LIQUIDITY RISK: INTRADAY LIQUIDITY AND PRICE SPILLOVERS IN EURO AREA SOVEREIGN BOND MARKETS

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Abstract

The purpose of this paper is to determine the cross-market liquidity and price spillover effects across euro area sovereign bond markets. The analysis is carried out with the constructed minute frequency order-book dataset from 2011 until 2018. This derived dataset covers the six largest euro area markets for benchmark 10-year sovereign bonds. To estimate the cross-market spillover effect between sovereign bonds, it was decided to use the empirical approach proposed by Diebold and Yilmaz (2012) and combine it with the vector error correction model (VECM). We also employed the panel regression model to identify why some bond markets had a higher spillover effect while others were smaller. The dependent variable was the daily average spillover effect of a particular bond. As the spillover effects vary highly across different bonds, country-specific fixed effects were used, and the clustered standard errors were calculated for robustness reasons. Lastly, the cross-market spillovers were analyzed daily to compare them with the results of the model with intraday data. The analysis was performed with rolling 100-day window variance decompositions and a 10-day forecast horizon for six sovereign bonds and the overnight indexed swap (OIS) market. The results of the created time-series model revealed that intraday cross-market spillovers exist but are relatively weak, especially in the case of liquidity spillovers. As the cross-market linkages became much more robust with the model using daily data, the liquidity or price disbalances between different markets are usually corrected on longer intervals than minutes. Distance between countries is the most important explanatory variable and is negatively linked to the magnitude of both liquidity and price spillovers. These findings should be of particular interest to bond market investors, risk managers, and analysts who try to scrutinize the liquidity and price transmission mechanism of sovereign bonds in their portfolios.

Keywords: Euro Area Sovereign Bonds, Intraday Market, Variance Decomposition, Liquidity, Liquidity Spillovers, Market Connectedness

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1. INTRODUCTION

Market liquidity, i.e., the ease and speed of trading, is one of the key issues monitored by all market participants: the issuers, investors, analysts, policymakers, market regulators, and operators. Market liquidity becomes a particularly acute concern during the stressful market periods when asset prices deviate further from the fundamental value due to the increased liquidity premium. The phenomena of market liquidity can be described as the market's ability to facilitate the purchase or sale of an asset, not changing its market price dramatically. As the asset market becomes less liquid, investors begin requiring additional returns to compensate for the high liquidity risk, therefore further weighing down on asset prices. So, the liquidity can be often regarded as the 'fear' indicator. The liquidity in sovereign bond markets is a particularly important issue for market regulators and policymakers. For instance, a larger liquidity premium leads to higher borrowing costs that all taxpayers indirectly pay. The government bond market plays a key role for central banks, institutional investors, and other financial market players. Central banks actively use government bonds in monetary policy operations and assess the inflation and economic outlook from the bond market's pricing data. Institutional investors and other market participants use those securities as risk-free investments, collateral, and hedging interest rate risks. Sovereign bonds play a crucial role in the euro area financial market as they include minimal risk, high market liquidity, a wide range of maturity, and well-developed market infrastructure. And this issue is becoming especially worrisome as the sovereign debts continue to grow — the outstanding nominal value of euro area government bonds has increased from 6.1 trillion EUR in June 2011 to 7.4 trillion EUR in March 2018 (ECB, 2018).

But can the liquidity and price of particular security be affected not only by the fundamentals of this security but also by other markets? The extreme-case example is the sharp liquidity and prices slump during the end-2008 period when the uncertainty surrounding the valuation of asset-backed securities caused the liquidity of various other asset markets, e.g., sovereign bonds dry-up (Brunnermeier & Pedersen, 2009). This has forced the liquidity premium to soar and thus weighted down on prices of different assets. Therefore, it is crucial to trace down which market has transmitted the liquidity and price shocks and what factors explain the spillover effects. Spillover effects can be defined as network effects when unrelated events in one country or market can impact other countries or markets. Such identification might help market regulators and operators to take necessary pre-emptive actions earlier and in a more substantiated manner.

This study aims to determine the cross-market liquidity and price spillover effects in euro area sovereign bond markets and assess which factors determine the magnitude of these effects. The analysis is carried out with the constructed minute frequency order-book data from June 2011 until March 2018. This period is chosen because we want to identify the cross-market liquidity and price spillover effects in different periods. Firstly, this period covers the euro area sovereign debt crisis (2011–2012). Secondly, during this period, various financial turbulences such as 'Taper Tantrum' in 2013 and 'Bund Tantrum' in 2015 took place. Finally, political risk and monetary policy issues strongly impacted the euro area sovereign bond market. We have chosen the frequency of one minute for our data because there is still a lack of research for this frequency, and we hope we can identify exciting effects.

Two econometrical methods are employed in this study: Diebold and Yilmaz (2012) variance decomposition helps to identify the cross-market liquidity and price spillover effects, while the panel regression model with a range of explanatory variables lets to answer the question of why some sovereign markets are transmitting the liquidity and price shocks more strongly than others. The analysis is performed for the six largest euro area sovereign bond markets and overnight index swap (OIS) market of 10-year residual maturity. Analysts and risk managers should particularly attentively monitor the markets with the strongest liquidity and price transmission signals, and traders, as such markets, are often shaping the liquidity and price conditions of other markets.

The results of the analysis lead to several important conclusions. Firstly, the liquidity spillovers are relatively week as the idiosyncratic country-specific factors dominate over the intraday liquidity spillovers. Secondly, the magnitude of liquidity spillovers is negatively linked to the distance between countries and positively — to the more volatile bonds with stronger signaling power to market participants. Thirdly, the intraday cross-market price spillovers are somewhat stronger than liquidity spillovers. Fourthly, relatively more factors explain the size of cross-market price spillovers: it is negatively linked to the distance between countries and positively — to the number of active dealers and order revision frequency. Lastly, the results revealed that liquidity and price connectedness is around four times stronger than in the case of intraday linkages.

The novelty of this study is several-fold. Firstly, only a few studies are concentrating on spillovers (especially liquidity) between different European bond markets. Lately, there appeared few studies related to market liquidity issues in the treasury market (Broto & Lamas, 2020; O'Sullivan & Papavassiliou, 2019; Clancy, Dunne, & Filiani, 2019; Ehrmann & Fratzscher, 2017). Some authors are focusing on stock market price and volatility spillovers (He, Liu-Chen, Meng, Xiong, & Zhang, 2020; Rappoport & Tuzun, 2020; Honkanen & Schmidt, 2017; Rindi & Werner, 2017; Sheng, Brzeszczyński, & Ibrahim, 2017), while others pointed basis trades and treasury market liquidity issues (Barth & Kahn, 2020) or covered commodity market liquidity aspects (Jiang, Kellard, & Liu, 2020; Gupta, Sehgal, & Wadhwa, 2018; Kandil, 2018), or even analyzed real estate market volatility and spillover effects (White, Taltavull de La Paz, & Lunde, 2018).

Secondly, the analysis is performed with the massive minute frequency order-book dataset of almost seven years. In contrast, the majority of other spillover analyses were performed encompassing both calm and stressful market periods. In contrast, most other spillover analyses were performed on less frequent and/or granular data. Thirdly, this study also tries to identify the reasons behind the strength of the cross-market liquidity and price spillover effects of particular importance for bond market participants.

The remainder of the paper consists of several parts. The study is started with a review of relevant literature in Section 2. The descriptions of the data and research methods are provided in Sections 3 and 4. In Section 5, the cross-market liquidity and price spillover effect results are provided for both intraday and daily periods. Additionally, the results of panel regression models that explain the differences between cross-market spillovers are presented in Section 6. Section 7 concludes the paper with the main findings and recommendations.

2. LITERATURE REVIEW

Several strands of literature are somewhat related to this study, i.e., the relation between spillover and connectedness, the spillover effect across different markets, the spillover of market liquidity and prices, the intraday spillover analysis, the determination of the driving factors behind spillovers.

Firstly, it is necessary to define the spillover term and contrast it with other interchangeably used terms. Despite many different theoretical and analytical analyses, there is still no generally accepted definition due to the complexity of modeling the linkages between variables. Forbes (2012) describes both spillover and interconnectedness as high correlations across assets/markets during various market conditions. The contagion occurs when there are brief but significant increases in inter-linkages after extreme events, e.g., during crisis periods. Kaminsky, Reinhart, and Végh (2003) argue that spillovers are gradual and protracted effects that only cumulatively might have major consequences, while contagion implies these effects as immediate and excessive. Elhorst, Gross, and Tereanu (2018) define spillover broadly as an effect that spreads from a particular source to the target over an identified channel. Wang and Liu (2016) use terms of interdependence and spillover interchangeably because new informational technologies led to the situation where information signals emerging from one market can be more and more easily transmitted to other markets so that markets become interdependent and react to each other movements. More explicitly, Diebold and Yilmaz (2015) define spillover as a "directional connectedness" because if one market/asset responds to signals coming from other assets (i.e., the spillover effect), they are interconnected. So, in this study, both terms, i.e., spillover and connectedness, will be used interchangeably.

A handful of studies have been conducted regarding the connectedness/spillover effect between different markets or asset classes (Mahanti, Nashikkar, Subrahmanyam, Chacko, & Mallik, 2008; Lin, Zhang, & Wang, 2013; Pelizzon, Subrahmanyam, Tomio, & Uno, 2013; International Monetary Fund, 2015; Dunne, Hau, & Moore, 2015; Albagli, Ceballos, Claro, & Romero, 2015; Bein, 2017; Han & Pan, 2017; Shaikh, 2018; etc.). The spillover effect is usually strongest when fundamentals of different assets are more correlated because investors then perceive changes in a specific market as conveying information about the valuations of other similar investments. For instance, International Monetary Fund (2015) finds that the equity market's liquidity often shocks spillover to the high-yield bonds and cause bond prices to fall. Pelizzon et al. (2013) perform a Granger (1980) causality test to investigate the interconnectedness between the Italian credit market and sovereign bond liquidity. They find that before introducing specific European Central Bank (ECB) measures in December 2011, credit risk aggravated the illiquidity of the Italian sovereign bond market, but the causality has reversed afterward. Pelizzon, Subrahmanyam, Tomio, and Uno (2016) also focused on the Italian sovereign bond market during the eurozone crisis and ECB interventions. They identified that central bank long-term refinancing operations weakened the sensitivity of market makers' liquidity provision to credit risk. Ter Ellen, Jansen, and Midthjell (2020) investigated ECB monetary policy spillovers on Denmark, Norway, and Sweden's sovereign bond market and revealed that it had a powerful effect on longer-maturity yields. Gertler and Horvath (2018) analyzed central bank communication issues and identified minimal impact on interest rates and the stock market. Lin et al. (2013) find that the spillover from equities to bond markets exists. Albagli et al. (2015), relying on an event study methodology, identify significant the US monetary policy spillovers to developed and emerging bond markets. This effect has increased substantially after the global financial crisis.

The market liquidity spillovers have been analyzed less extensively (Fleming, 2003; Chordia Sarkar, & Subrahmanyam, 2006; Holden, Jacobsen, & Subrahmanyam, 2015; Righi & Vieira, 2014; International Monetary Fund, 2015; Smimou & Khallouli, 2016). Righi and Vieira (2014) state that market liquidity usually becomes more destitute during the financial crisis as the decline of capital availability of financial intermediaries active in various securities usually impairs the supply and demand and thus liquidity in these securities. International Monetary Fund (2015) points out that the liquidity spillovers used to be larger during stressful market periods. Still, the spillovers have become more prevalent in recent years due to low and volatile returns, for instance, across emerging markets and between different riskiness of bonds. Smimou and Khallouli (2016) examine the period of the global financial crisis of 2007–2008 and find that non-linearity exists in the liquidity transmission across eurozone markets. These authors even find that liquidity often reverberates from smaller to larger (e.g., German, French, and Italian) markets. Kurosaki, Kumano, Okabe, and Nagano (2015), by utilizing the vector auto-regression model with the transaction and limit order data, point out that the linkages between cash, repo, and future market liquidity have increased since 2014.

Very few papers focus on bond spillovers on an intraday basis. Righi and Vieira (2014) recommended considering intraday data as the share of a segment of intraday traders is increasing rapidly, and thus daily data miss an important element of trading activity. Iwai (2009) uses intraday returns and liquidity indicators of the US and Japanese exchange-traded funds. The author finds that there is intraday liquidity spillover from the US to Japan markets. Still, this effect is not observable daily because markets move too quickly, and studies with low-frequency time-series are not reliable in capturing liquidity spillovers. Using a vector error correction model with 30-minute frequency data, Gyntelberg, Hördahl, Ters, and Urban (2013) find that the premium of credit default swaps adjusts more quickly to the incoming information than the spreads of bonds. Tsuchida, Watanabe, and Yoshiba (2016) investigate the liquidity of Japanese government bond futures on a five-minute frequency and reveal that the shock persistence in bond liquidity rises from around April 2013.

The examination of driving factors of liquidity and/or bond price changes is also quite a rare research topic. Bank for International Settlements (2016) points out that various structural factors (e.g., technological innovations, regulation) and cyclical drivers (e.g., monetary policy, financial cycles) might explain the linkages between markets. Still, these effects differ considerably across various jurisdictions. Schneider, Lillo, and Pelizzon (2018) analyze the liquidity dry-ups and how they spillover in the Italian government bond market at one-minute frequency. They find that bonds with longer residual maturity increasingly driving the illiquidity spillovers of the shorter-term bonds. Still, the authors do not find the difference between the more and less recently issued bonds.

After reviewing the most relevant studies, it is possible to conclude that current literature is relatively limited with quantified assessments of price and, especially, intraday liquidity spillovers between sovereign bonds. This is possibly due to the limited availability of high-frequency data necessary for the robust spillover analysis.

3. DATA

The data employed in this study is mainly sourced from EuroMTS Ltd (hereafter — MTS) that is the biggest inter-dealer platform for European sovereign bonds (MTS, 2017). This trading platform is operated as a central limit order-book where executable prices are offered in advance of any trade request[1].

Three different historical MTS datasets from June 2011 until March 2018 are used in this analysis: the bond reference, tick-by-tick order-book, and trade data. The most extensively used dataset in this study is the order-book data covering high-frequency limit-order and their revision information (including the prices and quantities on both the ask and bid side of the market) on a microsecond time stamp. The trade data encompass high-frequency information about executed transactions of every bond. To use these datasets in econometrical models, the order-book and trade data are sampled to discrete 1-minute intervals. These calculated statistics for each bond are joined with the reference data that contains information about bond-specific characteristics, e.g., maturity, country of issuance, number of enabled participants. In this study, the price measure used is the mid-point price between best (highest) bid, and best (lowest) ask price, while the liquidity indicator employed is the bid-ask spread.

The description of the explanatory variables used in the panel regression model and the expected signs of these variables on the liquidity and price spillover effect is provided in Table 1. Trading platforms and analysts often use the time since issuance to determine the "benchmark" bonds; as a result, liquidity and price changes of the newest issuances should contain higher signaling value for the whole bond market. Similarly, the bonds that have higher nominal value should be the most monitored bonds by market participants. The sovereign bonds with higher quoting and trading activity (i.e., the number of active dealers and executed trades) should be the bonds that most efficiently incorporate all incoming market information. In a similar vein, the order revision frequency is an indicator that reveals the automation degree of the quoting activity of a particular bond — the bonds with higher revision frequency should transmit the stronger signal to other bonds. The volatility of illiquidity-score or price implicitly contains more information; however, this information might be often regarded as a "noise" rather than an informative signal. The distance between countries and the share of exports should be directly linked to the cross-market spillover strength.

Table 1. Description of the explanatory variables and expected sign on price and liquidity spillover effect

Name	*Description*	*Exp. sign*
Time since issuance	Time since issuance until the spillover measurement day, in years	–
Issuance volume	Nominal value of the bond issue, in bn EUR	+
Number of active dealers	Number of dealers that submit limit-orders during the one-minute interval, daily average	+
Order revision frequency	Number of limit-order submissions during one-minute interval divided by the number of active dealers, daily average for a specific bond	+
Traded quantity	Traded quantity for particular bond during the day	+
Liquidity/Price volatility	Standard deviation of the log illiquidity-score/price during the one-minute interval, daily average for specific bond	~
The distance between countries	The distance between countries, in km	+
The share of exports	The share of exports from one country to another out of total country exports, in %	+

Notes: The expected sign is based on the results from other studies and authors' intuition.
Source: Prepared by authors.

We present explanatory variables in Table 1 and put the expected impact direction on the spillover effect based on our practical intuition.

[1] The contrast to this system is the request-for-quote platforms where the quotes are of indicative nature and are provided only to the requested party. This type of system is usually inherent for dealer-to-client market segment (Bank for International Settlements, 2016).

As sovereign bonds with different maturities have unlike liquidity levels and exhibit diverse characteristics, the empirical analysis is carried out with benchmark sovereign bonds. In this analysis, only the newest issuances of 10-year residual maturity are used. This analysis is performed for the six largest euro area sovereign bond markets: German, French, Italian, Spanish, Dutch, and Belgian. We included into our analysis those sovereign bond markets which are the most popular and liquid. Italian and Spanish sovereign bond markets also present the segment of lower credit risk sovereign bond markets. German sovereign bond market in euro area region is like a risk-free market and is like a benchmark for other sovereign bond markets. When a large number of securities is included in the model, the connectedness between bonds naturally increases. Hence, it is better to concentrate on the major markets with more reliable data. To capture common factor effects, the prices and bid-ask spreads of the OIS market[2] are additionally used. Elhorst et al. (2018) stated that the inclusion of common factors helps to remove the unobserved driver of cross-market linkages.

4. RESEARCH METHODOLOGY

A variety of econometric approaches can be used to examine the spillover effects (e.g., a survey of various approaches is provided by Forbes, 2012, Diebold and Yilmaz, 2015, De Santis and Zimic, 2017). While correlation-based methods remain widely-used, they have limited value in the financial market analysis due to embedded linear Gaussian procedure. To estimate the cross-market spillover effect between sovereign bonds, it was decided to use the empirical approach proposed by Diebold and Yilmaz (2012) and combine it with the vector error correction model (VECM). As we want to avoid the ordering of variables implicit in the Cholesky decomposition, we follow the generalized framework of Diebold and Yilmaz (2012) in this study. These authors innovatively propose to treat the forecast error variance decomposition as an adjacency matrix that shows the network of weighted directed contributions (see Table 2).

Table 2. Scheme of variable connectedness

	x_1	x_2	x_N	*From other*
x_1	d_{11}	d_{12}	d_{1N}	$\sum_{j=1}^{N} d_{1j}$, $j \neq 1$
x_2	d_{21}	d_{22}	d_{2N}	$\sum_{j=1}^{N} d_{2j}$, $j \neq 2$
x_N	d_{N1}	d_{N2}	d_{NN}	$\sum_{j=1}^{N} d_{Nj}$, $j \neq N$
To other	$\sum_{i=1}^{N} d_{1i}$, $i \neq 1$	$\sum_{i=1}^{N} d_{2i}$, $i \neq 2$	$\sum_{i=1}^{N} d_{Ni}$, $i \neq N$	$\sum_{j=1}^{N} d_{ij}/N$, $i \neq j$

Notes: e.g., d_{12} represents the connectedness between x_1 and x_2 variables.
Source: Diebold and Yilmaz (2012).

[2] Overnight index swap is an interest rate derivative instrument where the overnight rate is exchanged for a fixed interest rate. The underlying rate for its floating leg used in this paper is EONIA (Euro Overnight Index Average) rate of a particular maturity, while the fixed leg is set at an assumed rate. In order to jointly analyze sovereign bonds and OIS markets, we convert the OIS prices that are converted from OIS rates in this study. As OIS prices show the market expectations of future euro area interest rate expectations, it is a good proxy for common interest rate movements in euro area.

This table reveals the connectedness of variables and the effect of variable-specific idiosyncratic shock. The upper left block contains variance decompositions. The rightmost column depicts row sums, while the bottom row — column sums. The *h*-step ahead forecast error variance of variable *i* can be calculated from the widely-used impulse-response functions; then, the percentage contribution of shock *j* to the *h*-step forecast error variance of variable *i* can be decomposed by dividing its variance by the sum of variances of all variables. The diagonal values show the idiosyncratic shock of the variable *i*. The off-diagonal entries are the most relevant numbers. They show the directional connectedness among variables in this study — the connectedness between illiquidity-scores or prices of sovereign bond markets. The sum of off-diagonal entries measures overall connectedness. In this analysis, almost 1700 daily Diebold and Yilmaz (2012) models were run. For the reason to get the overall picture of the full review period, daily spillover effects are averaged by using winsorizing procedure, which can help to minimize the influence of outliers. The latter technique is useful as it modifies and does not eliminate the outliers.

We also employ the panel regression model to identify why some bond markets have a higher spillover effect, while others are smaller. The dependent variable is the daily average spillover effect of a particular bond, while eight explanatory variables are described in Table 1. As the spillover effects vary highly across different bonds, country-specific fixed effects are used, and the clustered standard errors are calculated for robustness reasons.

Lastly, the cross-market spillovers are analyzed daily to compare them with the results of the model with intraday data. The analysis is performed with rolling 100-day window variance decompositions and a 10-day forecast horizon for six sovereign bonds and the OIS market. Daily frequency was initially used by Diebold and Yilmaz (2012), who also selected a relatively similar — 12-day — forecast horizon. The rolling window estimation is employed as then the results are averaged to get an overall picture of both stressful and calm market periods. As governments issue 10-year bonds regularly (mostly — 2 times in a year), prices and liquidity indicator for the newly issued bond on the issuance and following days are adjusted by the last value of the 'previous' bond (i.e., one day before the issuance of a new bond) — this procedure lets to avert the jumps of the price and liquidity indicator that could impede the correctness of the variance decompositions on rolling windows.

5. RESULTS OF INTRADAY CROSS-MARKET SPILLOVER ANALYSIS

This section analyzes the liquidity and price spillovers across different euro area markets on an intraday basis. The results are presented separately for both liquidity and prices. Additionally, a panel regression model is used to explain the differences between magnitudes of cross-market spillover effects.

5.1. Cross-market liquidity spillovers

The analysis results on intraday liquidity connectedness between individual sovereign bonds and OIS markets reveal that the liquidity spillovers are relatively weak but vary somewhat between markets (see Table 3). Starting with, the highest share (from 85% to 98%) of all liquidity variation can be explained by idiosyncratic domestic liquidity developments in the past (shown under diagonal table entries). Only the remainder 2%–15% of sovereign bond liquidity variation is due to the liquidity shocks in other markets. As a result, the overall connectedness of seven markets amounts to marginally above 3%. This means that the liquidity of bond markets is mainly driven by domestic shocks on an intraday basis, possibly because liquidity conditions mostly change slowly and lightly throughout the trading day in the trading system dominated by market-makers who have obligatory requirements to submit prices that are inside pre-defined bid-ask spread range. Besides, different bond markets have very unlike liquidity levels and liquidity formation mechanisms (Claeys & Vašíček, 2014) and thus might not be fully inter-connected under high-frequency trading systems.

Table 3. Average intraday liquidity spillover effect between bond markets and OIS (%)

	Germany	*France*	*Italy*	*Spain*	*Netherlands*	*Belgium*	*OIS*	*From others*
Germany	97.73	0.19	0.17	0.19	0.25	0.25	0.69	1.73
France	0.17	97.71	0.17	0.22	0.25	0.29	0.59	1.69
Italy	0.14	0.16	97.72	0.27	0.24	0.24	0.63	1.68
Spain	0.15	0.16	0.26	97.89	0.19	0.21	0.58	1.55
Netherlands	0.19	0.23	0.20	0.19	96.55	0.36	0.93	2.10
Belgium	0.20	0.24	0.21	0.22	0.38	96.35	0.98	2.23
OIS	1.68	1.61	1.61	1.23	2.30	2.57	85.12	11.00
To others	2.53	2.60	2.63	2.31	3.60	3.92	4.40	3.14
From others	1.73	1.69	1.68	1.55	2.10	2.23	11.00	3.14
Net (to-from)	0.80	0.91	0.95	0.76	1.50	1.68	-6.60	

Notes: The liquidity spillover effect between individual sovereign bond markets and OIS for a 10-year maturity bucket is averaged across different trading days for the full data sample from June 2011 until March 2018. The VECM and Diebold and Yilmaz (2012) procedure was applied on an intraday basis with a 10-minute forecast period. 10% of highest and lowest values are winsorized before calculating a simple average across all days.
Source: Authors' calculations.

OIS liquidity variation is the dominant liquidity shock transmitter among sovereign bond markets on an intraday basis as the smallest idiosyncratic effects are for the OIS market (common factor). It has the strongest spillover effect on most days on the receiving and sending sides (see Table 4). The fact that market developments are mostly linked with the common factor is confirmed by many other studies (Claeys & Vašíček, 2014; International Monetary Fund, 2015). To be specific, OIS liquidity is much more often driven by sovereign bond markets (75% out of all days) than is transmitting signals by itself (18% out of all days) to other markets. The positive net effect of OIS liquidity spillovers again implies that the OIS market is more reactive to the liquidity developments in other markets[3].

Table 4. Relative shares of maximum liquidity spillover effect days (%)

Market	*Spillovers to others*	*Spillovers from others*
Germany	11.78	2.87
France	11.35	3.05
Italy	12.14	2.99
Spain	7.93	2.81
Netherlands	18.43	6.28
Belgium	20.32	7.38
OIS	18.06	74.62

Notes: Each value is calculated as the number of days a particular market has the strongest spillover effect divided by the total number of days. The spillover effect is measured both from the sending side ("Spillover from") and receiving side ("Spillover to").

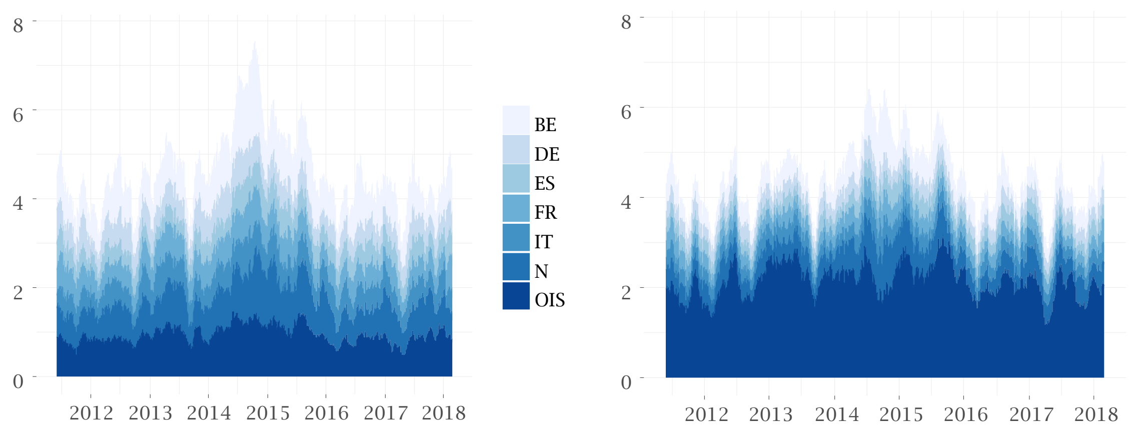
The liquidity spillovers between individual sovereign bond markets are relatively weak on an intraday basis. The strongest liquidity signals are transmitted by Dutch and Belgian sovereign bonds that somewhat even affect OIS liquidity developments. These two markets are also reacting most strongly to the OIS liquidity shocks, although less strongly. Some bonds are usually more sensitive to system-wide shocks, while others — less (Diebold & Yilmaz, 2010). Belgian market might have a strong effect as this country has one of the highest debt to gross domestic product (GDP) ratio, while both Belgian and Dutch markets have strong exposure to other markets through its financial system. Smimou and Khallouli (2016) also found that liquidity often reverberates from smaller to larger euro area markets. Simultaneously, all six sovereign bond markets are receiving relatively similar-sized marginal effects from other markets. Although other studies often find much stronger cross-market linkages (Diebold & Yilmaz, 2010; De Santis & Zimic, 2017; Claeys & Vašíček, 2014), such studies are mainly performed on lower frequency data (e.g., daily, weekly, monthly) where discrepancies are naturally more easily observed and corrected by market participants.

Regarding the overall connectedness during the time, the size of liquidity spillover fluctuated highly across markets. The connectedness between markets was smallest at the start and the end of the review period both for the sending (see Figure 1, LHS) and receiving sides (see Figure 1, RHS), indicating that during these periods, investors perceived liquidity developments in different markets as relatively distinct. The liquidity spillover effect has been strongest from around mid-2014 until mid-2015. This period encompasses several

[3] Net connectedness is calculated as the difference between total directional connectedness to others and from others (Diebold & Yilmaz, 2012).

important ECB monetary policy measures: the announcement of the introduction of negative deposit facility interest rate (June 5, 2014), Mario Draghi's speech at Jackson Hole (August 25, 2014) when market expectations of some sort of quantitative easing increased significantly, the start of public sector purchase program (March 9, 2015). Besides, this period corresponds to the increasing market expectations of very low inflation or even deflation. The liquidity connectedness among markets also increased significantly after several political shocks, e.g., Brexit vote, the US and French presidential elections. International Monetary Fund (2015) determined that liquidity spillovers used to be larger during stressful market periods. Still, the spillovers have become more prevalent in recent years due to low and volatile returns.

Figure 1. Average intraday liquidity spillover *from* (LHS) and *to* (RHS) different bond markets (%)



Notes: The liquidity spillover effect for a 10-minute forecast period is averaged between individual sovereign bond markets and OIS for a 10-year maturity bucket on a 30-day rolling window. 10% of highest and lowest values of country-specific spillover effects during the 30-day rolling window are winsorized to limit the outliers' impact. The country-specific averages are stacked on top of each other to get an overall connectedness value on a daily basis.
Source: Authors' calculations.

5.2. Cross-market price spillovers

The overall connectedness of prices across markets stands at 11% (see Table 5), i.e., almost four times more than for the liquidity cross-market linkages. The main contributor is the stronger OIS price inter-linkages with six sovereign bond markets. Similarly, as in the liquidity case, the OIS prices are receiving price shocks from other markets around two times more than it is transmitting shocks to others. The German and Dutch sovereign bonds are most strongly interconnected with the OIS market. The prices of bonds from these two sovereign bond markets also have the strongest relations with other bonds.

Meanwhile, Italian and Spanish sovereign bonds have the lowest price connectedness (both on receiving and sending side) with other markets. The variance decomposition exhibit also reveals interesting pairwise linkages, e.g., French bonds have a relatively strong price spillover effect to Belgian bonds, but not vice versa. In contrast, Dutch and German bonds are interconnected from both sides. Still, the idiosyncratic domestic dynamics of previous price changes from the same bond have the dominant effect (66%–92%) on price variations in all markets.

Table 5. Average intraday price spillover effect between bond markets and OIS (%)

	Germany	*France*	*Italy*	*Spain*	*Netherlands*	*Belgium*	*OIS*	*From others*
Germany	88.59	1.38	0.55	0.52	2.34	0.98	3.63	9.40
France	1.53	90.13	0.63	0.53	1.55	1.31	2.53	8.08
Italy	1.09	0.97	92.73	1.10	0.96	0.67	1.15	5.93
Spain	1.01	0.90	1.96	92.02	0.92	0.73	1.17	6.69
Netherlands	1.97	1.35	0.50	0.48	89.69	0.99	3.12	8.41
Belgium	1.69	3.11	0.63	0.58	1.80	87.33	2.67	10.48
OIS	7.61	6.21	2.12	1.94	6.99	5.35	65.54	30.22
To others	14.90	13.93	6.40	5.14	14.56	10.02	14.27	11.32
From others	9.40	8.08	5.93	6.69	8.41	10.48	30.22	11.32
Net (to-from)	5.50	5.84	0.47	-1.55	6.15	-0.45	-15.96	

Notes: The liquidity spillover effect between individual sovereign bond markets and OIS for a 10-year maturity bucket is averaged across different trading days for the full data sample from June 2011 until March 2018. The VECM and Diebold and Yilmaz (2012) procedure was applied on an intraday basis. 10% of highest and lowest values are winsorized before calculating a simple average across all days.
Source: Authors' calculations.

OIS market is the dominant transmitter of price shocks on the majority of days during the review period (see Table 6). To be specific, the OIS market has the strongest spillover effect on 1/5 of the days and is receiving signals most strongly from other markets on more than 2/3 of the days, so the proportion is relatively similar as in the case of liquidity spillovers. However, German and Dutch bonds transmit price shocks to other markets but respond to shocks from other markets much less often. Other markets (especially Italian and Spanish sovereign bonds) are rarely the dominant transmitter and receiver of price shocks on a particular day.

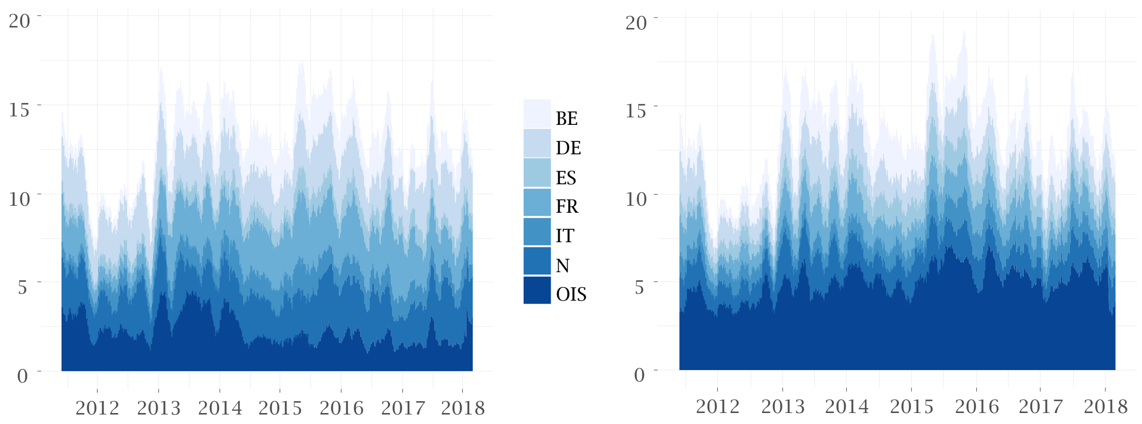
Table 6. Relative shares of maximum price spillover effect days (%)

Market	*Spillover to others*	*Spillover from others*
Germany	21.34	4.88
France	18.60	4.94
Italy	4.94	2.44
Spain	3.78	3.17
Netherlands	21.04	5.61
Belgium	10.85	8.11
OIS	19.45	70.85

Notes: Each value is calculated as the number of days a particular market has the strongest spillover effect divided by the total number of days. The spillover effect is measured both from the sending side ("Spillover from") and receiving side ("Spillover to").

The overall price connectedness between markets also fluctuates highly during the time. The strongest price linkages are visible in 2011 (during the euro area sovereign debt crisis), in 2013 (during 'Taper Tantrum'), and 2015 (during 'Bund Tantrum') when OIS price changes were impacting dynamics of sovereign bond prices (see Figure 2, LHS). Bekaert, Ehrmann, Fratzscher, and Mehl (2011) and International Monetary Fund (2015) have found that common fears drive investors during financial turmoil, so market prices become more correlated. Besides, during stressful periods, individual markets are often subject to frequent volatility shocks. Interestingly, the strong jumps of OIS spillovers during these periods are less visible on the receiving side (see Figure 2, RHS) as individual sovereign bond markets received stronger signals of price changes from OIS. This means that sovereign bond prices, in contrast with bond liquidity, are often driven by common factors, especially during stressful market periods.

Figure 2. Average intraday price spillover *from* (LHS) and *to* (RHS) different bond markets (%)



Notes: The price spillover effect for a 10-minute forecast period is averaged between individual sovereign bond markets and OIS for a 10-year maturity bucket on a 30-day rolling window. 10% of highest and lowest values of country-specific spillover effects during the 30-day rolling window are winsorized to limit the outliers' impact. The country-specific averages are stacked on top of each other to get an overall connectedness value on a daily basis.
Source: Authors' calculations.

To sum up intraday cross-market spillovers results, it is evident that liquidity spillovers are much weaker than price spillovers. Although the liquidity spillovers vary over time, the spillovers seem to be relatively weak, and the idiosyncratic country-specific factors explain the major part of a particular bond's liquidity variation. Meanwhile, price spillovers are somewhat stronger but still account for about 1/10 of the overall variation of bond prices. This implies that the disbalances from cross-market equilibrium are usually not corrected on a minute basis as markets can somewhat deviate from each other, especially when these pull-offs are relatively small. Thus, there is no economic rationale for market participants to correct these discrepancies.

5.3. Panel regression models of cross-market spillovers

Panel regression models were additionally performed to answer the question of what determines the strength of cross-market spillovers. Regarding liquidity spillovers, the only statistically significant explanatory variables are the distance between countries and intraday liquidity volatility (see Table 7). The distance between countries is negatively linked to the liquidity spillovers, possibly because different dealers are often concentrated (also due to historical reasons) in the neighboring countries. Hence, a liquidity shock in one country often usually affects bonds' liquidity from the nearest countries. Meanwhile, the more volatile bonds have larger spillover effects because such bonds naturally possess stronger signaling power to market participants. Other factors, e.g., export links, characteristics, and trading features of the bond, do not explain the size of liquidity spillovers.

Table 7. Panel regression results of cross-market liquidity and price spillovers

Explanatory variable	***Liquidity***	***Price***
Intercept	1.11077*** *3.23*	1.03651*** *3.67*
Time since issuance	0.00007 *0.02*	-0.00243 *-0.24*
Issuance volume	-0.00001 *-1.15*	0.00001 *1.05*
Number of active dealers	-0.00551 *-0.34*	0.06573** *2.00*
Order revision frequency	-0.00029 *-0.64*	0.00153** *2.40*
Liquidity/Price volatility	1.37536* *1.81*	0.89689 *1.52*
Distance between countries	-0.00035*** *-3.80*	-0.00070** *-2.69*
Share of exports	0.00199 *0.53*	0.00149 *0.17*
Fixed effect	Country	Country
R^2	0.01	0.03

Notes: The panel regression models were performed for daily cross-market liquidity and price spillover effects for 10-year residual maturity sovereign bonds for the full data sample from June 2011 until March 2018. The first line at each variable denotes the estimate of each variable explanatory effect on liquidity/price spillovers in a country-specific fixed-effects panel model. The second line (in italics) shows t-statistics that are calculated by clustering standard errors by each country. Asterisks indicate statistical significance at the 10% (*), 5% (**) and 1% (***) levels.
Source: Authors' calculations.

More factors explain the size of cross-market price spillovers (see Table 7). First, the distance between countries is also negatively linked to the magnitude of the price spillover effect. Interestingly, the quoting activity factors are positively correlated with the spillovers. If the number of dealers active on a particular day and average quoting (revision) frequency increases, such sovereign bond has a stronger price spillover effect because, possibly, such bonds incorporate new information faster and more efficiently, so price shocks have a stronger signaling power to bonds from other markets. Characteristics of particular sovereign bonds again do not have a statistically significant effect, meaning that plain differences between bonds can not explain cross-market spillovers.

6. RESULTS OF DAILY CROSS-MARKET SPILLOVER ANALYSIS

To compare the results of the intraday cross-market linkages, the analysis was additionally performed with daily data. Specifically, the examination was implemented with 100-day rolling window average variance decompositions for six sovereign bonds and the OIS market. As shown in Table 8, the average overall daily liquidity connectedness is around four times higher than with an intraday application and stands at almost 13%. This finding probably implies that the liquidity disbalances between different markets are usually corrected on longer intervals than intraday. Still, the idiosyncratic liquidity dynamic is the dominant factor, accounting for 63–91% of the liquidity variation of a particular market. OIS is the most inter-connected market both from the receiving and transmitting sides. Besides OIS, the overall daily liquidity connectedness is much more balanced across markets than with the intraday linkages, meaning that disbalances are corrected more homogenously across different sovereign bonds in longer periods. Still, the strongest net spillover effect on average can be attributed to Belgian sovereign bonds that are most strongly linked with the liquidity of OIS and, again, Dutch bonds.

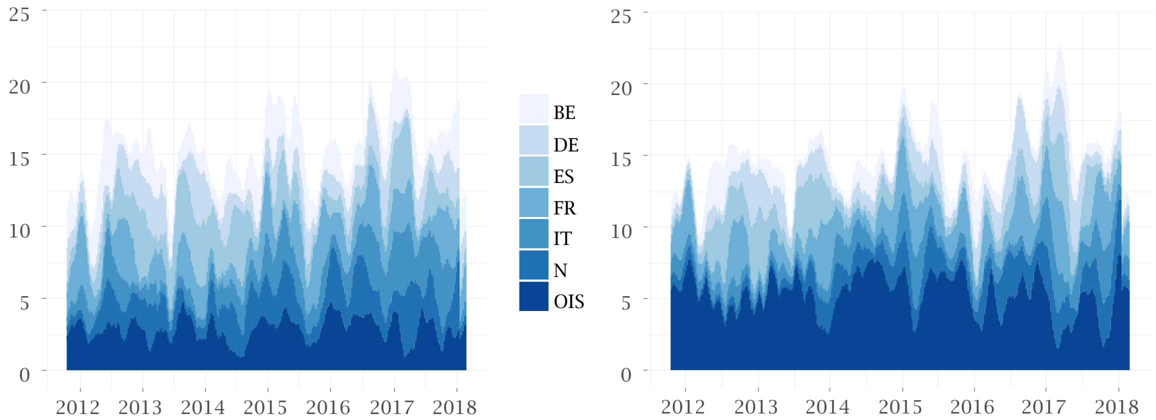
Table 8. Average daily liquidity spillover effect between individual bond markets and OIS (%)

	Germany	***France***	***Italy***	***Spain***	***Netherlands***	***Belgium***	***OIS***	***From others***
Germany	89.10	1.37	1.47	1.51	1.35	1.61	1.99	9.30
France	1.66	84.61	2.25	1.47	2.13	0.94	4.42	12.87
Italy	1.05	1.19	90.62	1.25	1.04	1.45	2.13	8.11
Spain	1.16	1.33	1.47	87.78	1.20	0.96	2.99	9.11
Netherlands	1.04	1.30	1.26	0.93	88.96	2.53	2.72	9.78
Belgium	0.89	0.96	1.31	1.25	1.64	91.16	1.65	7.69
OIS	3.83	7.45	3.93	6.31	5.43	5.16	63.04	32.10
To others	9.63	13.59	11.69	12.71	12.79	12.65	15.90	12.71
From others	9.30	12.87	8.11	9.11	9.78	7.69	32.10	12.71
Net (to-from)	0.33	0.72	3.58	3.60	3.02	4.95	-16.20	

Notes: The liquidity spillover effect between individual sovereign bond markets and OIS for a 10-year maturity bucket is averaged across different trading days for the full data sample from June 2011 until March 2018. The VECM and Diebold and Yilmaz (2012) procedure was applied on an intraday basis. 10% of highest and lowest values are winsorized before calculating a simple average across all days.
Source: Authors' calculations.

The dynamics of overall daily liquidity connectedness are relatively similar to intraday liquidity linkages (see Figure 3). For instance, connectedness increases markedly around the 'Taper Tantrum', Brexit vote, the US and French presidential elections. Also, the overall liquidity connectedness remains relatively muted during the most stressful market period in 2011–2012. However, the differences among markets are more evident on a daily than on an intraday basis. For instance, in mid-2012, the liquidity spillover effect from Italian sovereign bonds began decreasing significantly (when the concerns regarding the euro area sovereign debt crisis calmed down). At the same time, the linkages among other markets increased. However, this finding is not visible on an intraday basis, meaning that these shocks reverberated to other markets not instantaneously but gradually through several days. From the systemic risk perspective, it is often more important to analyze not only the overall market connectedness but also the dynamic spillovers from and to a particular market and on different time scales because such analysis might tell which market is responsible for the shock dissemination and what type of shock — short or long-lasting — hit the markets. So market participants and regulators should monitor both individual and aggregate spillover effects.

Figure 3. Average daily liquidity spillover *from* (LHS) and *to* (RHS) different bond markets (%)



Notes: The price spillover effect for a 10-minute forecast period is averaged between individual sovereign bond markets and OIS for a 10-year maturity bucket on a 30-day rolling window. 10% of highest and lowest values of country-specific spillover effects during the 30-day rolling window are winsorized to limit the outliers' impact. The country-specific averages are stacked on top of each other to get an overall connectedness value daily.
Source: Authors' calculations.

The overall daily price connectedness is also around four times higher than intraday price linkages (see Table 9). The cross-market price linkages amounts to marginally above 50%, while the remaining share — to the idiosyncratic domestic price variation. Interestingly, the daily price connectedness is much more heterogeneous on the sending side and more homogenous on the receiving side across markets. German, French, and, especially, Dutch sovereign bonds have the strongest price transmission powers to other markets, while Spanish and Italian bonds — much weaker. This conclusion (although not so stark) was also visible with intraday price data. All sovereign bond markets experience relatively similar effects from the receiving side (around 50%), except Dutch bonds that react relatively weaker to price shocks (40%). The overall net spillover effect is by miles strongest for Dutch sovereign bonds, meaning that this market is often the first market that drives prices from other markets but does not so strongly respond to price shocks from other markets. Meanwhile, the most negative net spillover effect is for the OIS market because it has relatively weak price transmission power to other markets.

Table 9. Average daily price spillover effect between individual bond markets and OIS (%)

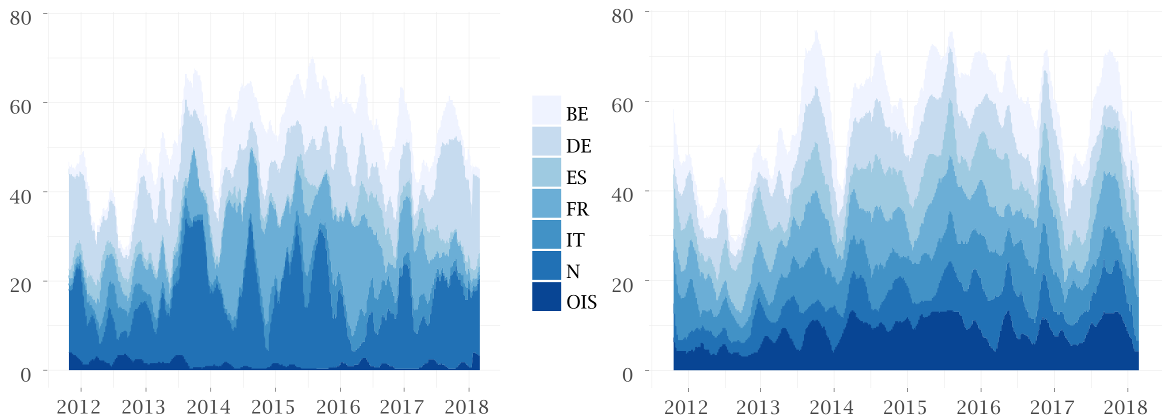
	Germany	***France***	***Italy***	***Spain***	***Netherlands***	***Belgium***	***OIS***	***From others***
Germany	39.17	13.15	3.69	3.38	24.61	9.10	1.32	55.24
France	14.15	39.50	3.44	3.47	21.19	10.63	1.09	53.98
Italy	10.19	11.01	43.98	3.08	13.58	9.67	1.57	49.09
Spain	11.85	9.95	6.22	41.34	13.76	9.68	1.18	52.64
Netherlands	13.13	11.34	2.86	3.02	53.77	8.36	1.12	39.83
Belgium	12.30	11.52	3.46	4.06	18.59	43.64	1.19	51.12
OIS	12.68	10.61	3.61	2.28	14.29	9.25	41.22	52.72
To others	74.30	67.58	23.26	19.28	106.03	56.69	7.46	50.66
From others	55.24	53.98	49.09	52.64	39.83	51.12	52.72	50.66
Net (to-from)	19.06	13.61	-25.83	-33.35	66.20	5.57	-45.26	

Notes: The liquidity spillover effect between individual sovereign bond markets and OIS for a 10-year maturity bucket is averaged across different trading days for the full data sample from June 2011 until March 2018. The VECM and Diebold and Yilmaz (2012) procedure was applied on an intraday basis. 10% of highest and lowest values are winsorized before calculating a simple average across all days.
Source: Authors' calculations.

Price connectedness on a daily frequency varies quite substantially during the time (see Figure 4). Overall linkages jumped relatively often from mid-2013 until mid-2016 when several shocks hit the market: 'Taper Tantrum', 'Bund Tantrum', Brexit, etc. These increases are often driven not by a common factor. Still, by specific markets, e.g., Dutch sovereign bonds were transmitting price shocks in many of these periods, while German bonds — relatively more during 'Bund Tantrum'. Meanwhile, the jumps on the receiving side are much more homogenous, meaning that markets react to a price shock from another market (e.g., from Dutch sovereign bonds) in a similar manner. The phenomenon of Dutch bonds importance probably stands from the fact that many 'overseas' investors (e.g., from the UK and the US) are trading through Dutch trading facilities[4] and thus has more international twist.

[4] Dutch financial sector is highly linked with the US and the UK markets because a lot of banks and investment firms establish their euro area headquarters in the Netherlands. The list of MTS dealers in Dutch markets is provided under this link: https://www.mtsdata.com/content/data/public/nld/anagraph/member.php

Figure 4. Average daily price spillover *from* (LHS) and *to* (RHS) different bond markets (%)



Notes: The price spillover effect for a 10-minute forecast period is averaged between individual sovereign bond markets and OIS for a 10-year maturity bucket on a 30-day rolling window. 10% of highest and lowest values of country-specific spillover effects during the 30-day rolling window are winsorized to limit the outliers' impact. The country-specific averages are stacked on top of each other to get an overall connectedness value on a daily basis.
Source: Authors' calculations.

To sum up, it is obvious that liquidity and price connectedness daily are much higher than in the case of intraday basis. This implies that markets self-correct the disbalances in longer frequency than minutes. Still, liquidity shocks do not spread so much through the other markets as the idiosyncratic domestic factor dominates even on a daily basis. Meanwhile, price shocks have stronger signaling power and thus more easily reverberates to other markets on a daily frequency, possibly because market participants concentrate and thus change their behavior due to larger and longer-lasting price shocks from other markets as adjusting prices on an intraday basis is still relatively costly, e.g., monitoring, search and bid-ask spread costs.

7. CONCLUSION

This study empirically investigates the cross-market liquidity and price spillover effects across European sovereign bonds by using constructed minute frequency order-book data from June 2011 until March 2018. The analysis was carried out for the six largest euro area markets and OIS. Two different econometrical methods were used: the vector error correction model with application for Diebold and Yilmaz (2012) variance decomposition and the panel regression model.

The intraday cross-market linkages analysis revealed that liquidity spillovers are relatively weak as they account for 2–5% of overall intraday liquidity variation. The idiosyncratic country-specific factors dominate over the intraday liquidity spillovers. Belgium and Dutch sovereign bonds have the strongest liquidity spillover effect, possibly due to a highly integrated financial system, while all bond markets seem to react relatively homogenously to liquidity shocks from other markets. The liquidity spillover effect has been strongest from mid-2014 until mid-2015, corresponding to when important monetary policy measures were undertaken. Panel regression model revealed that the magnitude of liquidity spillovers is negatively linked to the distance between countries and positively — to the more volatile bonds with stronger signaling power to market participants.

Intraday cross-market price spillovers are somewhat stronger and account for 8–15% of overall intraday price variation. Higher inter-linkages between markets might suggest that the price determination mechanism is somewhat more efficient than the liquidity formation among euro area sovereign bond markets. German and Dutch sovereign bonds are most strongly interconnected with other markets, while Italian and Spanish sovereign bonds have the lowest price connectedness. Still, the idiosyncratic country-specific factors explain the major part of price variation of the domestic market. In contrast to liquidity spillovers, the strongest price linkages were observed during financial turbulences when common factors were driving the price variation. Also, relatively more factors explain the size of cross-market price spillovers: it is negatively linked to the distance between countries and positively — to the number of active dealers and order revision frequency.

The variance decomposition model results with daily data revealed that liquidity and price connectedness are around four times stronger than in the case of intraday linkages. This finding implies that the liquidity or price disbalances between different markets are corrected more homogenously and on longer intervals than minutes because market participants concentrate and thus change their behavior in response to larger and longer-lasting shocks from other markets.

The main limitation for further research could be the access to data. It would be interesting to investigate all sovereign bond markets in the euro area. Still, it can be challenging to get high-frequency data for all bond markets, especially small ones. Also, it would be interesting to investigate all the euro area sovereign bond markets and make some clusters according to the size of the market. Using clustering methodology, maybe interesting spillover effects could be found.

The current research limitations are related with a specific period of data. So, it is very important to pay attention for that trying to make conclusions for spillover effects and tendencies in different economic periods and monetary policy stances.

The findings of this study have several implications for bond market participants. To start with, investors should direct their trading to the markets that most strongly transmit the liquidity and price shocks if they want to have the firmest direct control of their trading strategies' outcome. Specifically, investors should trade relatively more in Belgium and Dutch bonds if they want to hedge the cross-market liquidity spillovers and German and Dutch bonds if they want to have more control on domestic price shocks. From the systemic risk perspective, market supervisors from particular countries should pay more attention to the relatively close markets with one another and that are more actively quoted. However, the cross-market linkages change during financial turbulences and in anticipation of monetary policy actions, so market supervisors should also monitor dynamic inter-linkages on different time scales. Such analysis might tell which market is responsible for the shock dissemination and what type of shock — short or long-lasting — hit the market.

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