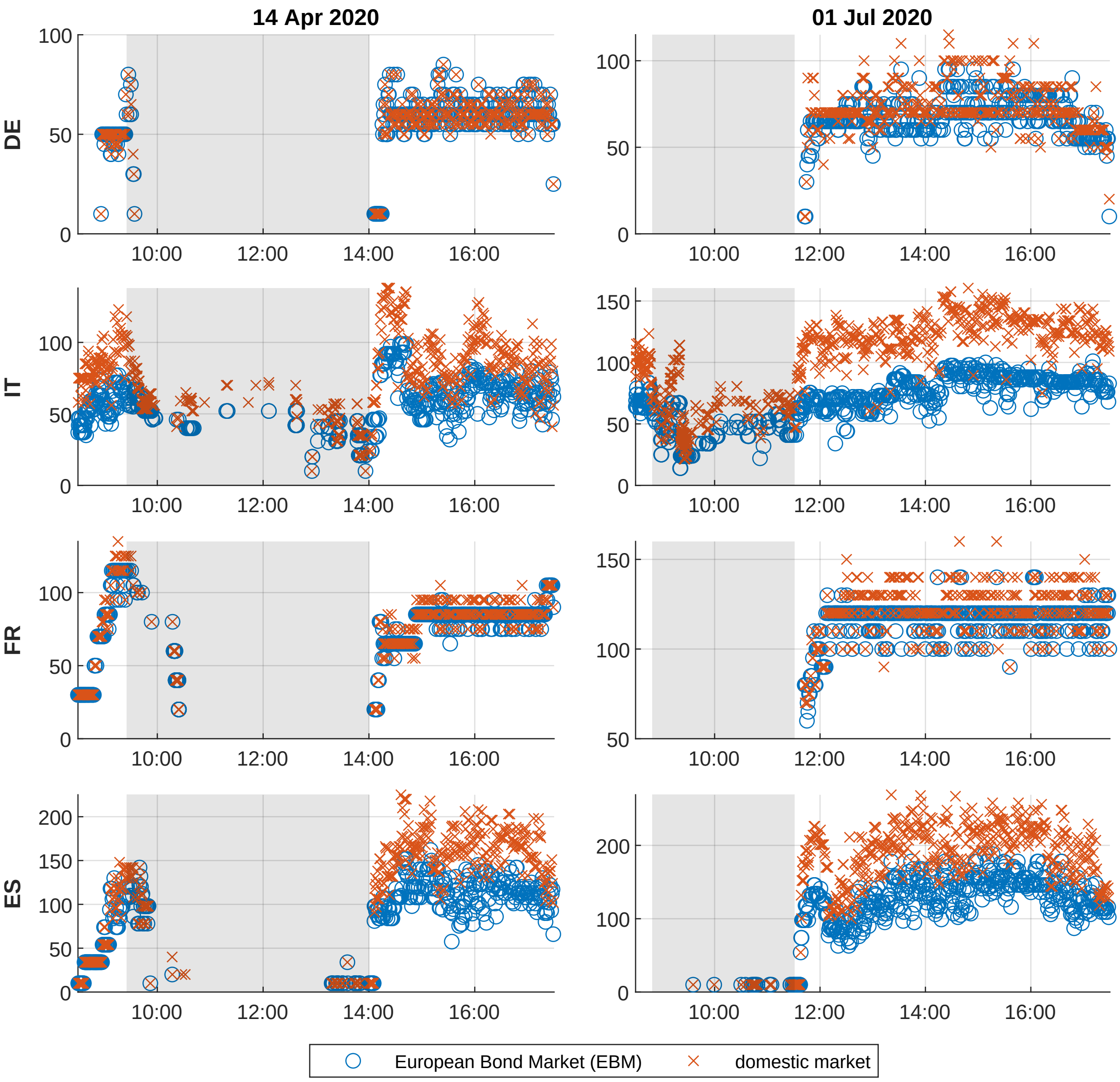

Figure A14: Order Book Depth of CTD bond on different MTS market segments. This figure shows the total quoted volume (in million €) across all three levels and both sides of the order book, for the cheapest-to-deliver bond underlying the 10-year future. Blue circles refer to the 'European Bond Market' segment (as in the main text), red crosses refers to the domestic market segment.

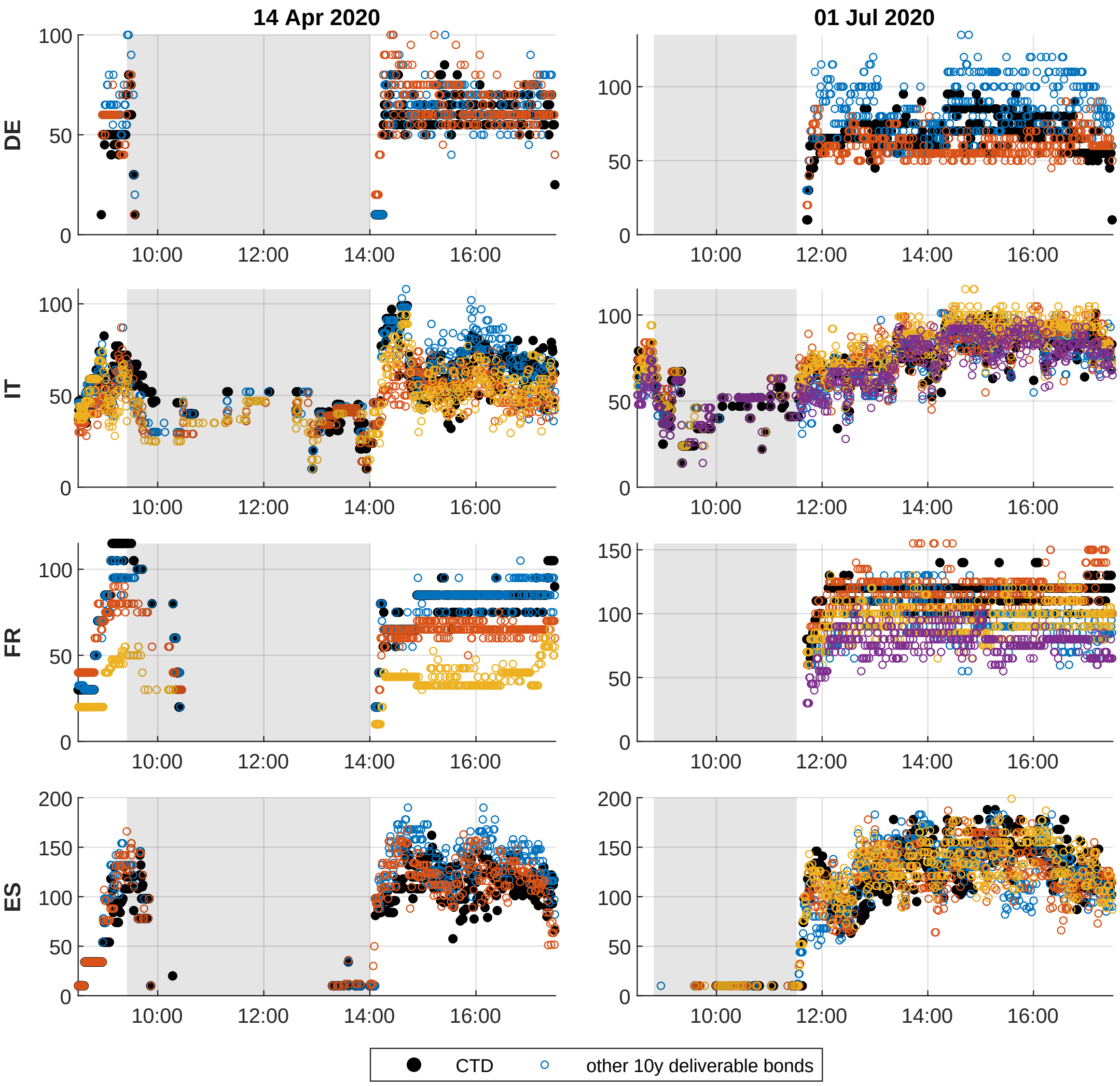

Figure A15: Order Book Depth of 10-year deliverable Bonds on MTS. This figure shows the total quoted volume (in million €) across all three levels and both sides of the order book. Black dots refer to the cheapest-to-deliver bond (as in the main text). Coloured circles refer to all other bonds that are deliverable into the 10-year future contract (one colour per ISIN).

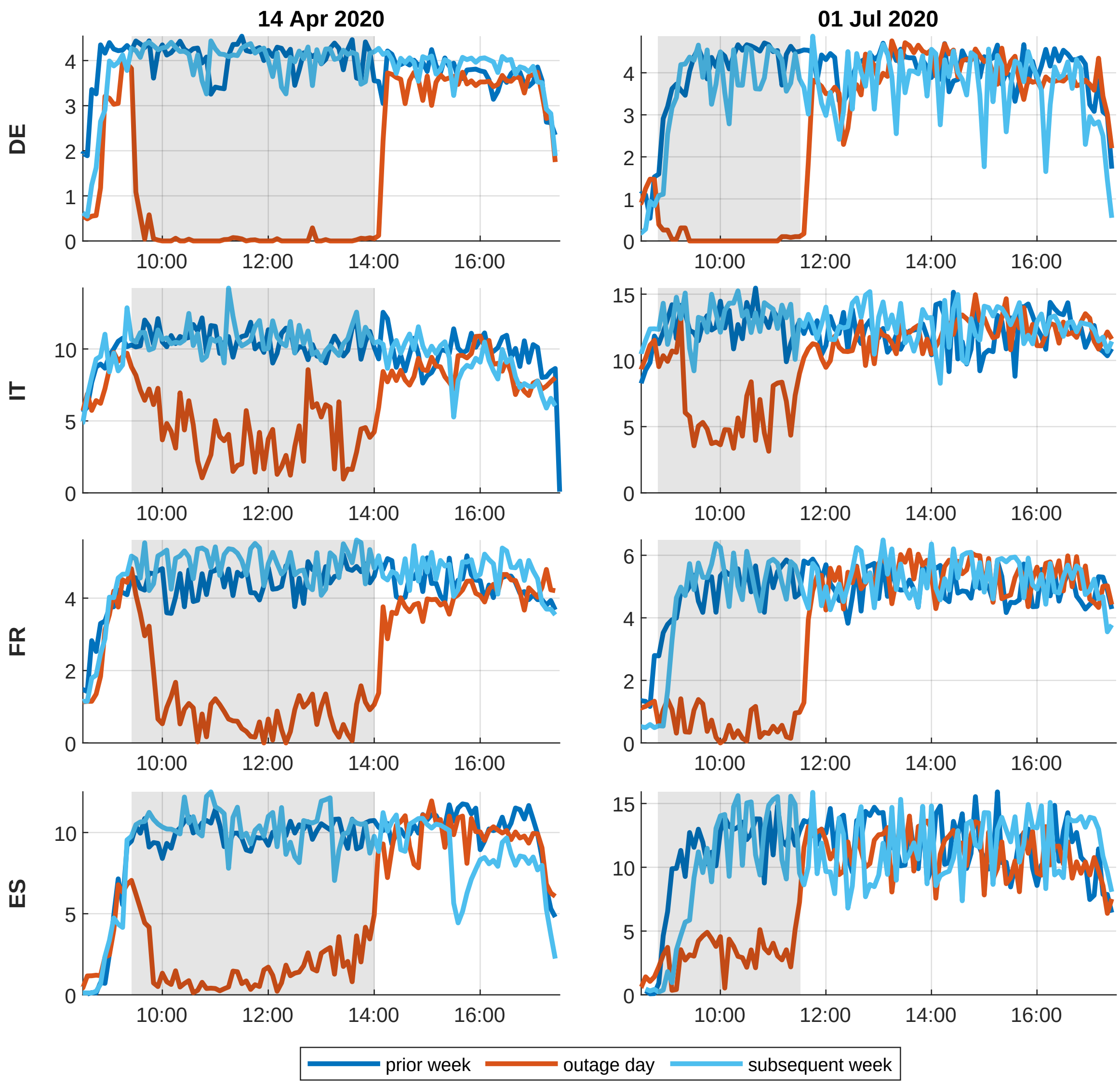

Figure A16: Total Order Book Depth on MTS across Countries. This figure shows the total quoted volume (in billion €) for German, French, Italian and Spanish bonds across all three levels and both sides of the order book, at 5-minute snapshots.

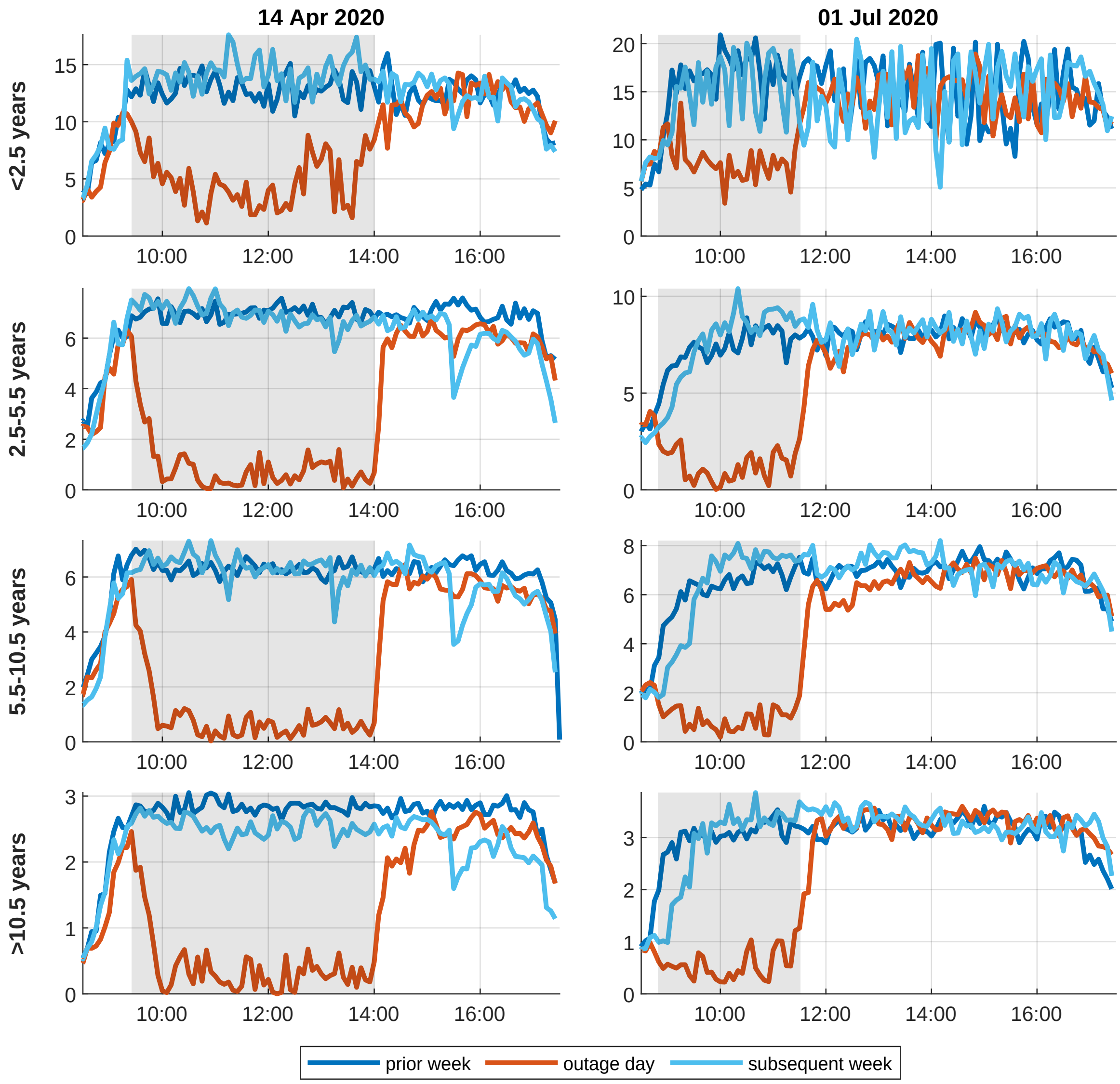

Figure A17: Total Order Book Depth on MTS across Maturity Buckets. This figure shows the total quoted volume (in billion €) for all German, French, Italian and Spanish bonds across all three levels and both sides of the order book, at 5-minute snapshots, broken down by the remaining maturity of the bonds (less than 2.5 years, 2.5 to 5.5 years, 5.5 to 10.5 years, and more than 10.5 years).

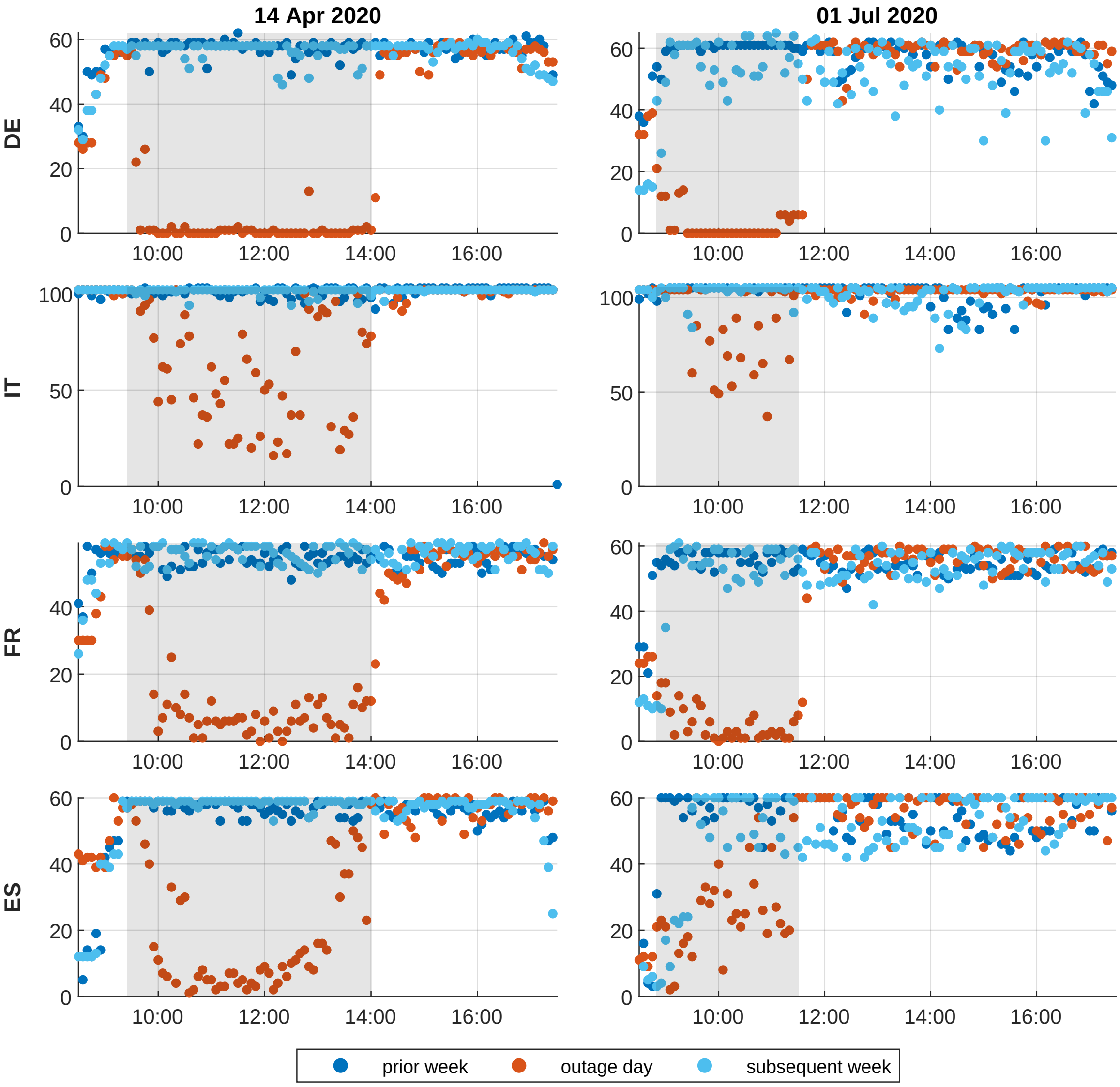

Figure A18: Number of ISINs quoted on MTS. This figure shows the number of quoted ISINs per country, in 5-minute intervals.

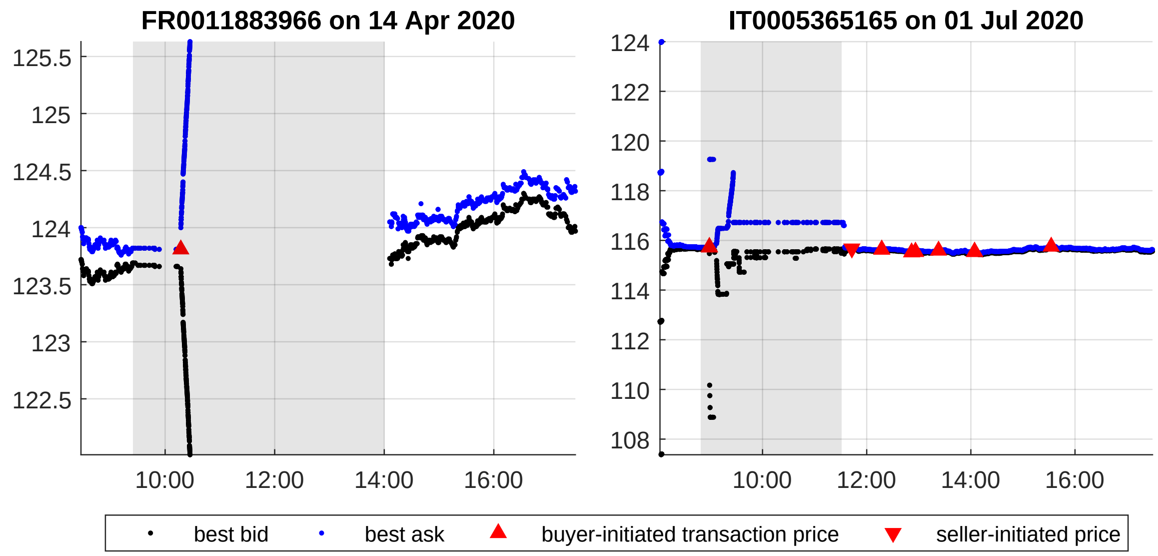

Figure A19: Quotes and Prices of Transactions on MTS during Eurex Outage. This figure shows the only two trades in 10-year bonds that were deliverable into a 10-year futures contract.

B.4 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 A20 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.

Hence, Table A12 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 A12: Differential Effect of Eurex Outages on MTS Market Segments. Each column shows results of a separate regression run at the country-level, see 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 columned header. We differentiate between the EBM and local market segment. *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

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

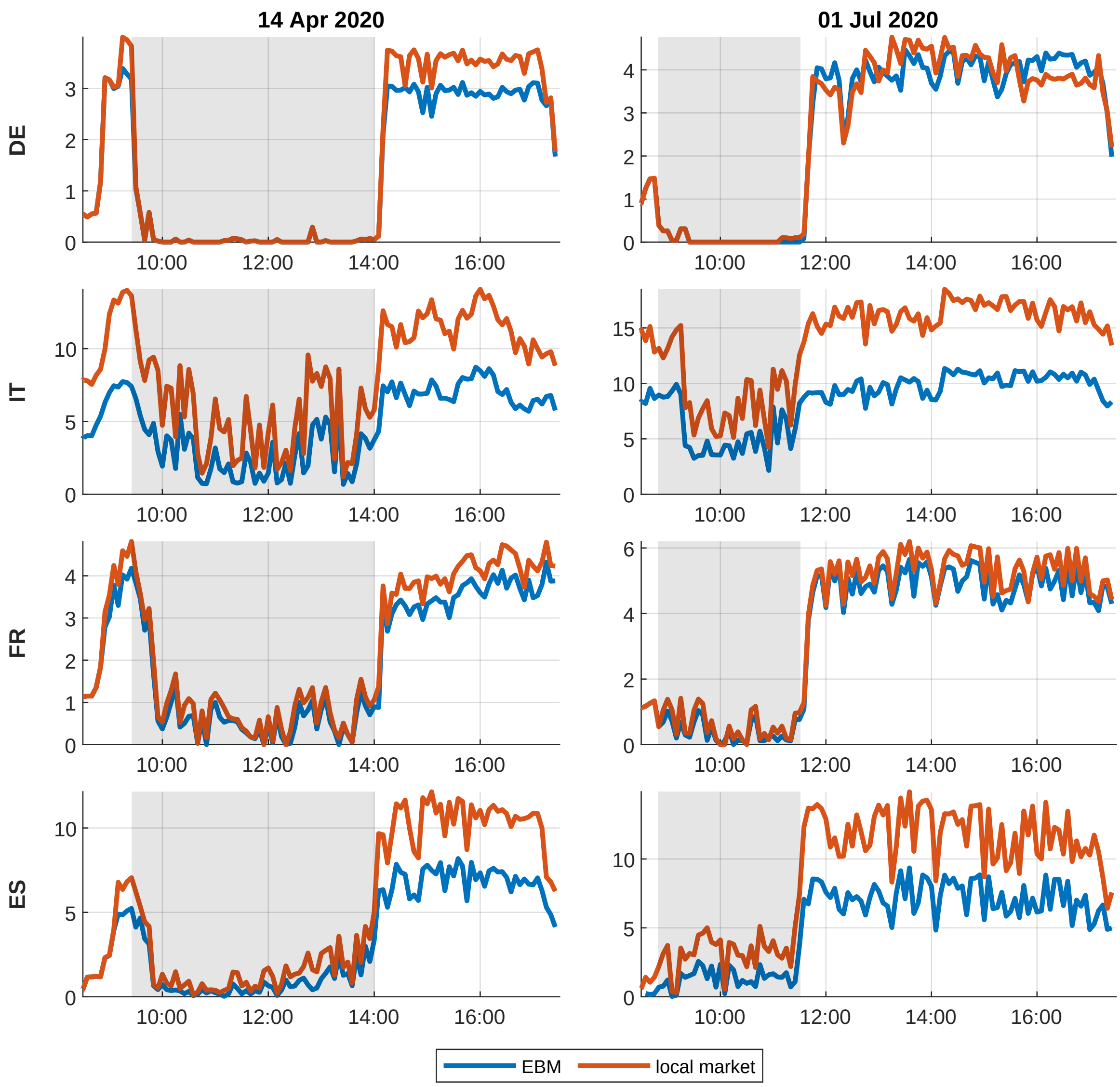

Figure A20: Order Book Depth across different Market Segments on MTS. This figure shows the total quoted volume (in million €) across all three levels and both sides of the order book, at 5-minute snapshots, for all bonds of a given country. Blue lines refer to the 'European Bond Market' segment (as in the main text), red lines refers to the respective domestic market segment.

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.

B.5 Bond-Level Regression Results

B.5.1 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 drops more for long-term than short-term bonds but equally 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 259 bonds throughout and use the logarithm of the trading volume plus one as the dependent variable.[35]

Table A13 reports the results. Trading volumes drop by about $exp(-3.04) - 1 = 95\%$ on average across ISINs when Eurex is offline, see model (1). Model (2) shows that during normal times, CTD and OTR bonds are traded more frequently, as are bonds with longer maturity. Zero coupon bonds and older seasoned bonds, by contrast, are traded less frequently. During the Eurex outage, however, we see a differential effect only for OTR bonds, where trading volumes fall particularly sharply, and for zero coupon bonds, where trading volumes are comparatively robust.

B.5.2 MTS Order Book Depth

In Section 3.2 in the main text we run dummy regressions 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:

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

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.3.

Table A14 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

[35] Appendix A.3 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.

	(1)	(2)
Outage	-3.04*** [0.24]	-2.99*** [0.31]
CTD		2.24*** [0.37]
OTR		2.12*** [0.25]
Zero Coupon		-2.15*** [0.20]
log(Years to Maturity)		0.98*** [0.09]
log(Years since Issuance)		-1.14*** [0.12]
Outage × CTD		-0.87 [0.82]
Outage × OTR		-2.71*** [0.36]
Outage × Zero Coupon		0.69* [0.29]
Outage × log(Years to Maturity)		-0.26 [0.30]
Outage × log(Years since Issuance)		0.21 [0.35]
FE Day	✓	✓
FE Time	✓	✓
FE ISIN	✓	
FE Country		✓
Observations	13986	13986
Adjusted R^2	0.329	0.257

Table A13: 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. 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. *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

are particularly hard hit. 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. Models (3)-(4) show that these last two effects differ markedly at the very short end of the yield curve. Within the 0-2.5 year bucket, older bonds with longer maturity usually have higher liquidity but are more affected by the Eurex outage, see model (3). Put simply, the liquidity of a ten-year bond that was issued eight years ago drops more than of a two-year bond that has just been issued. Similarly, a bond with two years to maturity falls much more than for a bond with one year to maturity. For bonds with more than 2.5 years to maturity, we observe this differential only for the bond's age but not its maturity, see model (4).

	All Bonds		<2.5y	≥2.5y
	(1)	(2)	(3)	(4)
Outage	-10.97***	-6.09***	-4.63***	-10.98***
	[0.53]	[1.11]	[0.80]	[0.98]
CTD		0.65**	-0.94*	0.40
		[0.21]	[0.44]	[0.23]
OTR		2.34***	3.59***	0.03
		[0.35]	[0.78]	[0.04]
Zero Coupon		0.35	3.05***	0.76
		[0.37]	[0.70]	[0.48]
log(Years to Maturity)		1.00***	2.27***	-0.50***
		[0.17]	[0.14]	[0.12]
log(Years since Issuance)		0.68***	1.85***	0.06
		[0.11]	[0.39]	[0.07]
Outage × CTD		-1.59***	1.20	-1.97***
		[0.07]	[0.61]	[0.25]
Outage × OTR		-2.12**	-1.76*	0.40
		[0.79]	[0.74]	[0.28]
Outage × Zero Coupon		-3.33***	-5.34***	-5.20***
		[0.58]	[0.43]	[1.01]
Outage × log(Years to Maturity)		-1.90***	-2.81***	-0.03
		[0.25]	[0.20]	[0.15]
Outage × log(Years since Issuance)		-1.49***	-2.85***	-0.72**
		[0.23]	[0.38]	[0.22]
FE Day	✓	✓	✓	✓
FE Time	✓	✓	✓	✓
FE ISIN	✓			
FE Country		✓	✓	✓
Observations	139230	139230	49686	89544
Adjusted R^2	0.514	0.446	0.375	0.605

Table A14: 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. 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. *,**,*** indicate statistical significance at the 10%, 5% and 1% level, respectively, standard errors (in brackets) are clustered at the daily level.

B.6 Indicative Quotes

This section provides robustness checks for the results in Section 3.2.2 in the main text.

Figure 4 and Figure 5 show across three different data sources, that indicative quotes for EGB cash bonds become stale during the Eurex outage.

For Bloomberg, Figure A21 confirms that 10-year EGB yields stay virtually constant during the Eurex outages. Figure A22 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 A23 shows that the number of newly submitted quotes drops dramatically during the Eurex outage. The only minor exception are Spanish bonds. Figure A24 shows that this is not due to any particular 'pricing contributor'. Virtually all the banks that usually provide quotes stop doing so during the Eurex outages. Note that for German and French bonds, quotes are from up to 11 large European banks while for Italian and Spanish bonds, only a 'composite price', computed by Refinitiv, is available. Figure A25 shows that the bid-ask spread of this computed composite price spiked. The quoted spread on German and French bonds stayed rather constant, because most quotes vanished altogether.

For the interdealer broker TPICAP, which publishes indicative prices for EGBs to intermediate trades between two dealers, Figure A26 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 5 which is based only on quote updates in the 10-year CTD bond.

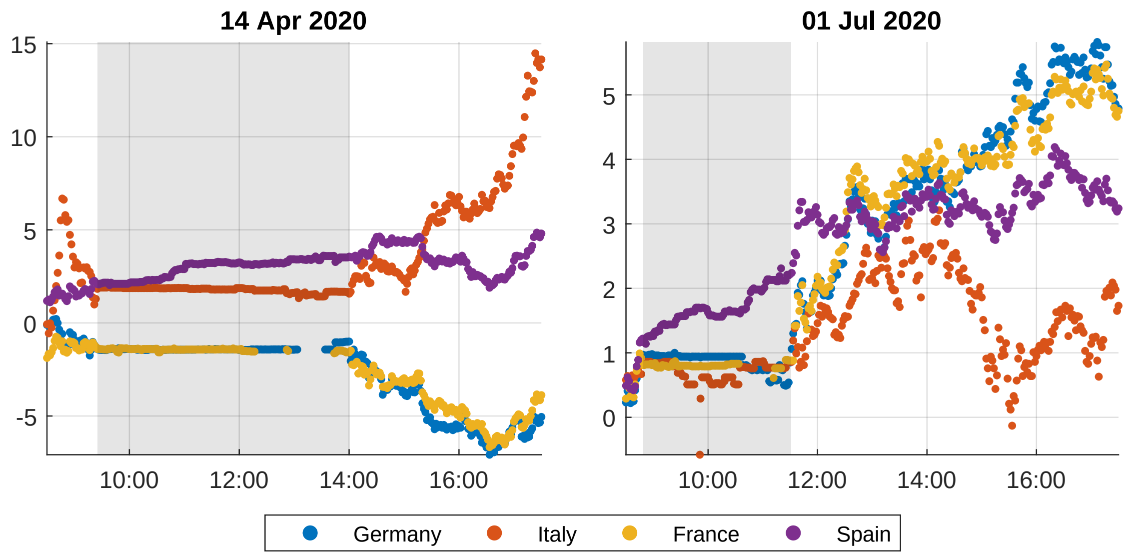

Figure A21: Yield Changes of 10-Year CTD Bonds on Bloomberg. This figure shows cumulated yield changes (in basis points, normalized to zero at 8:00 a.m.) for 10-year CTD bonds from Bloomberg.

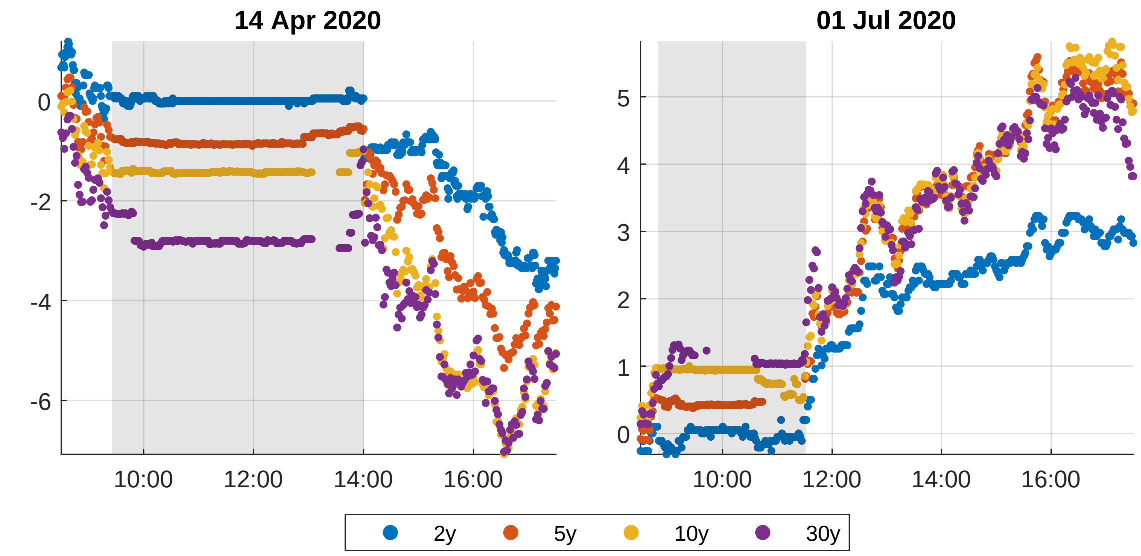

Figure A22: Yield Changes of German CTD Bonds on Bloomberg. This figure shows cumulated yield changes (in basis points, normalized to zero at 8:00 a.m.) for German CTD bonds of different maturity (2y refers to the FGBS future, 5y to FGBM, 10y to FGBL, 30y to FGBX).

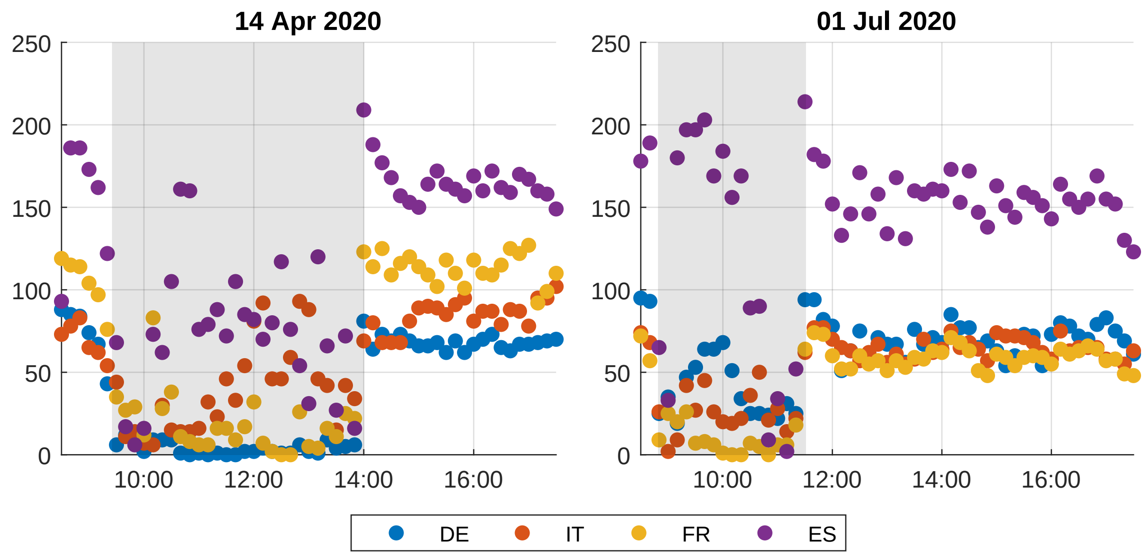

Figure A23: Number of Real-Time Feed Updates on Eikon. This figure shows the number of new bid and ask quotes submitted on Eikon in 10-minute intervals.

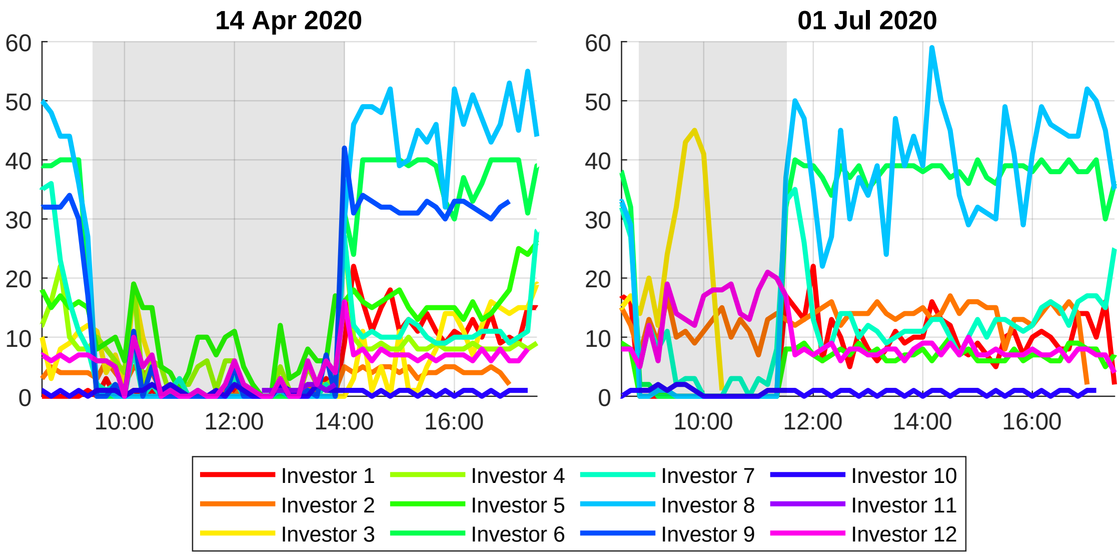

Figure A24: Number of Quotes for 10-Year Government Bonds on Refinitiv. Each color refers to a different 'price contributor'.

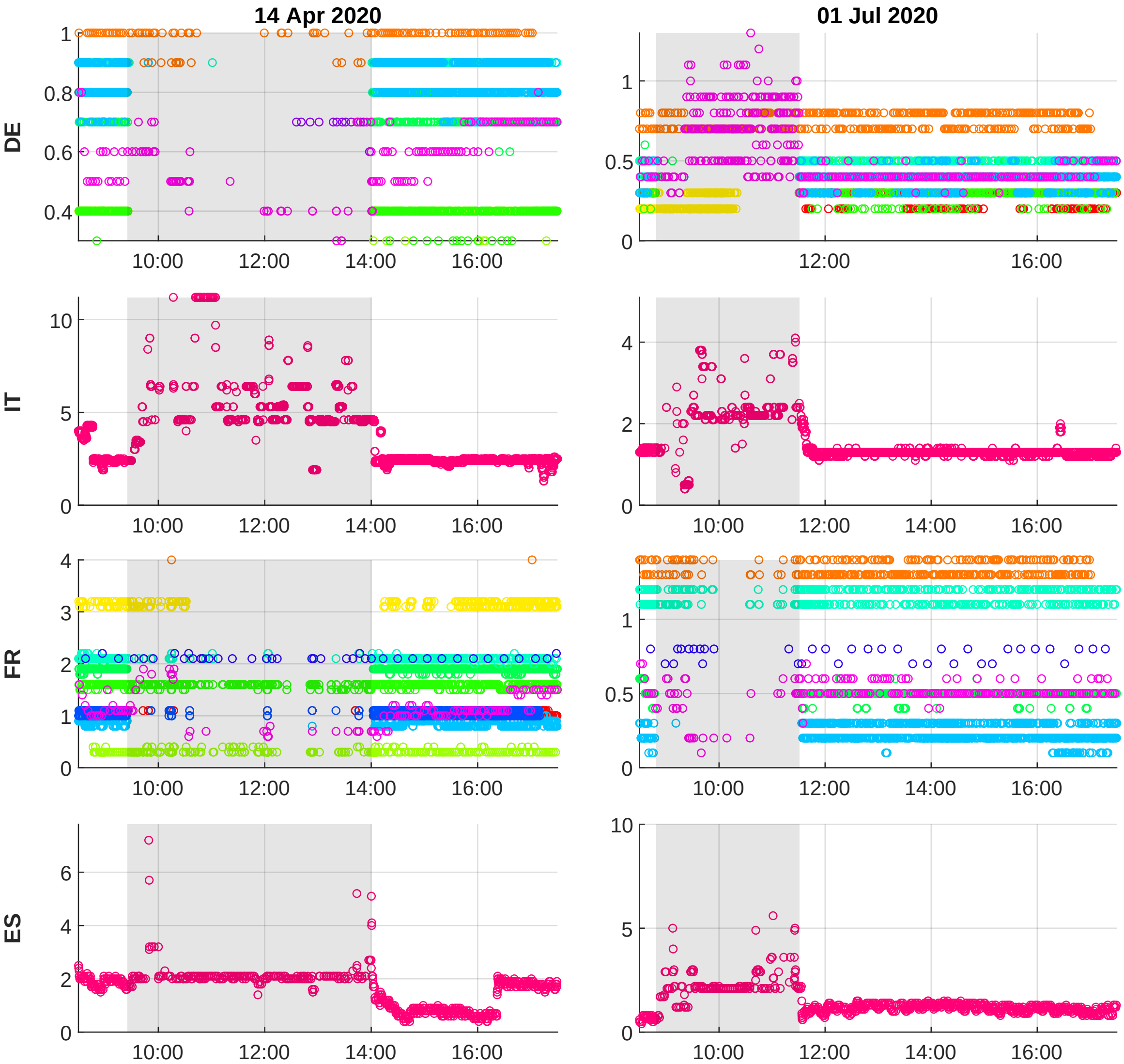

Figure A25: Quoted Bid-Ask Spreads of 10-Year Government Bonds on Refinitiv. Spread are in basis points and refer to the bond's yield. Each color refers to a different 'price contributor'.

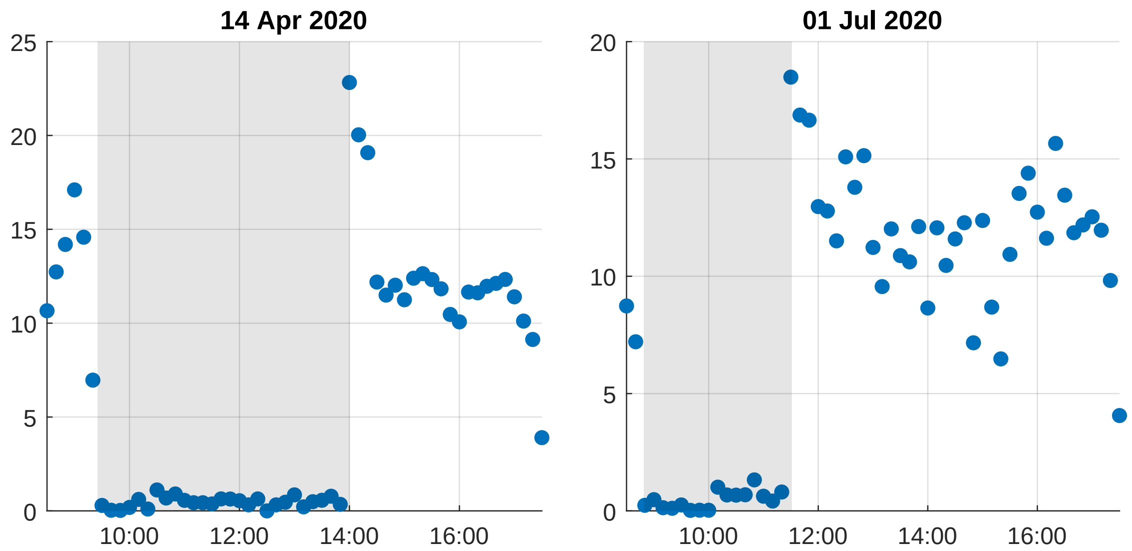

Figure A26: Number of Submitted Quotes on TPICAP. This figure shows the number of new bid and ask quotes (in thousands) for sovereign bonds submitted on TPICAP, in 10-minute intervals.

B.7 Trading Activity on Different Cash Market Segments

Section 3.1 in the main text shows that the aggregate trading volume in EGBs is abnormally low during Eurex outages. Figure A27 shows results across the four selected euro area countries, Figure A28 shows results across different maturity buckets. While bonds with less than two and a half years to maturity were still traded almost as much as usual, trading in longer-dated bonds almost stopped entirely. In fact, Figure A29 shows that when excluding these short-term bonds, trading activity drops in all countries.

The above-mentioned evidence is all based on an aggregate dataset that combines transactions from a variety of different data sources, see Section 2.2 and Appendix A.4. Next, we report results from individual datasets.

Regulatory Transaction-Level Dataset

First, we report results solely based on the regulatory 'Mifir' dataset. Figure A30 reproduces results for the aggregate trading volume across all countries, Figure A31 shows country-level results and Figure A32 provides a breakdown into different maturity buckets.

MTS

Figure 3 in the main text documents an impaired market functioning on MTS. This is also visible in reduced trading volumes on the platform. Figure A33 shows that the trading volume on MTS was lower than usual during the Eurex outage and Figure A34 shows that this effect is particularly pronounced for longer-term bonds. While bonds with less than two years to maturity were still traded almost as much as usually, trading in longer-dated bonds almost stopped entirely.

Tradeweb

We can verify the drop in trading volumes using data sourced directly from Tradeweb. According to the company's own estimates, roughly half of all trading in European government bonds occurs via Tradeweb. Its trading platform is based on an RFQ protocol and is used by over 100 financial institutions, including virtually all tier 1 global investment banks. Its market share in the Dealer-to-Customer (D2C) segment is particularly large. One caveat is that the Tradeweb data excludes many trades with a transaction volume above €6.5 million, since these trades are often not subject to an immediate reporting requirement.[36]

Figure A35 shows that trading volumes were substantially lower than usual during the Eurex outage. This is true for all four countries we study (Figure A36), for both

[36]Under MiFID II, transactions above specific 'large in scale' (LIS) or 'size specific to the instrument' (SSTI) thresholds benefit from deferred publication. These transactions are not published individually. Instead, only the weekly aggregate volume of these transactions is published on the ISIN-level. The thresholds vary across ISINs and are regularly updated by the European Securities and Markets Authority (ESMA). At the time of the two Eurex outages in 2020, the LIS threshold for sovereign bond transactions was €15 million and the SSTI threshold was €6.5 million (the latter only applies for trades where a party was dealing on own account). Lastly, 'in order not to expose liquidity providers in non-equity instruments to undue risk', MiFID II allows 'volume masking' for some transactions, i.e. some transactions are reported without volumes.

trading venues run by Tradeweb and also for trades where Tradeweb acts as an Approved Publication Arrangement (APA) (Figure A37).[37]

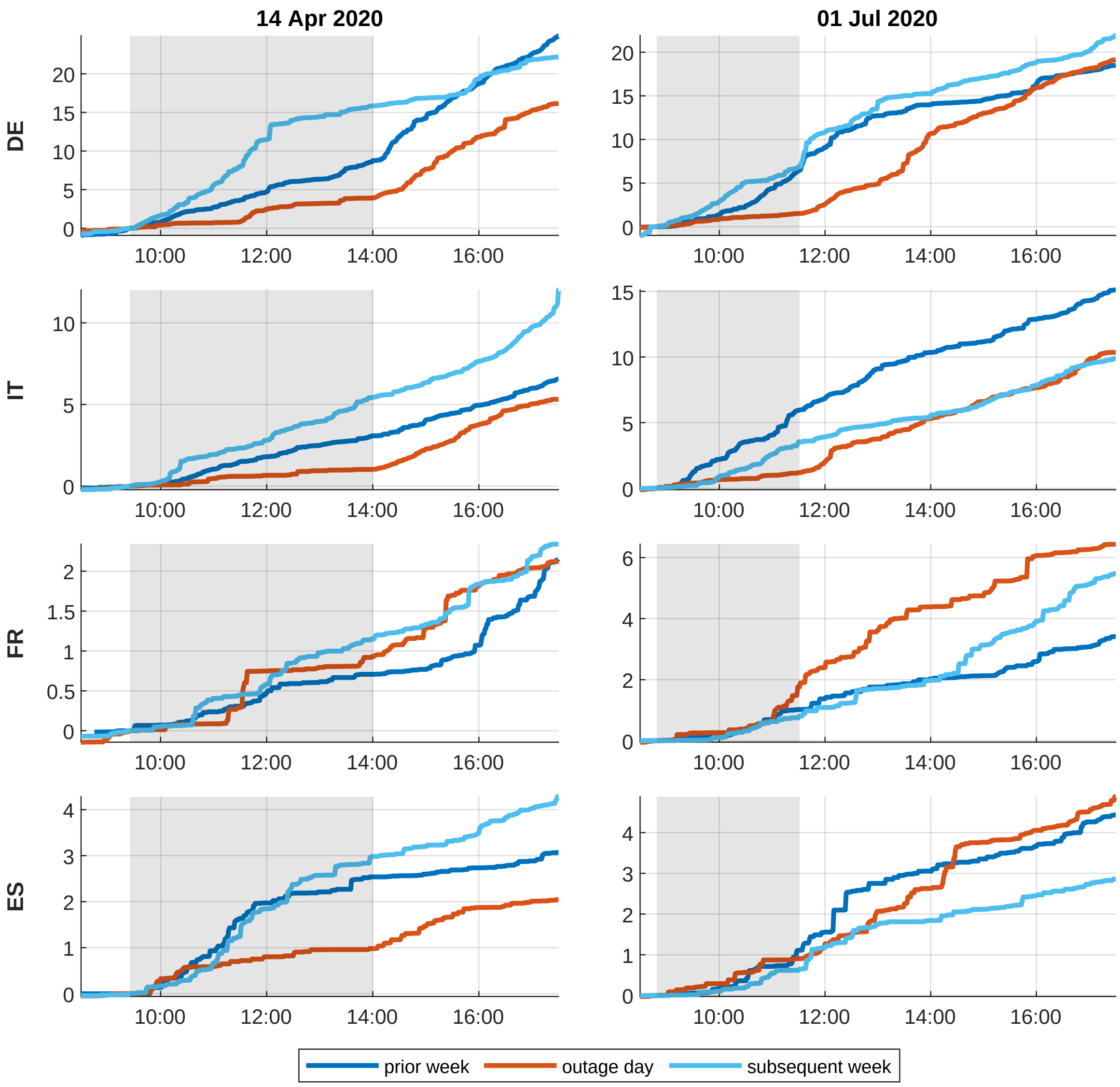

Figure A27: Trading Volume in EGBs across Countries. This figure shows the cumulative trading volume on the cash market, separately for German, French, Italian and Spanish sovereign bonds (in billions of Euro, normalized to zero at the intraday time of the outage). See previous figure for details.

[37]Due to Brexit, Tradeweb runs separate Multi Lateral Trading Facilities in the UK and the EU (MIC Codes 'TREU' and 'TWEM'). Similarly, Tradeweb runs two Organised Trading Facilities, which are focused on the dealer-to-dealer market, but these are quantitatively negligible for EGBs. Lastly, Tradeweb also reports trades from systematic internalisers ('SINT'), via its APA service.

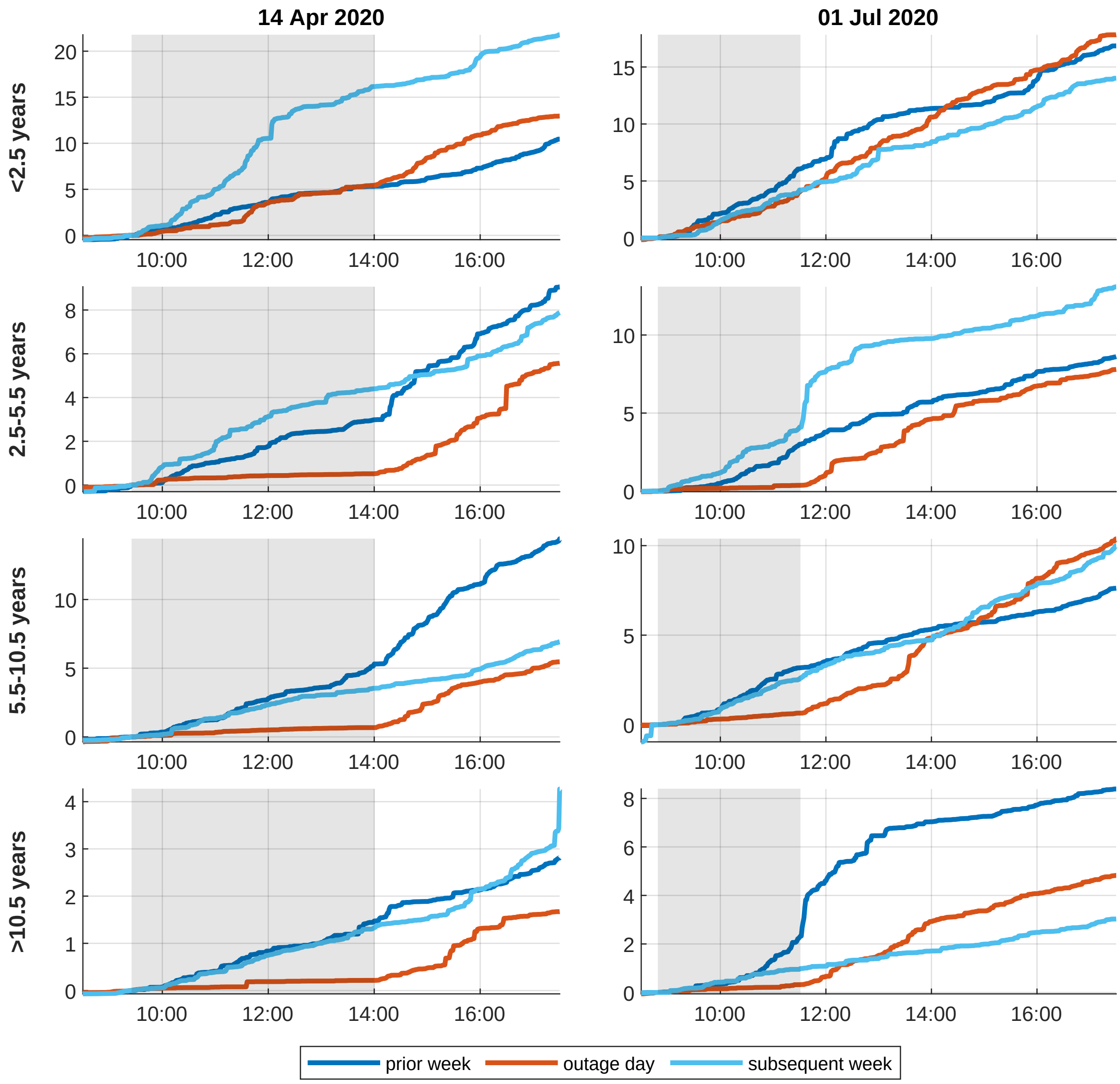

Figure A28: Trading Volume in EGBs across Maturity Buckets. This figure shows the cumulative trading volume in German, French, Italian and Spanish sovereign bonds (in billions of Euro, normalized to zero at the intraday time of the outage), split up into maturity buckets (less than two years, two to five years, and more than five years). See previous figure for details.

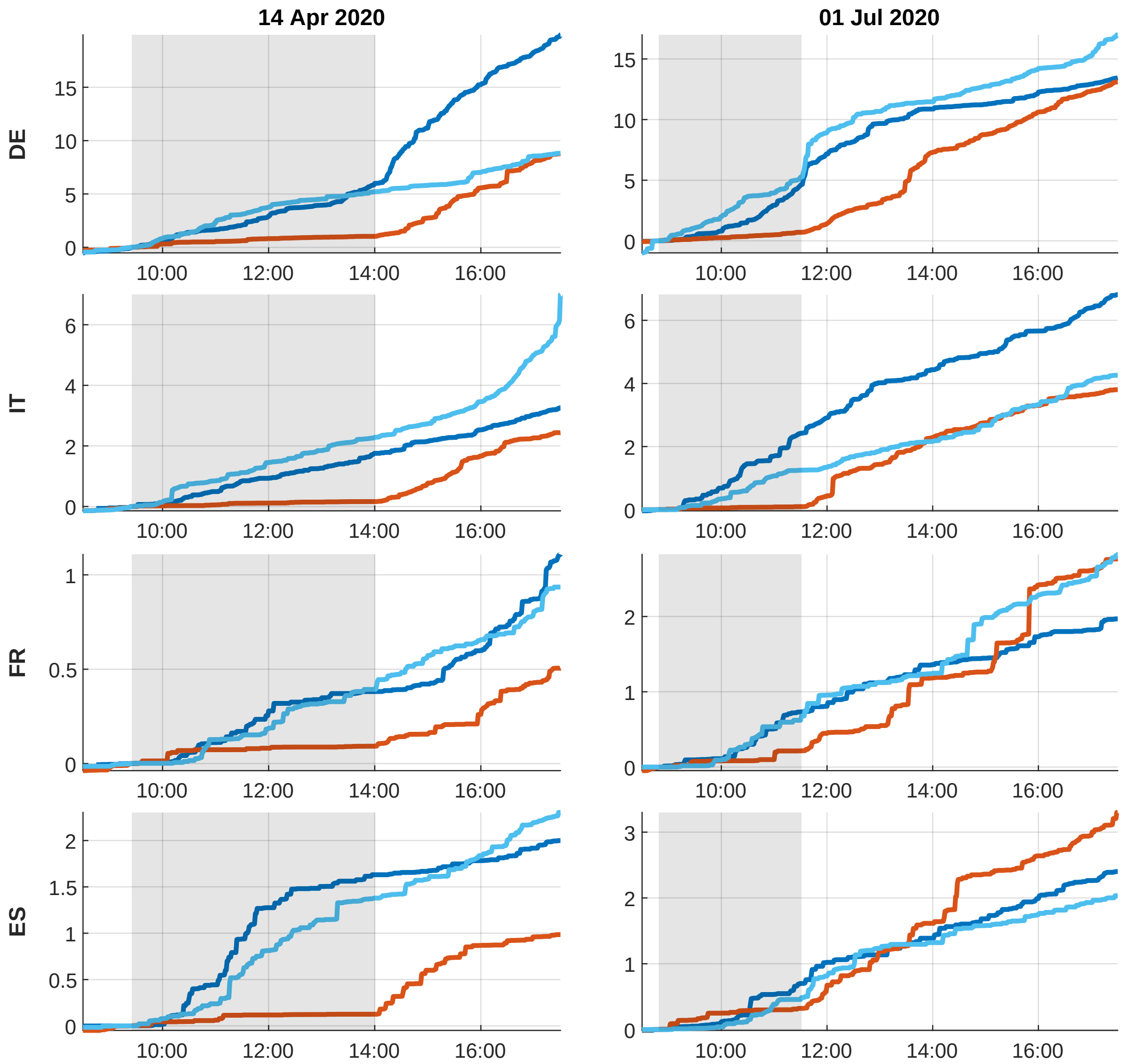

Figure A29: Trading Volume in Longer-Term EGBs across Countries. This figure shows the cumulative trading volume on bonds with more than two and a half years to maturity, separately for German, French, Italian and Spanish sovereign bonds (in billions of Euro, normalized to zero at the intraday time of the outage). See previous figure for details.

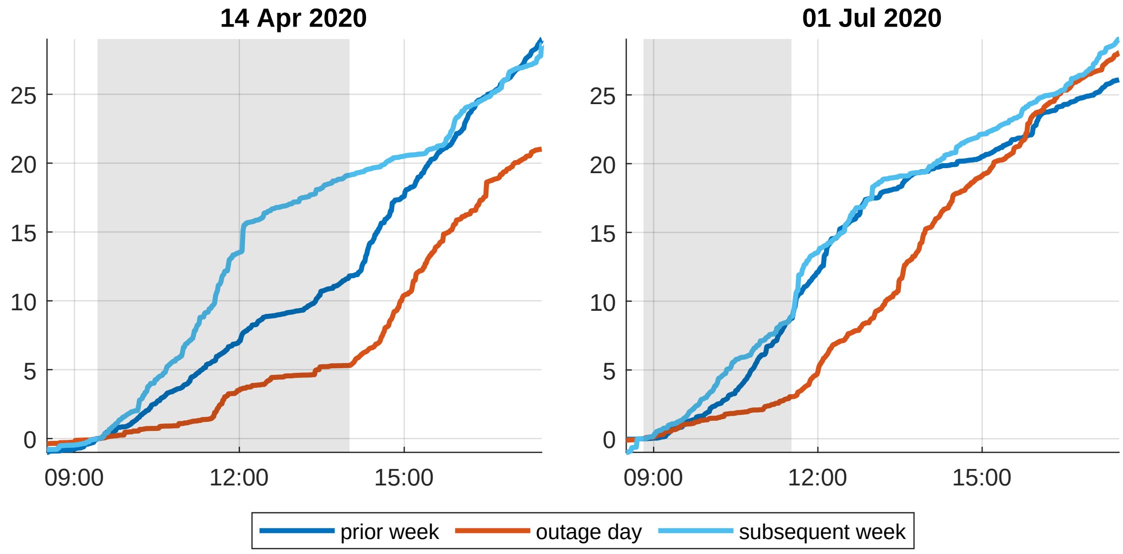

Figure A30: Cash Market Trading Volume in EGBs based on Mifir data. This figure shows the cumulative trading volume on the cash market in all German, French, Italian and Spanish sovereign bonds (in billions of Euro, normalized to zero at the intraday time of the outage). Red dots refer to outage days, dark and light blue dots to the previous and subsequent week.

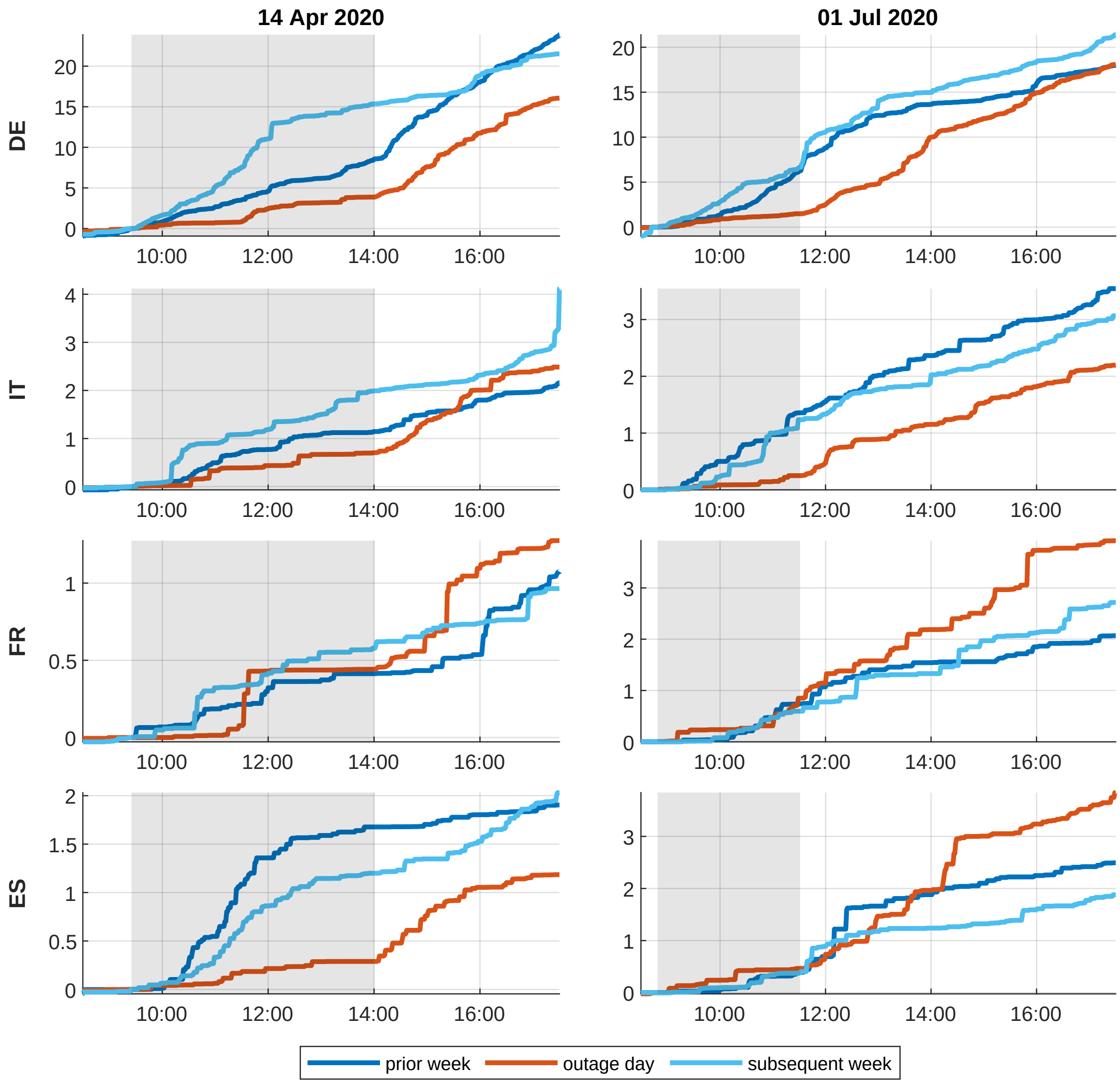

Figure A31: Trading Volume in EGBs across Countries based on Mifir data. This figure shows the cumulative trading volume on the cash market, separately for German, French, Italian and Spanish sovereign bonds (in billions of Euro, normalized to zero at the intraday time of the outage). See previous figure for details.

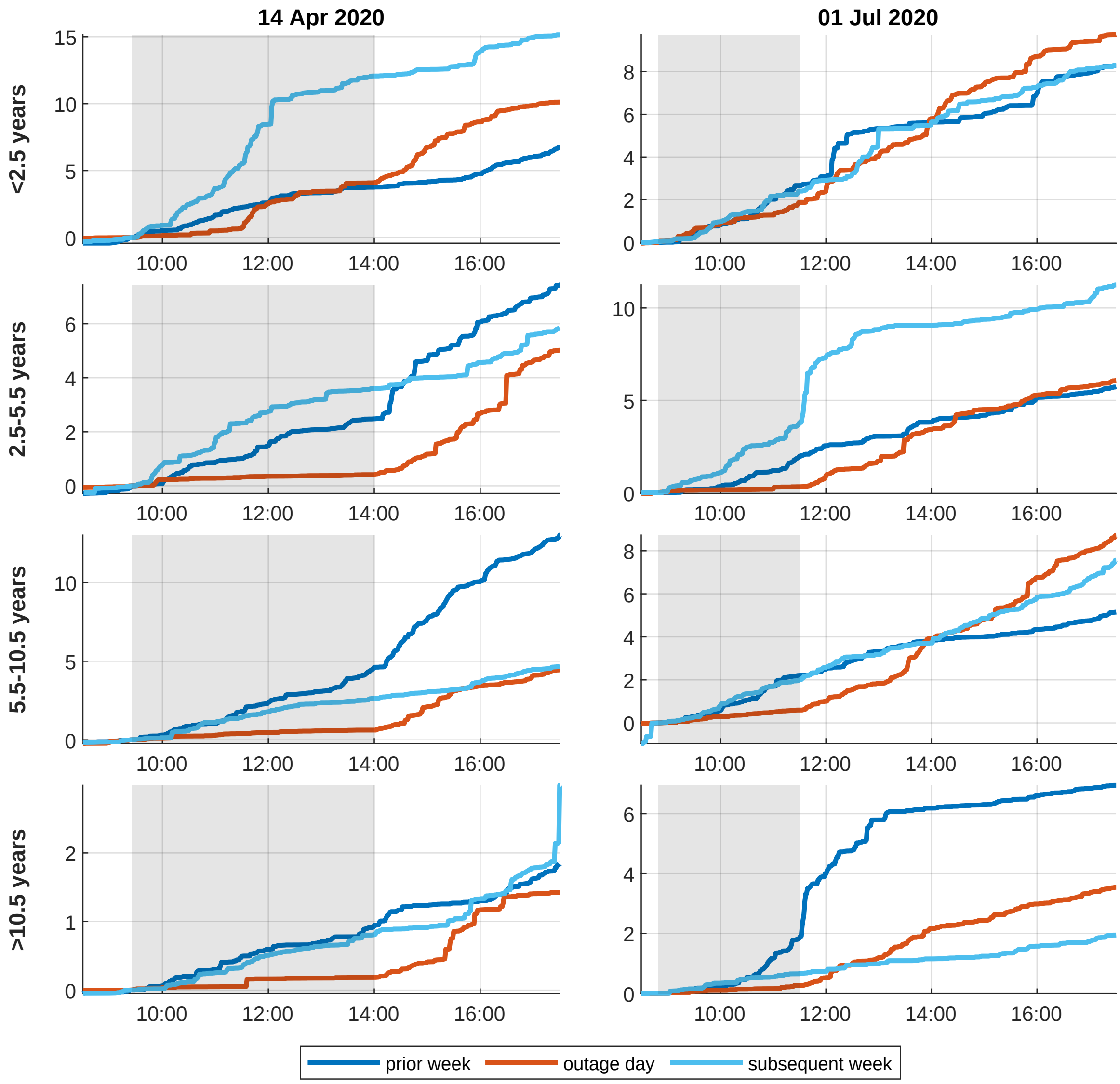

Figure A32: Trading Volume in EGBs across Maturity Buckets based on Mifir data. See previous figure for details.

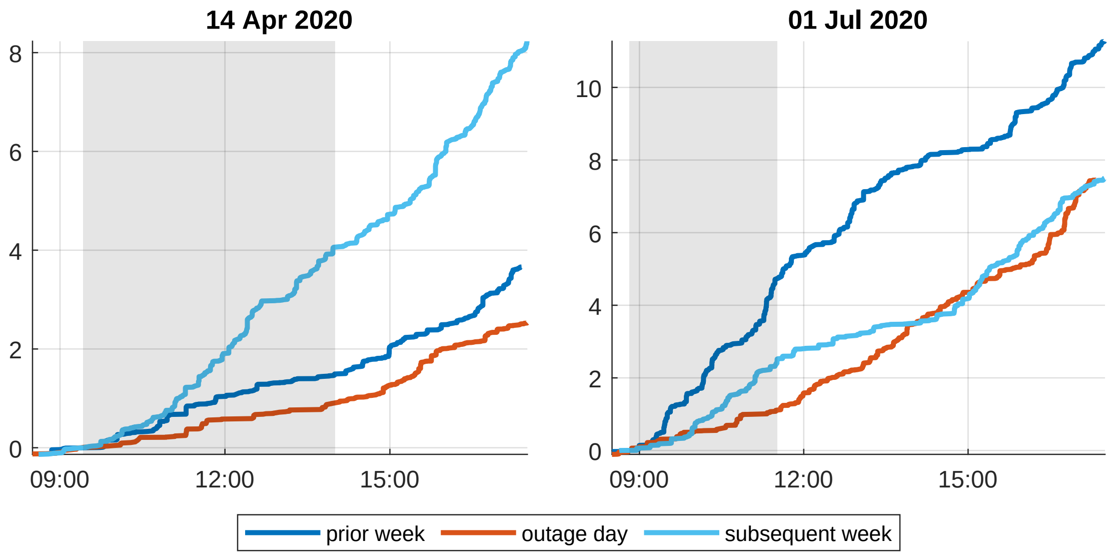

Figure A33: Trading Volume on MTS. This figure shows the cumulative trading volume (in billions of Euro, normalized to zero at the intraday time of the outage) in all German, French, Italian and Spanish sovereign bonds. Red lines refer to outage days, dark and light blue lines to the previous and subsequent week.

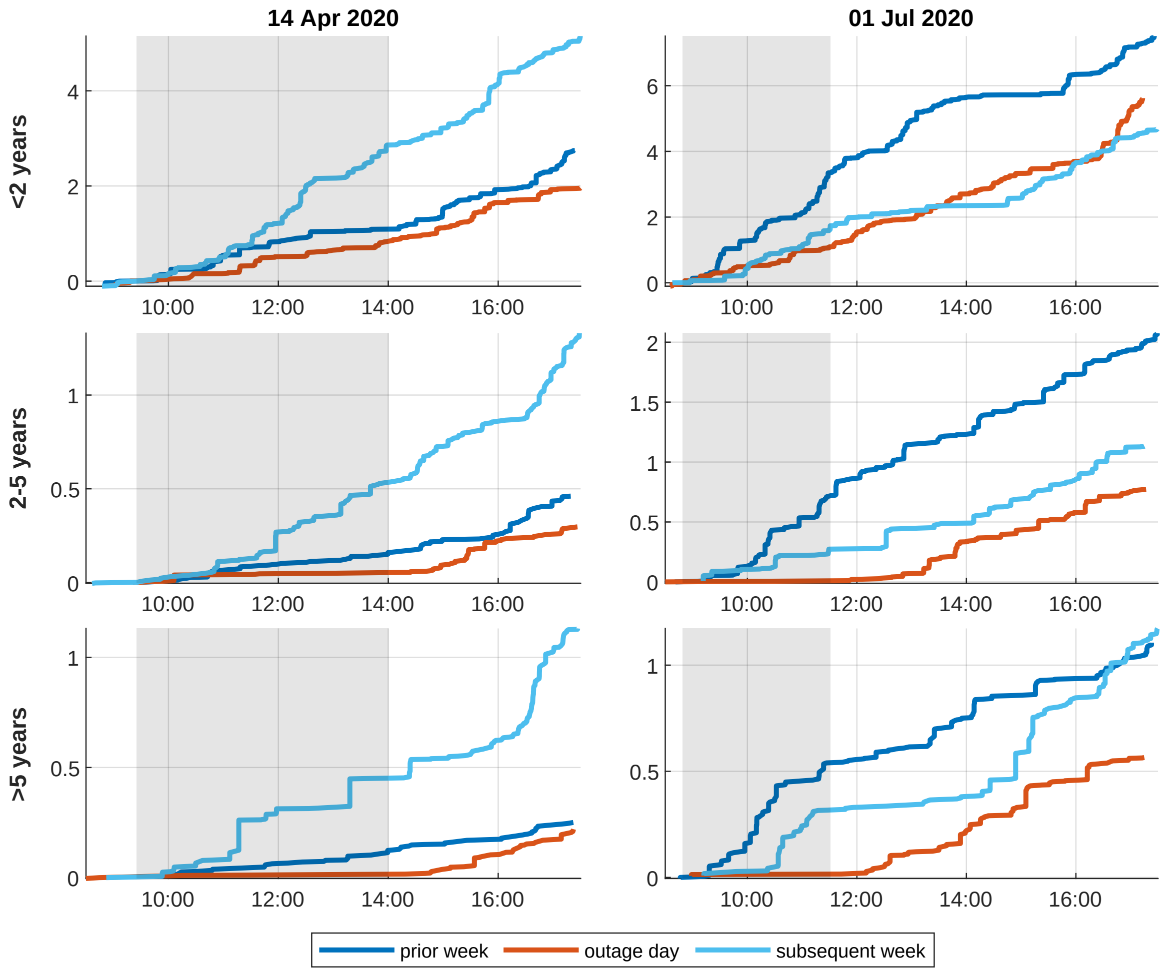

Figure A34: Trading Volume on MTS across Maturity Buckets. This figure shows the cumulative trading volume (in billions of Euro, normalized to zero at the intraday time of the outage), broken down by the remaining maturity of the bonds (less than two years, two to five years, and more than five years).

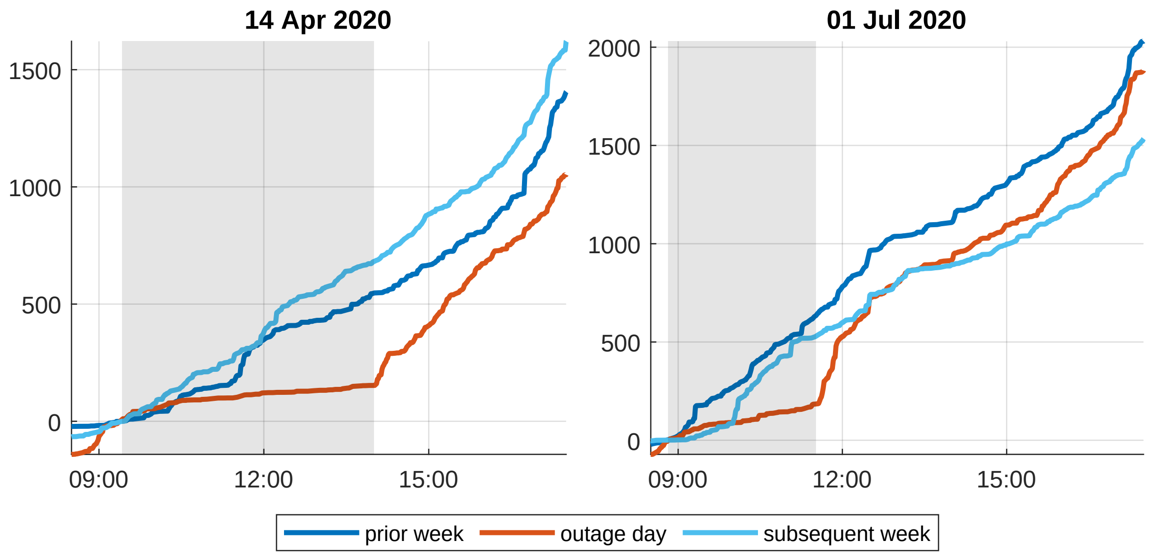

Figure A35: Trading Volume on Tradeweb. This figure shows the cumulative trading volume (in millions of Euro, normalized to zero at the intraday time of the outage) in all German, French, Italian and Spanish sovereign bonds. Red lines refer to outage days, dark and light blue lines refer to the previous and subsequent week.

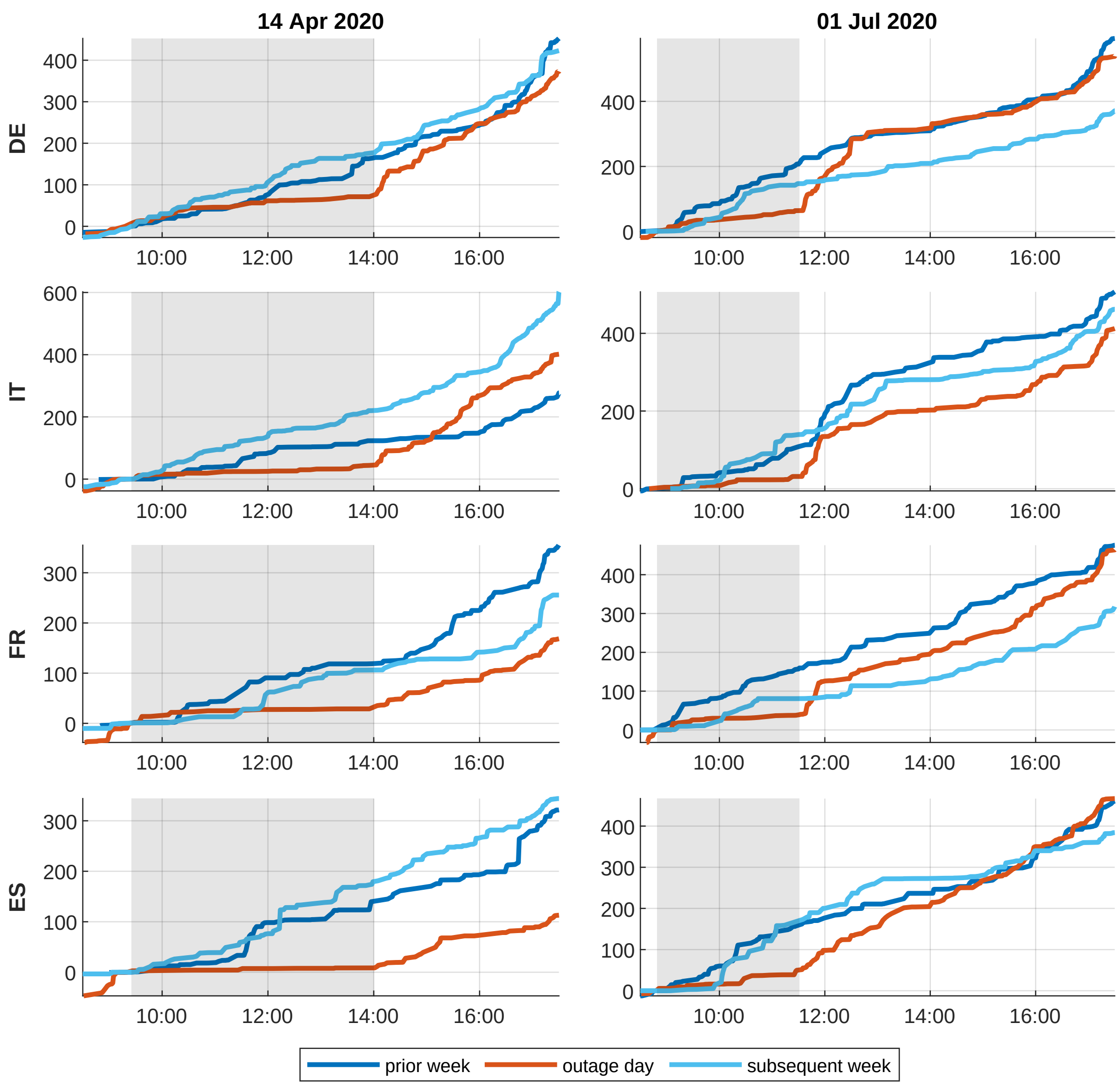

Figure A36: Trading Volume on Tradeweb by Country. For details see previous figure.

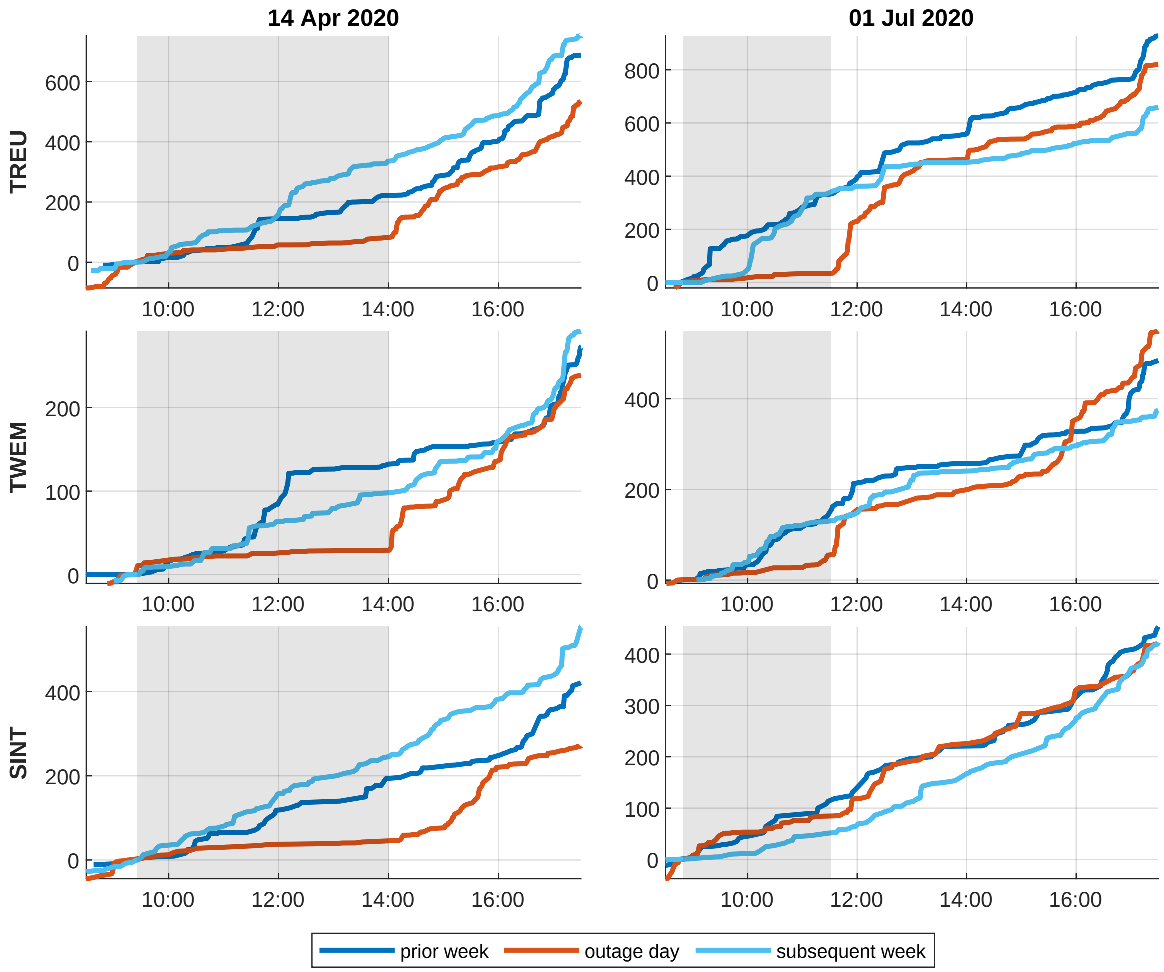

Figure A37: Trading Volume on Tradeweb by Venue. For details see previous figure. The MIC Code 'TREU' refers to the UK trading venue in London, 'TWEM' refers to the EU trading venue in Amsterdam. 'SINT' refers to trades by systematic internalisers reported via Tradeweb.

B.8 Cash Market Response to previous Outages

This section provides robustness checks for the results in Section 4.1 in the main text.

Table 4 shows that trading volumes in German bonds are significantly lower during eight system-wide Eurex outages between 2008-2017. Figure A38 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.

Table 5 confirms for nine outages between 2008-2018 that the liquidity on MTS vitally depends on Eurex being online. Figure A39 confirms this visually. Every time Eurex has been offline, liquidity on MTS has been much lower than usual. Figure A40 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 A41, 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.

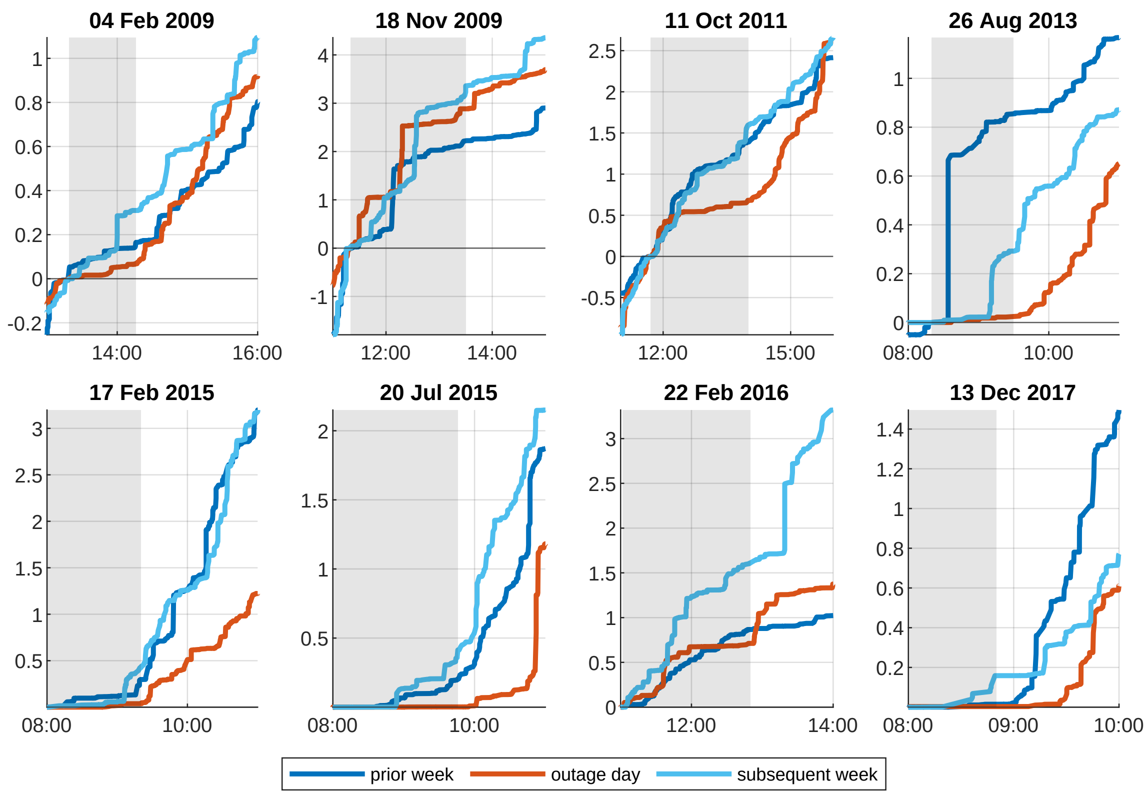

Figure A38: Cumulative EGB Trading Volume during previous Eurex Outages. This figure shows the cumulative trading volume (in billion €) in German, French, Italian and Spanish bonds. Note that the underlying 'Bafin' dataset almost exclusively covers trades in German bonds, see Section 4.1 for details. 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.

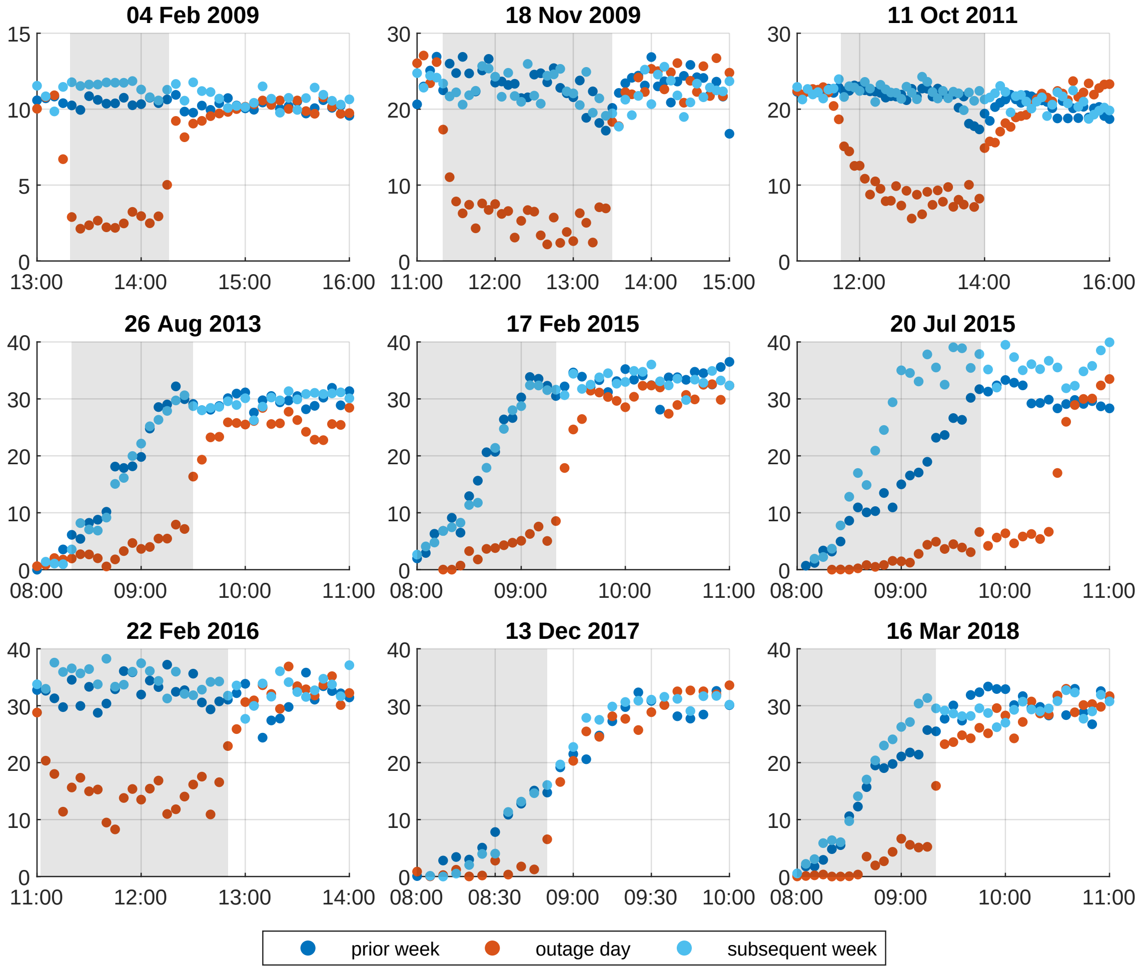

Figure A39: Total Order Book Depth on MTS during previous Eurex Outages. This figure shows the total quoted volume (in billion €) for all German, French, Italian and Spanish bonds across all three levels and both sides of the order book, at 5-minute snapshots. Each panel refers to a Eurex outage between 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.

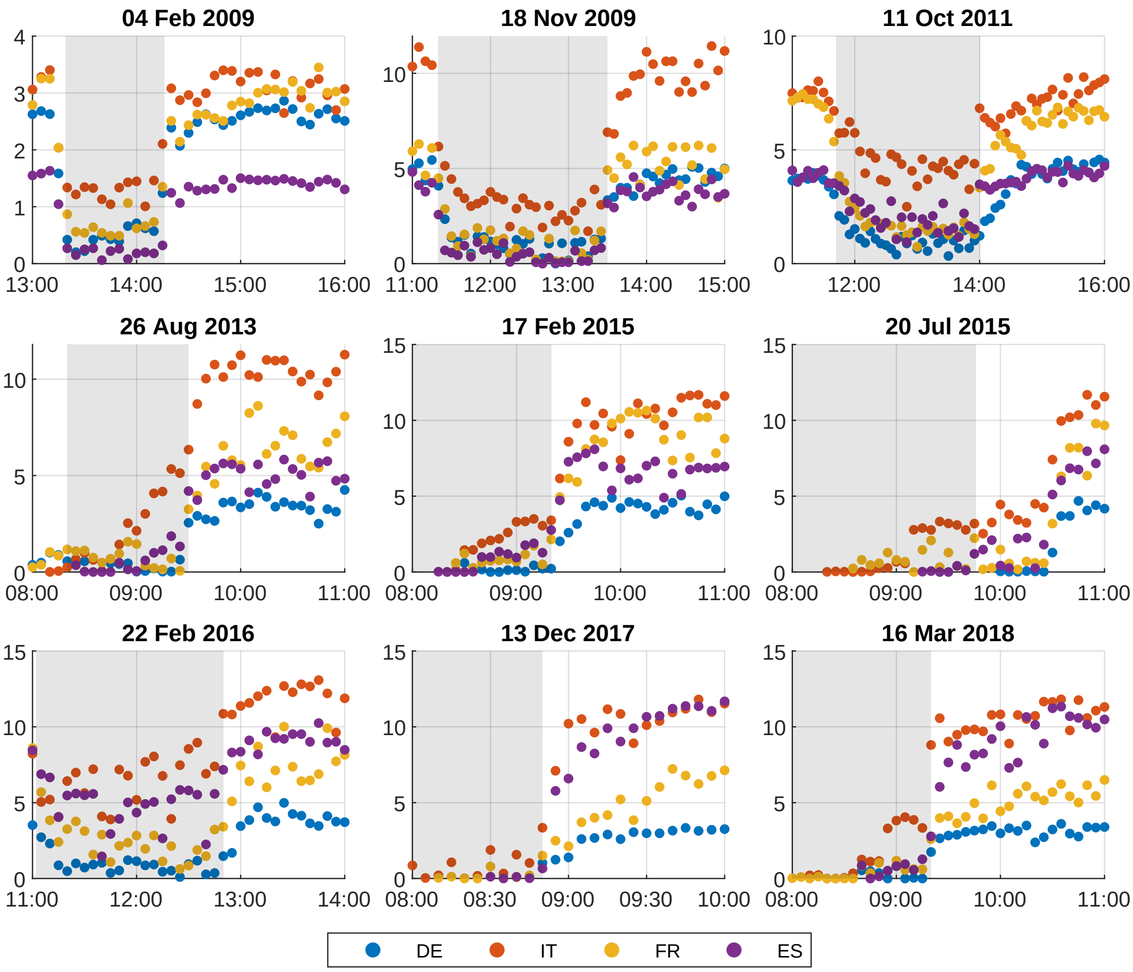

Figure A40: Total Order Book Depth on MTS at the Country-Level. This figure shows the total quoted volume (in billion €) for German, French, Italian or Spanish bonds, across all three levels and both sides of the order book, at 5-minute snapshots. See previous figure for details.

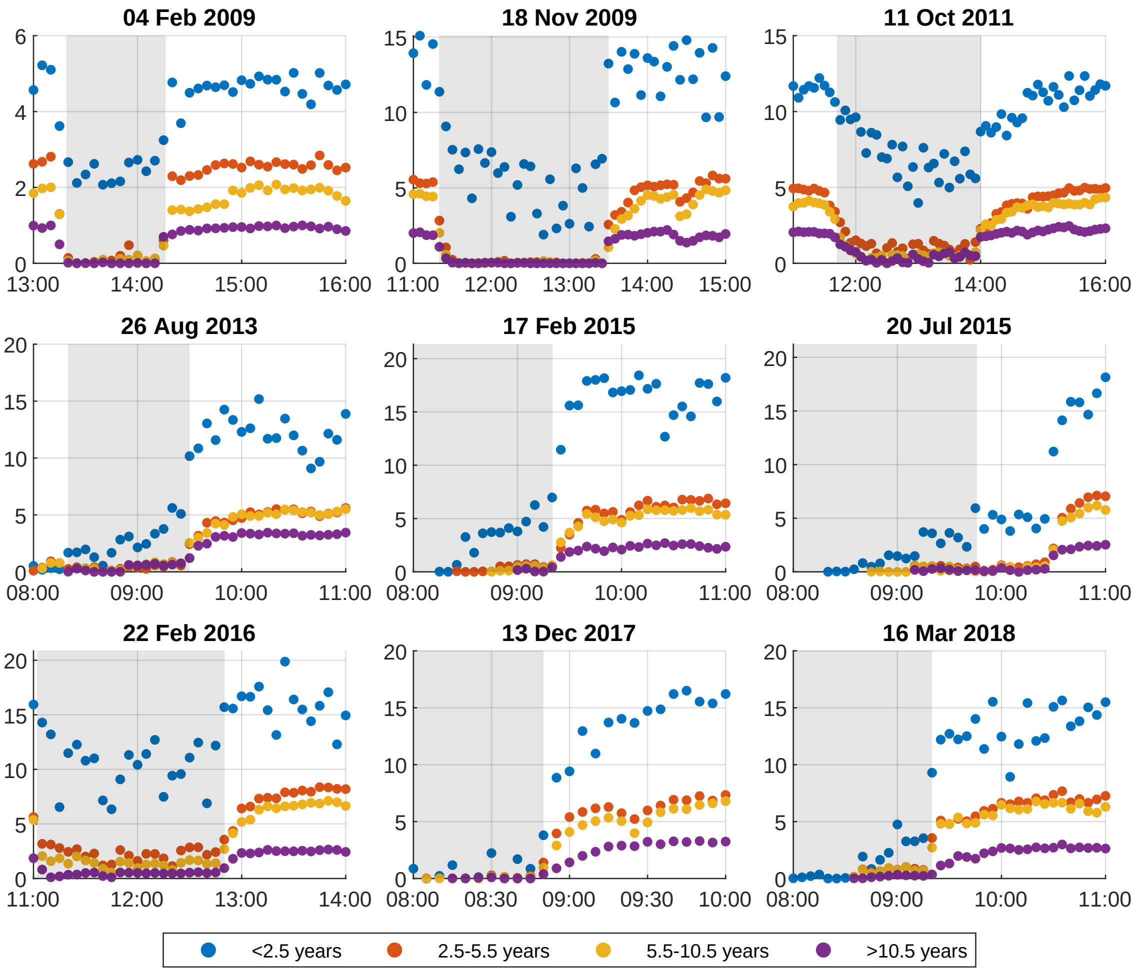

Figure A41: Total Order Book Depth on MTS across Maturity Buckets. This figure shows the total quoted volume (in billion €) for all German, French, Italian and Spanish bonds, across all three levels and both sides of the order book, at 5-minute snapshots, broken down by the remaining maturity of the bonds (less than two years, two to five years, and more than five years). See previous figure for details.

Appendix C Narrative Evidence

This section contains narrative evidence. Section C.1 recounts real-time reports on the two Eurex outages studied in Section 3 of the paper. Section C.2 contains newspaper reports about the previous Eurex outages studied in Section 4. Section C.3 contains selected quotes from two ESMA consultation papers that shed light on market participant's views on euro area bond market functioning.

C.1 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' (Twitter link). 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' (Twitter link).

On 1 July 2020 at 10:11 a.m.: 'Due to technical problems the trading system T7 is not currently available' (Twitter link). At 11:54 a.m. the same day: 'Update on the disruption: continuous trading on Eurex resumed at 1130.' (Twitter link).

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.'

C.2 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: Btp and Oat futures, delayed opening due to technical problems
Italian, French bond futures trading delayed, Eurex recorded message citing technical problems at exchange

17 February 2015: Eurex Restarts Trading After Market Halt

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

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

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

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.

C.3 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.

C.3.1 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 responses 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**'

Deutsche Börse Group: 'The derivatives and cash market exchanges of DBG, Eurex and FWB utilize stable and resilient systems and aim to minimize disruption and uncertainty for their market participants. This is also reflected by the high **average availability rates of 99.97% for Eurex** and 99.98% for FWB over the last 20 years.'

C.3.2 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 responses in **bold font**.

HSBC: ‘We consider it is important to address the current situation whereby essentially all trading stops in the event of a primary market outage.’

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.’

FESE: ‘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.’

AFME: ‘By way of example, **where a firm is appointed primary dealer, the relevant DMO will generally require the primary dealer to participate in the secondary market on e-trading platforms and comply with its quoting obligations on the primary venue**. For instance, in Italy, primary dealers are required to support the liquidity of the overall market for Treasury Securities. On MTS Italy a PD is allocated financial instruments and is required to send double sided quotes continuously with competitive prices for at least 4 hours and 45 minutes during each trading day. The dealer also cannot have differences in the quantity of bid vs. ask of greater than 50%. The MTS would also set guidelines on the maximum bid - offer spreads. A primary dealer is ranked based on the quality and performance of the quotes and can be deemed non-compliant should the performance be consistently poor.’

ICMA: ‘More specifically, **Primary Dealers in EU government bond markets have obligations defined in agreements with specific DMOs**. Those obligations were set to promote liquidity and transparency in the secondary markets including: quoting obligations in terms of minimum duration of the quotation, maximum bid-offer spreads, minimum size to be displayed. Primary Dealers as per their Primary Dealer agreements with their DMOs, are free to fulfil their quoting obligations on eligible trading venues. A few examples of these trading venues are, MTS, BrokerTec, BGC Brokers, SENAF (Spain) and HDAT (Greece).'

GBIC: '**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. Forcing haste in this matter will often lead to further issues later on, which was apparent in at least one of the outages in 2020. Initial haste in restarting trading led to an additional halt later in the day, which led to a missed close and knock-on effects that lasted for multiple days following. It is therefore far better to take the appropriate time to restart properly than to rush into a disorderly restart to meet an arbitrary deadline. 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: '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**.'

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**.'

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.'