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Determinants of the bid-to-cover ratio in Eurozone sovereign debt auctions☆,☆☆

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ABSTRACT

Building on a unique dataset of Eurozone sovereign debt auctions, this paper analyzes the determinants of their bid-to-cover ratios, which is the most common measure of the outcome of an auction. We find that the secondary market yield on the same maturity instrument, past domestic and foreign bid-to-cover ratios and occasionally the number of primary dealers tend to exert a positive effect on the current bid-to-cover ratio, while the opposite is the case for the supply and the volatility of the yield. The results thus suggest that past information helps to predict the demand in auctions.

1. Introduction

When sovereign funding conditions are under stress, sovereign debt auctions move to the center stage of media reporting. They are regarded as a test of market appetite for sovereign bonds. Unsuccessful auctions are typically associated with higher funding costs. Hence, while debt management offices (DMOs) may be under pressure to issue large amounts of government debt, they also have a strong interest in preventing undersubscribed auctions. This dynamic was at play during the euro area sovereign debt crisis. When government funding needs increased, capital market became more wary about the sustainability of countries' public debts and the outcomes of sovereign bond auctions became indicators of the market's confidence in countries' creditworthiness. More

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recently, fears about Italian budgetary plans for 2019 made clear that sovereign debt auctions continue to be important moments for measuring the markets' sentiment about a sovereign debt issuer.[2]

A key measure of the demand in an auction is the so-called "bid-to-cover ratio", which is the total amount bid during an auction divided by the total amount of new debt allotted. To the best of our knowledge, this is the first paper to relate the bid-to-cover ratio to its determinants. Our empirical analysis is motivated by a simple theoretical framework with a key role for the primary dealers, whose bidding behavior implies a price-elastic aggregate demand curve. The theory predicts that the bid-to-cover ratio is decreasing in the degree of market risk aversion, market volatility, the amount of debt to be issued and the concentration of dealer wealth. Using a sample of Belgian, French, German, Italian and Spanish auctions for the period 1 January 1999 until 31 December 2017,[3] we find that the secondary-market yield on same-maturity debt tends to have a positive effect on the bid-to-cover ratio, while market volatility has a negative effect. A highly significant negative effect is found for the supply itself. An increase in the number of primary dealers appears to push up bid-to-cover ratios for some maturities, while a higher bid-to-cover ratio in the previous auction of the same maturity predicts a higher bid-to-cover ratio for the new debt issue. This also tends to be the case for the latest foreign bid-to-cover ratio, suggesting cross-border spill-overs of issuing conditions. Higher Eurozone sovereign debt purchases by the European System of Central Banks (ESCB) exert a negative effect on bid-to-cover ratios for some debt maturities. Overall, the empirical results are in line with some of the theoretical predictions.

Our findings should be of interest to DMOs, because they help to identify the conditions for successful auctions, i.e. to issue debt against the lowest possible costs, given the aggregate funding needs over time and potential objectives in terms of the maturity structure, which may result from trade-offs involving roll-over, default and other risks (e.g., see Broner et al., 2013; Beetsma et al., 2019). For example, when the current environment is challenging, raising the risk of an undersubscribed auction, the DMO may choose to shift issuance volume to the future, while making use of the money market to bridge a temporary funding gap.[4]

This paper relates to several strands in the literature on sovereign debt. First, there is the literature that studies the demand for sovereign debt. According to the mean–variance model, investors in international bonds wish to maximize their portfolio return for a given risk or to minimize risk for a given portfolio return. As such, a higher yield would be the equilibrium response to a higher volatility of returns relative to that on alternative assets. However, in markets with frictions, like the primary debt markets we study, demand may respond to the yield and volatility of bonds. Vayanos and Vila (2009), for example, develop a model of demand for bonds with preferred habitat investors. In their model demand from investor clientless with a preference for specific maturities is a function of the bond's yield, while arbitrageurs have a mean–variance utility function.

Second, our paper is linked to the literature that explores pricing in sovereign debt auctions. Spindt and Stolz (1989) develop a theoretical model in which a higher number of bidders in a discriminatory auction increases the stop-out price of the auction. In line with this model, Spindt and Stolz (1992) find that U.S. Treasury bill auctions with more participant bids result in less underpricing in the auction (relative to the secondary market price). Goldreich (2007) compares the degree of underpricing between discriminatory and uniform price auctions for U.S. sovereign bonds. Cammack (1991) finds that the underpricing in auctions is smaller when the bid-to-cover ratio is higher. She also finds that secondary market prices increase when the number of competitive bidders in the auction is higher than expected. Nyborg et al. (2002) study the outcomes of Swedish treasury auctions and find (among other things) that bidders vary their prices and quantities in response to changes in uncertainty. Han et al. (2007) explore the buyback by the U.S. Treasury of outstanding illiquid bonds. The auction is discriminatory since offers are either accepted or rejected at the offer price. Given the eligibility of a variety of bonds, the auction can be viewed as a multi-item multi-unit auction and, given the active secondary market for the eligible instruments, the auction can be considered a pure common-value auction. Mann and Klachkin (2015) assess the effect of quantitative easing by the Federal Reserve on auction yields. Relatedly, Song and Zhu (2018) study reverse auctions by the Fed in the quantitative easing programs. Again, these can be considered multi-item, multi-unit and discriminatory price auctions. It is found that the Fed purchases more of bonds that are more undervalued relative to the Fed's internal valuation model.

Third, our paper connects with the literature that explores the interplay between primary and secondary markets for sovereign bonds. A number of contributions find evidence for so-called "auction cycles" in secondary-market yields around primary-market issues of sovereign debt.[5] These include Fleming and Rosenberg (2007), Lou et al. (2013), Beetsma et al. (2016, 2018b) and Sigaux (2017). Beetsma et al. (2018a) show that for euro area sovereign bond auctions a higher bid-to-cover ratio leads to smaller secondary market yield cycles following the auctions, and that this effect is stronger when market volatility is higher. Klinger and Sundaresan (2020) find that primary dealers' excess demand in auctions is a key driver of Treasury bill yields in the U.S. These effects are shown to be more pronounced when primary dealers face higher participation costs at auctions and less pronounced when secondary-market demand for Treasury bills is high. Gorodnichenko and Ray (2017) and Lengyel and Giuliodori (2020) use intraday government bond

[2] In fact, the Financial Times (October 11, 2018) writes "*Italy's cost of funds has hit a five-year high in its latest debt auction, as the wider market sell-off and investors' jitters over its domestic politics continue to push bond yields up. [. . .] The bond sale was pushing the limits of investors' appetite for Italian debt — it had a bid-to-cover ratio of 1.26 per cent.*", see https://www.ft.com/content/9a026742-cd39-11e8-b276-b9069bde0956. Related press coverage is provided by Reuters (August 30, 2018) who writes "*The Italian Treasury is due to sell up to 7.75 billion euros of bonds in an auction on Thursday that will be closely watched as a barometer for risk appetite.*", see https://www.reuters.com/article/eurozone-bonds/italian-bond-auction-to-test-risk-appetite-idUSL8N1VL1PS.

[3] We also have auction data for the Netherlands. However, the Netherlands uses tap auctions, where the price is adjusted during the auction, and bids at the prevailing price are fully allotted. So the bid-to-cover ratio is one by construction.

[4] For example, in its outlook for 2018 the Dutch State Treasury Agent (2018, p.15) writes "*The money market has historically been used as a buffer when it comes to accommodating changes in the funding need". Likewise, the OECD (2018) writes "T-bill funding, in particular, is often considered as a shock-absorber for any unexpected financing needs*".

[5] An auction cycle refers to the phenomenon that secondary-market yields go up before the auction and come down after the auction.

Table 1
Auction characteristics.

	Announced volume	Type	Primary Dealer participation obligations and benefits
Belgium	Combined Range[a]	Discriminatory	Place on average 2% of total competitive bids
France	Combined Range[a]	Discriminatory	Place on average 2% of total competitive bids
Germany	Indicative target[b]	Discriminatory	Buy 0.05% of total amount issued per calendar year
Italy	Range[c]	Uniform	Buy 3% of total amount issued per calendar year A discount for having collected bids from the public
Spain	Indicative target	Combination[d]	Place bids for at least 3% of the amount allotted, priced no lower than 5 to 30 cents below the marginal price, depending on the maturity

[a]Belgium and France announce a target range for the combined volume of all the issued maturities on the auction day.

[b]Italy announced the exact auction volume until October 2008, so the DMO did not have the discretion to scale down bids. This switch took place in December 2011 for 2-year zero coupon bonds ("CTZs").

[c]Germany announces a target volume. However, during the auction the DMO issues only a portion of the target volume. In contrast to the other countries in our sample, the German debt management office tends to retain a substantial amount of the targeted supply. This leaves Germany with greater discretion to scale down bids than the other countries in our sample.

[d]Spanish auctions combine elements of discriminatory and uniform auctions. Bids below the weighted-average price pay the price at which the individual bid was made and bids above the weighted average price pay the weighted-average price.

futures price data to estimate the effects of demand shocks at auctions on the term structure of interest rates in the U.S. and the Eurozone, respectively.

The remainder of this paper is structured as follows. The next section provides a brief description of the organization of Eurozone sovereign debt auctions. This is followed by the presentation of our theoretical framework in Section 3. Section 4 describes the data and the construction of some variables used in the empirical analysis. Section 5 estimates the baseline regression framework motivated by our simple theoretical framework. A robustness analysis and extensions are also included in this section. Finally, Section 6 concludes the main body of the paper.

2. The auction process

This section briefly reviews the main aspects of the organization of Eurozone public debt auctions. More detailed information can be found in the European Primary Dealers Handbook (AFME, 2017). Based on the expected public deficit and the amount of maturing debt that needs to be rolled over, the DMO decides on an annual target for funding. Most of the Eurozone public debt is placed through auctions. These form the primary market for the debt. Most of the auctions are re-openings for an instrument that already exists in the secondary market. OECD (2018) reports that re-openings are the most common practice across OECD DMOs to increase liquidity in the secondary market. While these auctions may differ across countries, they also have a number of important elements in common. They are announced in an annual calendar. Some countries, such as Germany, France and Italy, in addition publish a quarterly calendar with further information about the bonds to be issued in the quarter ahead.[6] Finally, detailed information, such as the target (or issuance) volume or range of the maturity (or maturities) on auction, is announced in a press statement some business days before the auction actually takes place. After the auction, on the same day, the results of the auction are published in a press statement. The financial settlement and transfer of ownership of the allotted securities to the successful bidders is typically two days later.

Only the so-called "primary dealers", major international or national commercial banks, participate in the auction.[7] They buy the debt sold in the auction and sell the newly-issued debt on to other parties, such as end-users like pension funds and other institutional investors. Primary dealers are typically subject to a number of obligations, such as purchasing a minimum amount and providing liquidity in the secondary markets by quoting prices for the bonds. However, they also enjoy benefits. Specifically, DMOs may financially reward primary dealers for their activities. For example, in the case of Italy, the primary dealers are awarded a commission on the order of 0.20% to 0.40% of the amount allotted. Of course, these commissions will get factored into the bids that are made, so primary and secondary market prices of the same instrument may differ.

Different types of auction designs are possible — see Table 1, which summarizes the main features of the auctions by our sample countries. Belgium, France and Germany use "multiple-price" (or "discriminatory-price") auctions, with bids exceeding the lowest accepted price allotted in full against the submitted price. By contrast, for the maturities in our analysis the Italian DMO uses "marginal-price" (or "uniform-price") auctions, in which all bidders pay the same, so-called marginal price.[8] In the case of Spain, the design is a combination of a marginal-price and a multiple-price auction, in which bids made at the minimum price are accepted at this price, bids between the minimum and the weighted-average price of the bids pay the price at which the individual bid was made and bids above this weighted-average bid price pay the weighted-average bid price.

[6] The calendar is monthly in the case of France.

[7] Formally, Germany does not work with a primary dealer system, but with a so-called "Bund Issues Auction Group", which is a set of banks that fulfills certain requirements, such as a minimum purchase requirement. For convenience, we will in all instances refer to "primary dealers" as the institutions that buy debt at the auctions.

[8] In order for the accepted yields to be in line with the market yields, a minimum acceptable yield, also called the safeguard yield, is calculated. Similarly, a maximum acceptable yield, or the exclusion yield, is calculated to avoid speculative behavior.

DMOs announce target amounts or ranges before the auction, hence the actual allotment may not be fixed in advance. For example, the German DMO may scale down bids quoting the lowest accepted price and/or scale down non-competitive bids, and retain a certain amount of the instrument for secondary market operations. Figures A.1 and A.2 in the Appendix (not for publication) show two examples of press releases of the German DMO to announce a 10-year maturity bond auction and to publish its results. By contrast, during the first part of our sample Italy only announced target amounts and switched to announcing target ranges as of October 2008 for 5- and 10-year auctions and as of December 2011 for 2-year auctions, thereby allowing itself some discretion in terms of the eventually allotted volume (Italian Treasury, 2014). The French and Belgian DMOs announce a target range for the combined volume of all the issued maturities on an auction day. Auctions may be followed by a non-competitive round in which primary dealers can buy more of the auctioned instrument. For example, in the case of Italy a further amount of between 10% and 35% (depending on the type of the bond) of the auctioned volume is available for selected primary dealers for a non-competitive supplementary re-opening on the next business day with settlement at the marginal price of the auction.

3. Theoretical framework and hypotheses

The literature on sovereign debt auctions presents theoretical frameworks that can differ in various dimensions. In particular, models may feature uniform versus multiple pricing and risk-neutral versus risk-averse bidders. The set of bidders, the primary dealers, is usually finite, and hence forms an oligopsony. Goldreich (2007) explores the relationship between under-pricing and whether a uniform or multiple pricing mechanism is used. He assumes risk-neutral bidders who receive a common plus an idiosyncratic signal of the value of the instrument. He finds that under-pricing is stronger when the spread in individual signals is larger and the number of bidders is smaller given the amount on offer. Keloharju et al. (2005) compare different underlying frameworks, including risk-neutral versus risk-averse bidders. They also vary the degree of competition among the bidders. The pay-off value of the instrument on offer is uncertain, but bidders do not have private information. Under-pricing depends on the number of bidders, given the amount on auction, and, in the case of risk aversion, on the pay-off uncertainty. In Song and Zhu (2018) the value of the bond has a common component and a private component. The Fed buys the bond and attaches a value that is common knowledge. Among the offers of the primary dealers (the prices they ask) it picks the lowest, subject to the offer being lower than its own value. The authors find that the auction price is higher when the value that the Fed attaches is higher.

This section presents a simple theoretical framework that helps to rationalize our regression framework and the hypotheses to be tested. The basic structure of our framework, which is in spirit quite related to the models discussed above, is borrowed from Beetsma et al. (2018a) and starts from a simplified version of the models in Kyle (1989), Boyarchenko et al. (2016) and Sigaux (2017).[9] We consider a bond that is to be auctioned and that *prior* to the auction, and conditional on all public information, including that from previous auctions, has a stochastic normally-distributed pay-off v with mean $E[v] = \overline{v}$ and variance σ_v^2. Participation in sovereign bond auctions is limited to a selected group of primary dealers who have to satisfy minimum participation requirements. We therefore assume that bidding for the bond is done by N primary dealers. This institutional set-up of the auction produces a friction, because the primary dealers have to absorb the full quantity of the auction supply. After the Treasury announces the quantity to be auctioned, but during the auction process, the primary dealers receive a signal $s = v - \overline{v} + \xi$ about the "quality" of the bond. This signal may, for example, come from observing the order flow from their customers (e.g., see Lyons, 1995) and will affect the primary dealer's demand for the bond. The noise term ξ is normally distributed with mean zero and variance σ_ξ^2 and uncorrelated with v.

Our focus is on a rational-expectations equilibrium with the primary dealers using their signal information. From Bayesian updating, $E[v|s] = \overline{v} + \beta s$ with $\beta = \frac{Cov(v,s)}{Var(s)}$. Further, denote by $\sigma^2 = Var(v|s)$ the *conditional* variance of the bond given the signal s. In practice, the primary dealers may be able to hedge the increased supply by short-selling similar bonds. In that case, we should interpret the volatility parameter σ^2 as the residual volatility after optimally hedging the auctioned bond (see Beetsma et al., 2018a, for more details).[10] We assume that each primary dealer $n \in \{1, \ldots, N\}$ maximizes a one-period constant absolute risk aversion (CARA) utility function with absolute risk aversion A_n. The dealer's demand for the bond is (e.g., see De Jong and Rindi, 2009, Subsection 2.3),

$$x_n = \frac{E[v|s] - p}{A_n \sigma^2 + \lambda_n}, \tag{1}$$

with $\lambda_n \equiv dp/dx_n$ the effect on the bond price of dealer n's demand for the bond. We will solve for λ_n below and confirm that it is positive. The sensitivity of demand to the difference between the *posterior* value $E[v|s]$ and the price p is stronger when absolute risk aversion A_n is smaller and the signal is more precise, hence the conditional variance σ^2 is lower.

The price impact λ_n follows from the equilibrium condition for the bond. Taking the demands of the other primary dealers given, the demand of primary dealer n for the bond must satisfy:

$$\lambda_n = \frac{dp}{dx_n} = \left[\sum_{i \neq n} \frac{1}{A_i \sigma^2 + \lambda_i} \right]^{-1}$$

where every dealer takes into account that the demands of the other dealers depend on their risk aversion and the price impact coefficients λ_i. This equation, however, is not easily solved in a setting with heterogeneous agents. To simplify matters, let us assume

[9] In particular, in contrast to these papers, we abstract from liquidity traders.

[10] In the case of a re-opening, the newly-auctioned supply can in principle be hedged perfectly, but other market frictions such as short sale constraints, margin requirements and the uncertainty about the allotted amount to each individual dealer may also make this hedge imperfect.

that each dealer n ignores that the other dealers take into account their impact on the equilibrium price. So dealer n assumes that $\lambda_i = 0$, for $i \neq n$. Furthermore, we assume that the absolute risk aversion is inversely proportional to dealer wealth, i.e. $A_n = \eta/W_n$. Applying these assumptions to the above expression for λ_n yields

$$\frac{1}{\lambda_n} = \sum_{i \neq n} \frac{W_i}{\eta\sigma^2} = \frac{W - W_n}{\eta\sigma^2},$$

where $W = \sum_{i=1}^{N} W_i$ is aggregate dealer wealth. Plugging this back into the demand function (1), using $A_n = \eta/W_n$ and $\lambda_n = \eta\sigma^2/\left(W - W_n\right)$, gives

$$x_n = \frac{E\left[v|s\right] - p}{\eta\sigma^2/W_n + \eta\sigma^2/\left(W - W_n\right)} = W_n \frac{E\left[v|s\right] - p}{\eta\sigma^2}\left(1 - \frac{W_n}{W}\right),$$

Aggregate demand then is:

$$X = \sum_{n=1}^{N} x_n = \frac{E\left[v|s\right] - p}{\eta\sigma^2} \sum_{n=1}^{N}\left(W_n - \frac{W_n^2}{W}\right) = W \frac{E\left[v|s\right] - p}{\eta\sigma^2}\left(1 - HHI\right)$$

where $HHI \equiv \sum_{n=1}^{N}\left(W_n/W\right)^2$ is the Herfindahl–Hirschman Index of dealer capital concentration, with W_n/W the capital share of dealer n. Equating the aggregate demand with the given asset supply Q gives the equilibrium price:

$$p = E\left[v|s\right] - \eta\sigma^2\left(\frac{Q}{W}\right)\left(1 - HHI\right)^{-1}. \tag{2}$$

The second term on the right-hand side of (2) is the degree of under-pricing relative to the pay-off conditional on the signal. A lower degree of capital concentration, i.e. a lower value for the Herfindahl–Hirschman Index, leads to less under-pricing. In the special case in which all dealers have an equal amount of capital, we have $HHI = 1/N$. Hence, the degree of under-pricing is falling in the number of dealers. Under-pricing is minimized when the number of dealers goes to infinity and there is perfect competition in the bidding process. A higher degree of innate risk aversion η, more volatility σ^2, smaller aggregate dealer wealth W and a larger amount to be issued all lead to more under-pricing.

To keep the setup general we assume that, besides the stochastic signal s which affects the demand for the auctioned instrument, the auction quantity Q^A is also stochastic:

$$Q^A = \overline{Q} + \mu$$

where $\overline{Q}$ is the announced quantity to be auctioned and μ is a mean-zero shock to the actual amount auctioned. Such a shock may arise from unforeseen changes in market circumstances, for example, but is observed by the primary dealers just before the actual auction.

We assume that before the auction the DMO sets a reservation price p^R for the bond. This reservation price determines the bid-to-cover ratio. The reservation price cannot be directly observed. In reality, it is likely to be implicit, as there is an understanding that the DMO expects the primary dealers to make bids at reasonable prices. If a primary dealer bids too low a price, the on-going relationship between the DMO and the primary dealer may be harmed. In fact, Boyarchenko et al. (2016, pp. 3/4) notice that in U.S. treasury auctions, "Primary dealers are expected to bid [...] with prices that are 'reasonable' compared to the market". Nyborg et al. (2002, pp. 404) mention the existence of an implicit reservation price in Swedish treasury auctions. Keloharju et al. (2005) also assume the existence of a reservation price for Finnish treasury bond auctions. Denote by Q^R the amount bid at the reservation price. It follows from the equilibrium price curve (2) for the bond that:

$$p^R = \overline{v} + \beta s - \eta\sigma^2\left(\frac{Q^R}{W}\right)\left(1 - HHI\right)^{-1}. \tag{3}$$

Hence, an auction price of p^R corresponds to an amount bid of Q^R, which depends on the signal s and is therefore only realized after the auction.

As we do not observe the reservation price, we make an assumption that its value is set as the *a priori* expected value of the bond minus a discount. The discount is a positive and increasing function of the announced amount to be auctioned $\overline{Q}$. Thus, we assume that $p^R = \overline{v} - \delta(\overline{Q})$. Substituting this expression into (3), we can re-write the latter equation as

$$\eta\sigma^2\left(\frac{Q^R}{W}\right)\left(1 - HHI\right)^{-1} = \beta s + \delta(\overline{Q}).$$

Dividing both sides by $(\eta/W)\,\sigma^2 Q^A\left(1 - HHI\right)^{-1}$ and taking logs yields:

$$log\left(\frac{Q^R}{Q^A}\right) = log\left[\frac{\beta s + \delta(\overline{Q})}{(\eta/W)\,\sigma^2\left(1 - HHI\right)^{-1}\left(\overline{Q} + \mu\right)}\right].$$

Assume that $\delta\left(\overline{Q}\right)$ is parametrized as $D_0\left(\overline{Q}\right)^{\delta_1}$. Hence, $log\left[\delta\left(\overline{Q}\right)\right] = \delta_0 + \delta_1 log\left(\overline{Q}\right)$. Using the following first-order Taylor approximations around $s = 0$ and $\mu = 0$,

$$log\left(\beta s + \delta\left(\overline{Q}\right)\right) \approx \delta_0 + \delta_1 log\left(\overline{Q}\right) + \frac{\beta s}{\delta\left(\overline{Q}\right)},$$

$$log\left(\overline{Q}+\mu\right) \approx log\left(\overline{Q}\right) + \frac{\mu}{\overline{Q}},$$

we obtain

$$log\left(\frac{Q^R}{Q^A}\right) \approx \delta_0 - \left(1-\delta_1\right) log\left(\overline{Q}\right) - log\left(\eta\right) + log\left(W\right) + log\left(1-HHI\right) - log\left(\sigma^2\right) + \left(\frac{\beta}{\delta\left(\overline{Q}\right)} s - \frac{\mu}{\overline{Q}}\right). \quad (4)$$

This expression will form the basis of our empirical analysis. Note that the demand shocks s and supply shocks μ have opposite effects on the (log of the) bid-to-cover ratio, but cannot be identified separately. In summary, according to (4), the (log of the) bid-to-cover ratio is determined by:

- the risk aversion η of the individual market participants: higher (log of) risk aversion lowers the demand for the asset.
- the aggregate amount of dealer capital W: higher (log of) dealer capital raises the demand for the asset.
- the degree of capital concentration HHI: a higher degree of capital concentration lowers the demand for the asset.
- the market volatility σ^2: a higher (log of) market volatility lowers demand.
- the announced size of the auction $\overline{Q}$: a larger expected auction lowers the bid-to-cover ratio. The effect of the auction size may be less than one-for-one, if the maximum discount $\delta\left(\overline{Q}\right)$ offered by the DMO is an increasing function of the auction size.

Some remarks are warranted. First, the model allows for credit risk: higher credit risk will result into a lower expected pay-off on the bond, i.e. $E\left[v|s\right]$ will be lower. New information reflecting worsening repayment prospects implies a lower value of s, hence reduces $E\left[v|s\right]$, which feeds into a lower value for the error term ϵ.

Second, in the special case in which all dealers have equal capital, i.e. $A_n = \eta/(W/N)$ for all n, the term $log\left(1-HHI\right)$ in the estimating equation (5) will be replaced by $\log\left(\frac{N-1}{N}\right)$. In this case, because of more competitive bidding, a larger number of primary dealers N raises the expected demand and, therefore, the bid-to-cover ratio.

Third, if in addition to assuming equal dealer capital we assume that each dealer does account for the fact that the other dealers also take their impact on the equilibrium price into account, as in the Kyle (1989) model, one can show that the term $log\left(1-HHI\right)$ in (5) should be replaced by $\log\left(\frac{N-2}{N-1}\right)$. Again, a larger number of primary dealers N raises the bid-to-cover ratio. Hence, assuming equal primary dealer capital, "full rationality" of primary dealers yields predictions that are qualitatively identical to those when primary dealers are myopic in the sense of ignoring other primary dealers taking into account their effect on the equilibrium price.

4. The data

Our data cover Germany, France, Belgium, Spain and Italy in the period from 1 January 1999 until 31 December 2017. From Bloomberg and from the websites of the national DMOs we collect data on auctions of sovereign bonds with maturities of 2, 5, 10 and 30 years. We exclude foreign currency debt and inflation-linked debt from our analysis, so as to have a relatively homogeneous sample of auctions, in particular to avoid having to deal with complications in terms of exchange-rate risk and inflation risk that might affect bid-to-cover ratios of different types of instruments in systematically different ways. For Belgium and Spain we also exclude the 2-year maturity from the analysis, because the number of 2-year auctions is very low.

The bid-to-cover ratio is normally measured as the total amount bid over the volume that is actually allotted. This is the bid-to-cover ratio that is reported by the media, and we term this the "*ex-post* bid-to-cover ratio". The actual allotment will in the sequel be referred to as the "*ex-post* supply" (Q^A in the theoretical model). However, as explained in Section 2, the amount allotted may respond to how the auction proceeds. For example, DMOs may choose to restrict the amount they allot if the bidding volume is lower than expected. Such reductions in the supply would inflate the bid-to-cover ratio at moments when demand is low. We can correct for this potential endogeneity effect in the bid-to-cover ratio by calculating the bid-to-cover ratio as the ratio of the total amount bid over the target volume (henceforth, the "*ex-ante* supply", $\overline{Q}$ in the theoretical model) that the DMO announces *prior* to the auction. We term this the "*ex-ante*" bid-to-cover ratio. In those cases where the DMO announces a target range, the *ex-ante* supply is the upper bound on the target range and we calculate the *ex-ante* bid-to-cover using this value of the *ex-ante* supply.

Fig. 1 shows the *ex-post* bid-to-cover ratios for our sample countries over the sample period. The bid-to-cover ratios are on average reasonably stable over time, except for Italy and, to a lesser extent, in France, where the bid-to-cover ratios decrease somewhat over the sample period. Table 2 reports summary statistics for the bid-to-cover ratios. The standard deviation of the bid-to-cover ratio ranges from 0.32 to 1.38, while the difference between the maximum and minimum values exceeds 4 in multiple cases. Table 3 shows descriptive statistics for demand and the target supply at the auctions. We see that the standard deviation of auction demand in all cases exceeds the standard deviation of the amount supplied. Germany features the highest standard deviations of demand and supply and Belgium the lowest, which is likely the result of German debt issues on average being the largest and the Belgian on average being the smallest.

We collect data on secondary market sovereign and corporate bond yields from Datastream. Sovereign bond yields are available for all countries and maturities. Fig. 2 shows that yields exhibit a general downward trend, although there have been moments in

Table 2
Descriptive statistics of *ex-post* bid-to-cover ratios.

	Observations	Mean	Maximum	Minimum	Standard deviation
Germany					
2-Year	172	2.03	5.84	1.07	0.70
5-Year	142	1.77	4.26	1.02	0.53
10-Year	167	1.64	4.12	1.06	0.57
30-Year	59	1.57	2.69	1.04	0.38
France					
2-Year	143	3.40	8.39	1.55	1.38
5-Year	195	2.61	7.55	1.33	0.93
10-Year	194	2.40	5.28	1.39	0.70
30-Year	75	2.44	8.99	1.41	1.07
Belgium					
2-Year	NA	NA	NA	NA	NA
5-Year	70	2.24	8.48	1.13	1.04
10-Year	111	1.98	5.12	1.14	0.63
30-Year	40	2.05	5.44	1.12	0.84
Italy					
2-Year	240	2.07	5.25	1.03	0.69
5-Year	236	1.70	3.10	1.00	0.42
10-Year	223	1.57	4.09	1.07	0.32
30-Year	86	1.70	3.75	1.00	0.41
Spain					
2-Year	NA	NA	NA	NA	NA
5-Year	185	2.33	4.94	1.33	0.74
10-Year	180	2.22	7.11	1.20	0.76
30-Year	79	2.08	5.46	1.10	0.71

Table 3
Descriptive statistics of actual demand and *ex-post* actual supply.

	Demand		Supply	
	Mean	Standard deviation	Mean	Standard deviation
Germany				
2-Year	9.95	4.85	4.84	1.33
5-Year	7.55	3.64	4.19	1.26
10-Year	7.56	4.24	4.50	1.53
30-Year	3.63	2.70	2.25	1.48
France				
2-Year	7.17	2.20	2.38	1.07
5-Year	7.02	2.24	3.00	1.26
10-Year	8.48	2.47	3.78	1.42
30-Year	3.31	1.75	1.49	0.78
Belgium				
2-Year	NA	NA	NA	NA
5-Year	1.88	0.71	0.89	0.31
10-Year	2.30	0.88	1.22	0.44
30-Year	1.38	0.60	0.74	0.33
Italy				
2-Year	4.30	1.18	2.24	0.79
5-Year	4.06	1.35	2.51	0.93
10-Year	4.23	1.18	2.76	0.83
30-Year	2.47	1.13	1.50	0.67
Spain				
2-Year	NA	NA	NA	NA
5-Year	3.41	1.39	1.62	0.87
10-Year	3.09	1.23	1.52	0.74
30-Year	1.58	0.75	0.84	0.46

Notes: Demand and supply are measured in billions of euros.

2011 and 2012 when yields for Belgium and Italy peaked at high levels. For the corporate bond yields we use the Merill Lynch euro-area corporate bond index, which we depict in Fig. 3. The largest peaks occur shortly after the fall of Lehman Brothers.

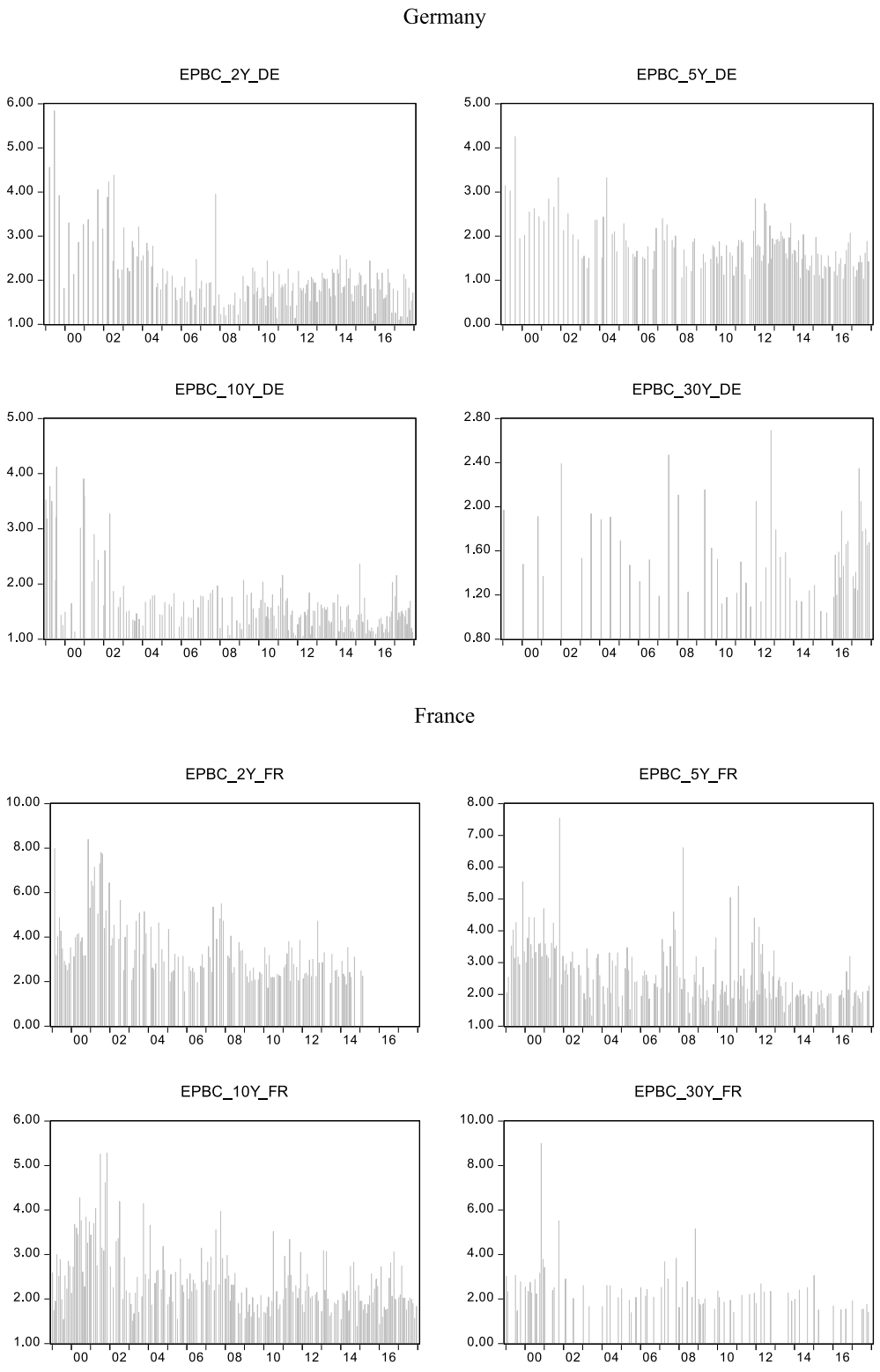

Fig. 1. *Ex-post* bid-to-cover ratios. *Notes*: this figure shows the *ex-post* bid-to-cover ratios. From left-to-right and from above to below the charts are based on the 2-year (if available), 5-year, 10-year and 30-year auctions, respectively.

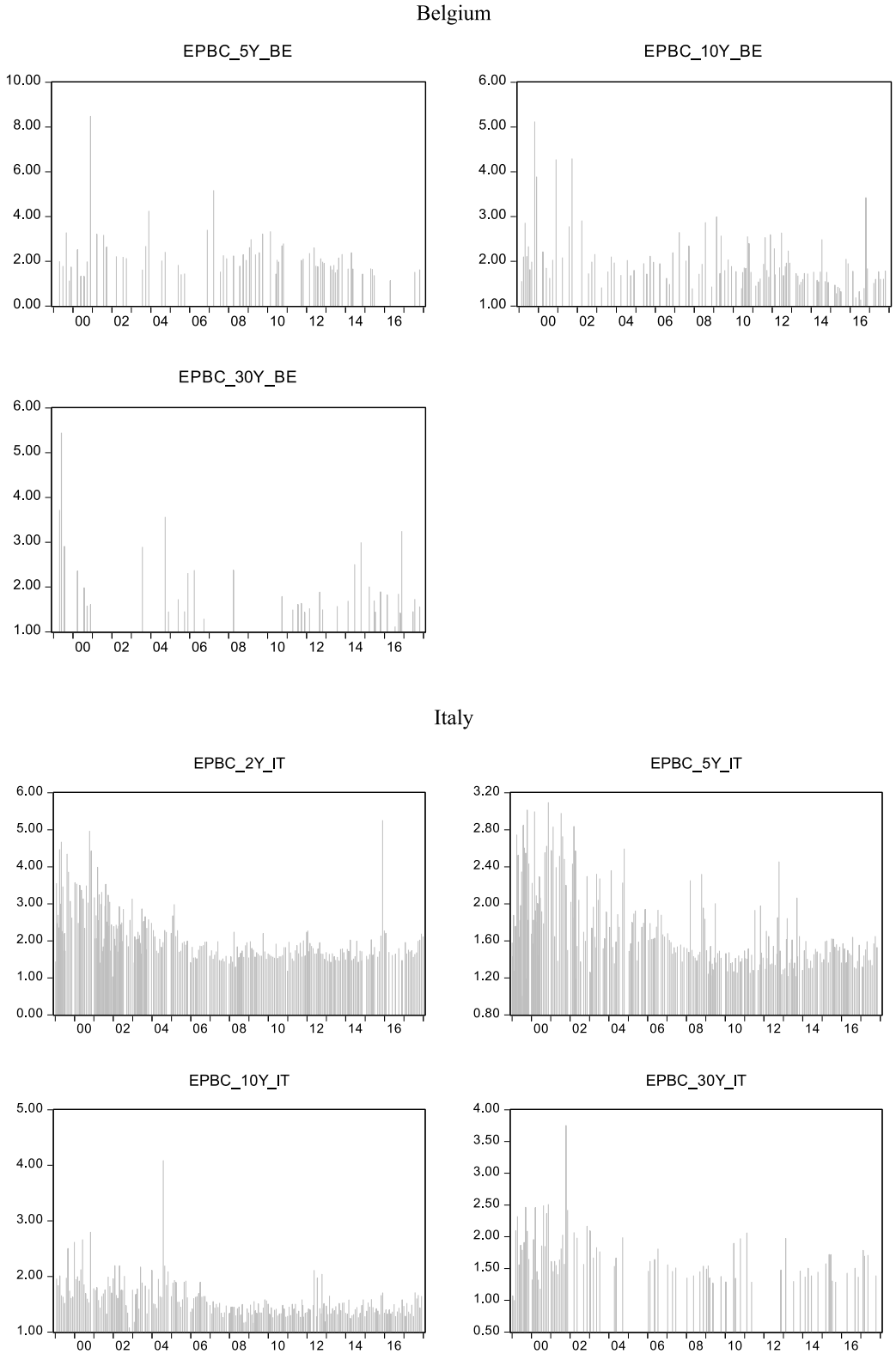

Fig. 1. (*continued*).

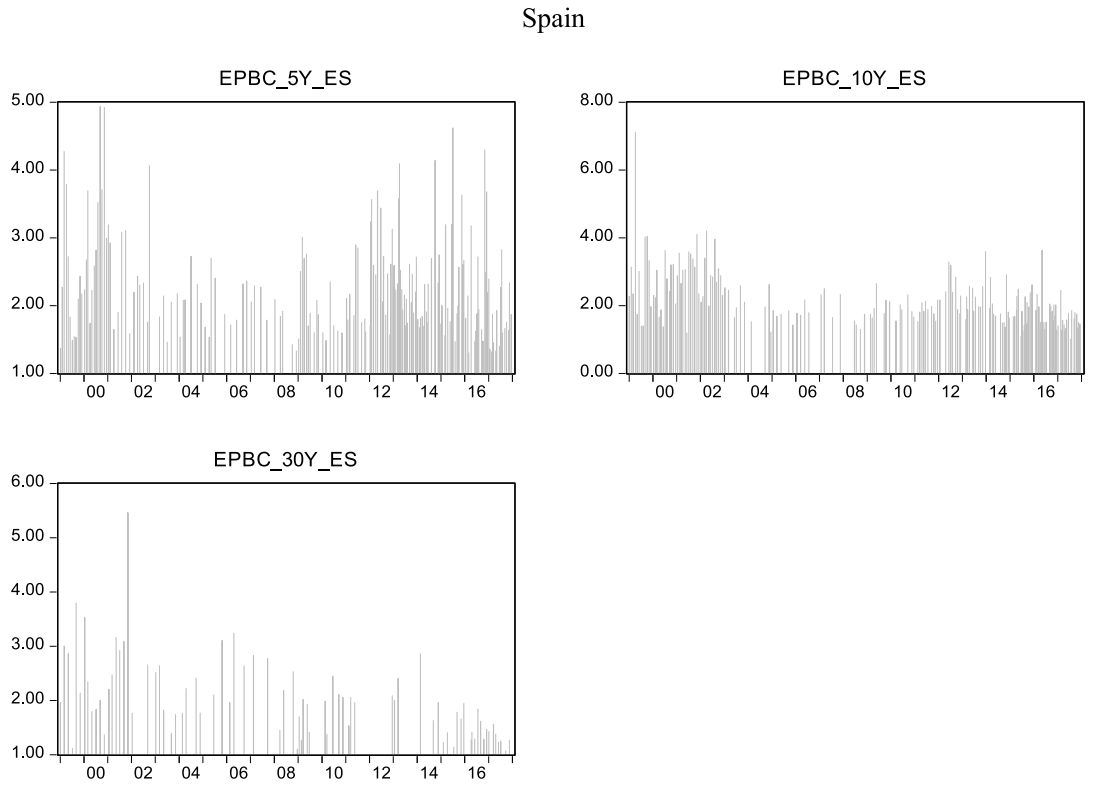

Fig. 1. (*continued*).

From Datastream we also obtain implied volatilities of bund future options traded on Eurex. The futures have as underlying value a hypothetical German 10-year bond with 6% coupon, so the futures price is essentially the price of this bond. The options are then short maturity (1 month, or so) call and put options on that futures price. Datastream reports the implied volatilities of at-the-money calls and puts. As the data are somewhat noisy, we use as our measure of market volatility a five-day moving the average of the implied volatilities of the call and the put. Market volatility fluctuates substantially and reaches high peaks in the period 2011–2012. As an alternative volatility measure, we calculate the 20-day rolling standard deviation of daily yield changes. The advantage of using the implied volatilities of the options is that they are forward-looking and, hence, capture the uncertainty over the period shortly before and until after the auction. The advantage of the other measure is that it is country-specific and that it measures the uncertainty about the return on the specific debt issued by the country itself. The two measures are depicted in Fig. 4. High volatility periods largely coincide across the different panels of Fig. 4.

Further, we gather data on the annual funding target of the government, which we will use as an instrument in one of the regressions. It is based on the government deficit, the amount of government debt that needs to be rolled over and the desired mutation in the cash balances. We collect vintage (real-time) data of the European Commission's forecast of the budget surplus in the fall of the preceding year from the FIRSTRUN database. This forecast is in the information set of the DMO when it prepares the debt issuance outlook for the consecutive year. The FIRSTRUN-database is only available from 2005 onwards, so we also collect data from the original documentation of the European Commission for the years before 2005.[11] Fig. 5 depicts for each country the government budget surplus by calendar year. We observe that the deficit volumes of France and Spain are shrinking towards the end of the sample period, while that of Germany is even turning into a surplus. Finally, we use Datastream to collect data from the ECB on monthly redemptions of sovereign bonds with an initial maturity of above 1 year. Fig. 6 shows for each country the total volume of redemptions by calendar year. Obviously, this variable depends on the size and maturity of the outstanding debt. Hence, the volume of redemptions is smallest for Belgium, but generally largest for Italy, even though the Italian economy is substantially smaller than that of Germany. Redemption patterns are generally rather irregular. For France, they are upward trending, while Spain has a substantial concentration of redemptions towards the end of the sample. German redemptions are upward trending during the first part of the sample, but falling towards the end, which may be explained by the improving government balances since 2010. This has reduced the need to issue debt that would have to be redeemed before the end of our sample.

Finally, we gather data on the primary dealers of the sample countries. From the Association for Financial Markets in Europe (2017) and with the help of the debt management offices of the sample countries we collect the lists of the primary dealers in

[11] We use GDP data to express the budget surplus in euros. We do not have vintage data on GDP for the years 1999–2005, so for these years we use *ex-post* GDP values to construct the budget surplus in euros.

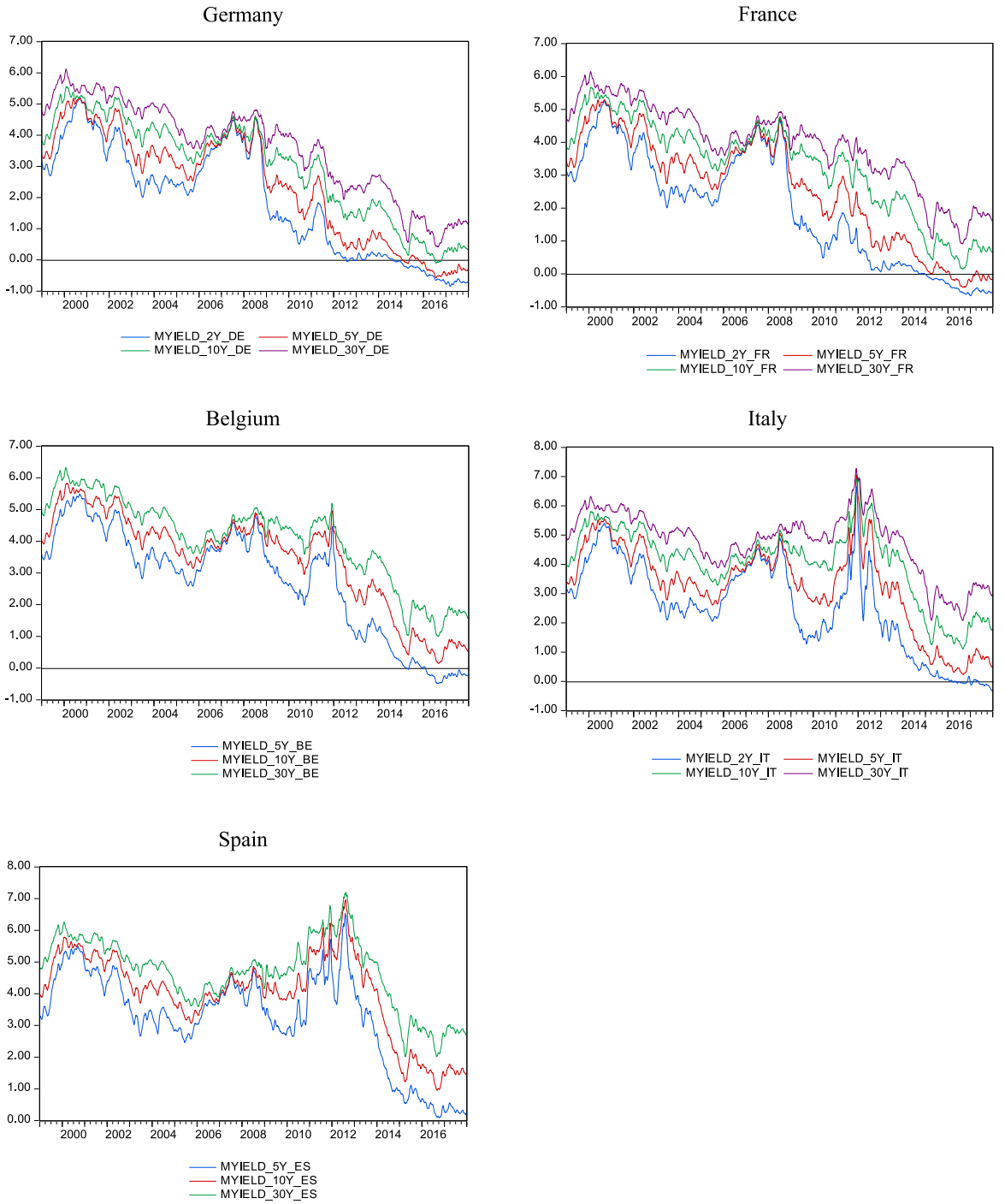

Fig. 2. Secondary market yields. *Notes*: this figure shows the 20-day moving average of secondary market bond yields.

each sample year. From this we construct for each (country, year) – combination the number of primary dealers $N_{i,t}$, which is depicted in Fig. 7. We also construct total dealer wealth and the Herfindahl – Hirschman index, which requires a measure of wealth of the individual primary dealers. One possibility is to proxy dealer wealth with dealer trading capital. However, we do not avail of high-frequency data on dealer trading capital and, besides this, the question is whether this is the most appropriate measure, as there is the possibility of internal capital transfers between the various branches of financial institutions. Hence, the value of a primary dealer's equity seems to be the more relevant quantity, as is also argued by He and Krishnamurthy (2013) and He et al. (2017). These considerations result in a country's total primary dealer wealth $W_{i,t}$ calculated as $W_{i,t} = E_{i,t} = \sum_{n=1}^{N_{i,t}} E_{n,i,t}$, where

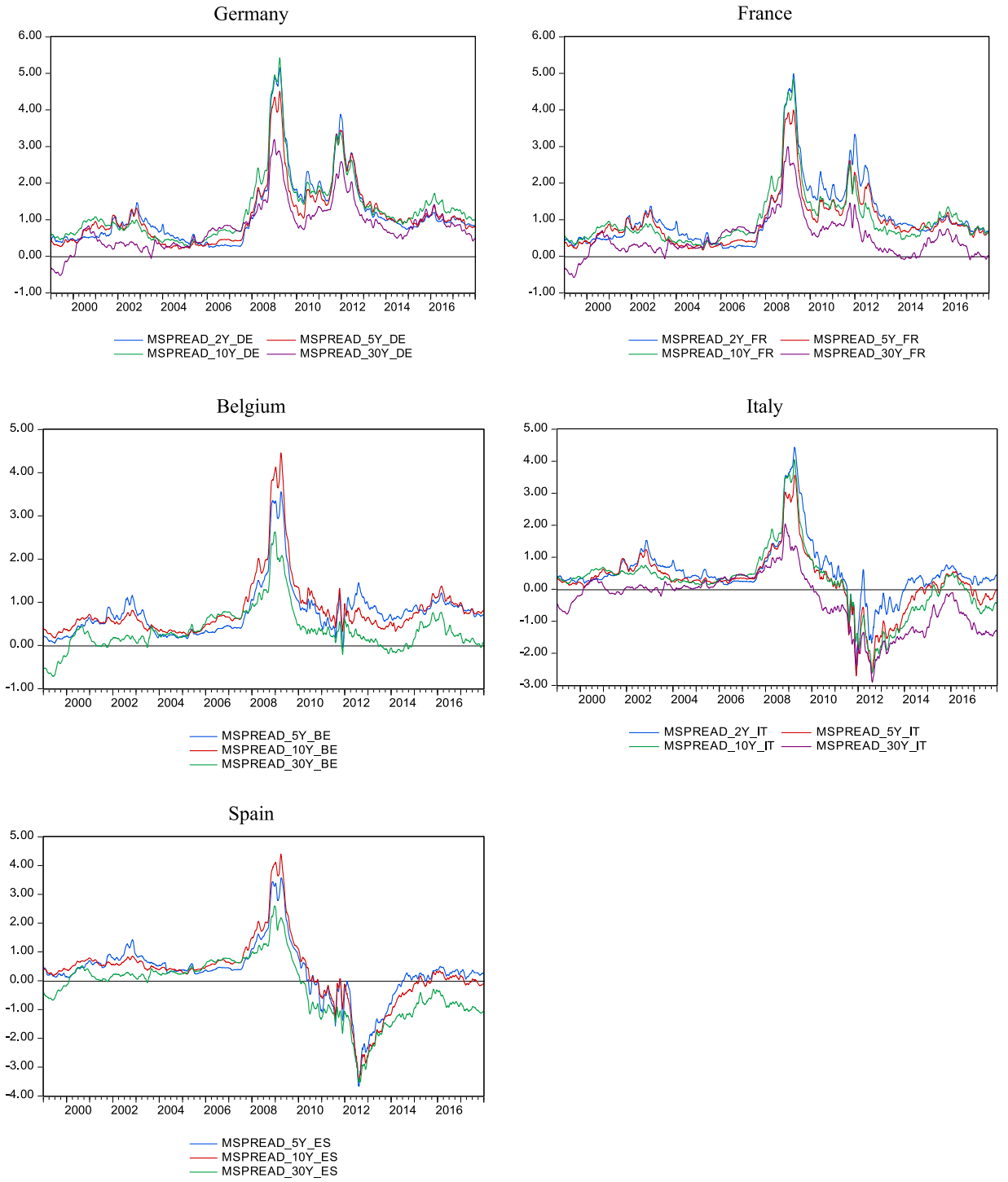

Fig. 3. Corporate bond spreads. *Notes*: this figure shows the 20-day moving average of corporate bond spreads.

$E_{n,i,t}$ is the market value of the equity of the *nth* primary dealer of country i in period t and $E_{i,t}$ is the aggregate market value of the equity of all primary dealers of country i in period t. The Herfindahl–Hirschman index for country i at date t is calculated as

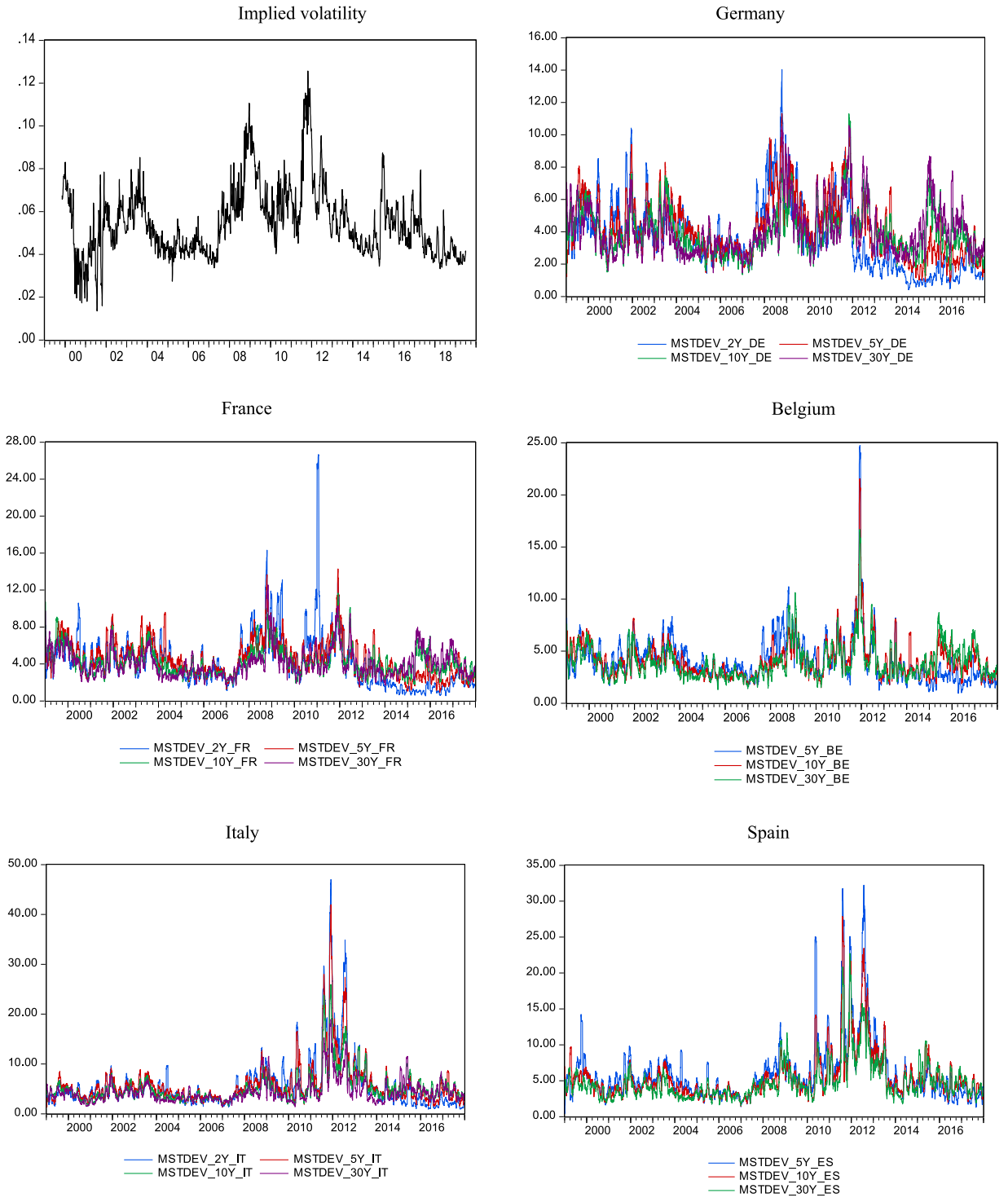

Fig. 4. Implied volatility and rolling standard deviation of country yield changes.

$HHI_{i,t} = \sum_{n=1}^{N_{i,t}} \left(E_{n,i,t}/E_{i,t}\right)^2$. A disadvantage of this way of constructing $W_{i,t}$ and $HHI_{i,t}$ is that the daily market value of equity

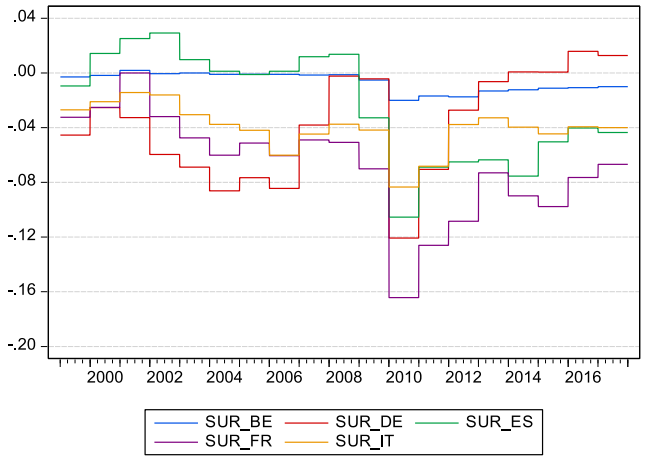

Fig. 5. Government budget surplus (in 100 billion euros).

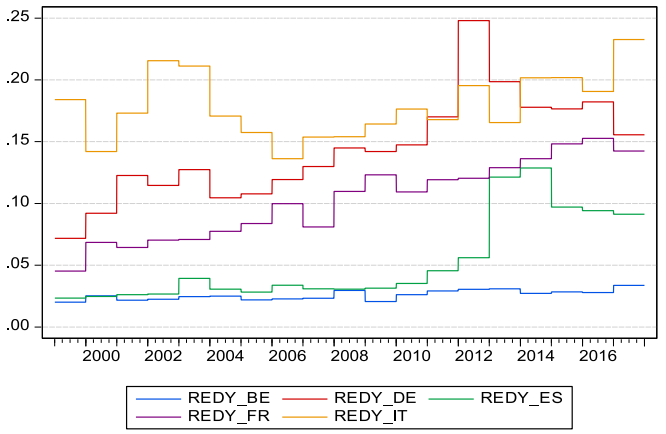

Fig. 6. Redemptions of debt with initial maturity longer than 1 year (in 100 billion euros).

is subject to substantial day-to-day fluctuations and that it is not available for all primary dealers over the whole sample.[12] Fig. 8 depicts the natural logarithm of total primary dealer wealth expressed in millions of euros and Fig. 9 the Herfindahl–Hirschman index. Both graphs exhibit a number of jumps, resulting from primary dealers moving into or out of the sample.

5. Empirical results

5.1. Baseline regression

The regression framework is based on the theoretical model presented in Section 3. Crucial in the model is the role of the primary dealers who initially buy the newly-issued debt and then sell it to other parties, such as institutional investors. The DMO establishes a reservation price that is a negative function of the amount of debt on offer. The model suggests that the bid-to-cover ratio is decreasing in (i) the aggregate risk aversion of the market participants, because more risk aversion lowers the demand for the asset, (ii) market volatility, which lowers the slope of the demand curve, and, hence, reduces the difference between the quantity on auction and the quantity bid at the reservation price, and (iii) the size of the auction, although its effect is less than one-for-one if the maximum discount offered by the debt agent is an increasing function of the auction size. The model suggests that

[12] Some primary dealers may not be listed at all, while some others may feature an incomplete series of equity values, especially early on in the sample. In those cases in which the market value of equity is missing for one or more primary dealers, we calculate $W_{i,t} = \left(N_{i,t}/M_{i,t}\right)\sum_{n=1}^{M_{i,t}} E_{n,i,t}$, where $M_{i,t}$ is the number of primary dealers for which the market value of the equity is available for country i on date t. That is, we calculate the average market value of the primary dealers for which we have the equity value at the particular point in the sample and then multiply by the actual number $N_{i,t}$ of primary dealers. For ease of notation, at each data point we order the primary dealers such that the first $M_{i,t}$ are those for which the equity value is available. We calculate the Herfindahl–Hirschman index as $HHI_{i,t} = \left(M_{i,t}/N_{i,t}\right)\sum_{n=1}^{M_{i,t}}\left(E_{n,i,t}/E_{i,t}\right)^2$. The factor $M_{i,t}/N_{i,t}$ in $HHI_{i,t}$ corrects for the fact that basing the calculation of the index on a smaller than the actual number of primary dealers drives up its value.

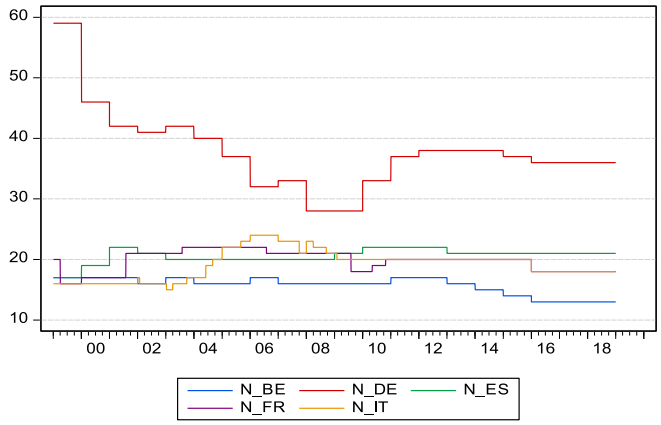

Fig. 7. Number of primary dealers.

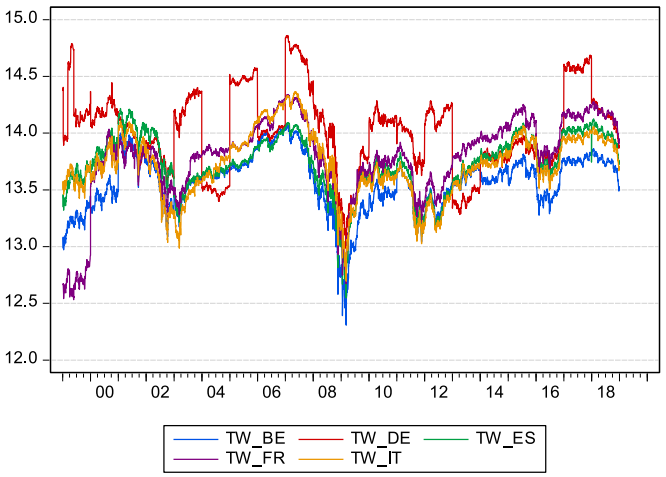

Fig. 8. Total primary dealer wealth.

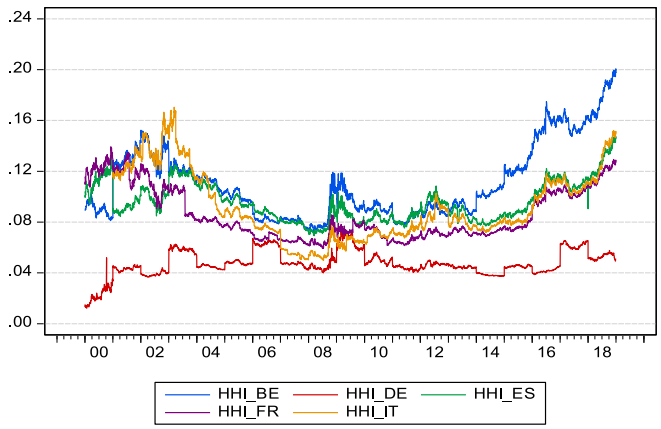

Fig. 9. HHI indices.

the bid-to-cover ratio is increasing in the amount of primary dealer wealth, as this reduces market risk aversion, and the number of primary dealers, due to decreasing oligopsony power.

In addition to the variables suggested by the theoretical framework, we include the yield level and the previous bid-to-cover ratio. In a perfect market, we would not expect the yield level to affect the bid-to-cover ratio, because the yield would reflect the market risk associated with the debt instrument. However, the current setting features an imperfect market since a limited number of primary dealers have to absorb all the newly-issued debt. In addition, in reality markets are not perfectly integrated with different investor groups being active in different markets. A general increase in yields on the public debt may attract investor capital from other markets, such as the equity market. We will indeed see that the yield level is of empirical relevance. This is also the case for the previous bid-to-cover ratio.

A positive correlation between subsequent bid-to-cover ratios may be generated in various ways. First, a policy of changing the amount of outstanding debt may be implemented over an extended period of time, thereby affecting reservation prices at subsequent auctions and thus causing subsequent bid-to-cover ratios to be correlated. In particular, the possibility of the DMO to resort to the money market to bridge the additional need for funds or to store a temporary excess of funds makes it easier for the DMO to follow such a policy. Second, market volatility and risk aversion may be difficult to measure. If, as is the case in our sample, these variables are highly persistent, their mismeasurement could result in residuals that are correlated over time. This would be picked up by a significant lagged bid-to-cover ratio. Finally, primary dealers may receive serially correlated order flows that are not perfectly observed by the DMO, causing it to set a too high or too low reservation price in the subsequent auction.

These considerations lead us to the following baseline regression:

$$BC^{p}_{i,t} = c_i + \alpha_1 Y_{i,t-1} + \alpha_2 VOL_{i,t-1} + \alpha_3 CSpread_{i,t-1} + \alpha_4 SUP^{p}_{i,t} + \alpha_5 log\left(W_{i,t-1}\right) + \alpha_6 N_{i,t} + \alpha_7 BC^{p}_{i,prev} + \varepsilon_{i,t} \quad (5)$$

where $BC^{p}_{i,t}$ is the natural logarithm of the *ex-post* bid-to-cover ratio of the auction of country *i*'s debt on day *t*, c_i is a country-specific constant, $Y_{i,t}$ is the 1-month (i.e. 20 working days) moving average of secondary market country-*i* sovereign bond yields, $VOL_{i,t}$ is our measure market volatility based on the implied volatilities of the 10-year bund future options, $CSpread_{i,t}$ is the 20-day moving average of the spread of same-maturity corporate bonds over sovereign debt of country *i* included to proxy for risk aversion, $SUP^{p}_{i,t}$ is the *ex-post* supply of the bond (i.e. the amount that is allotted at the auction) and $BC^{p}_{i,prev}$ is the *ex-post* bid-to-cover ratio of the latest ("previous") auction by country *i* of same maturity debt, which took place at day *prev*. We take a moving average of the yields over the past month in order to reduce the noise. We include the 1-day lag of this moving average, as well as of the other variables, so as to avoid potential feedback from the dependent variable onto the explanatory variables. Only the number of primary dealers $N_{i,t}$ is entered with its date *t* value, as this value is known before the auction starts. We include the number of primary dealers rather than the more general Herfindahl–Hirschman index, because unlike the latter, the number of primary dealers does not suffer from an incomplete sample nor from the noise in the daily equity valuations that affects the Herfindahl–Hirschman index. We will use the Herfindahl–Hirschman index in one of the variants on the baseline. The error term $\varepsilon_{i,t}$ may include news not captured in the explanatory variables, as well as deviations of variables from their values anticipated before the auction, as shown by the theoretical model. In order to save on notation, we omit the maturity index from the coefficients and variables, but notice that all variables are defined maturity-specifically. We will estimate the model separately for each maturity, but we may pool over the countries.

Table 4 reports the estimates of specification (6). We observe that the same-maturity secondary market is (highly) significant in many of the individual country estimates, and always in the panel estimates.[13,14] In line with the theoretical framework of Section 3, the volatility of the bond yield exerts a strongly negative effect on the bid-to-cover ratio. The corporate bond spread, an indicator of the market risk aversion, is insignificant in all panel estimations. Total primary dealer wealth hardly plays any role. It enters, contrary to the theoretical prediction, with a significantly negative coefficient for two-year debt panel. However, this estimate is driven by Germany. The coefficient on the number of primary dealers is significant in a number of individual country estimations and in the 2- and 5-year panel estimations, where it is significantly positive, in line with the theoretical prediction that more bidders imply more demand for the asset, *ceteris paribus*. However, one should not over-interpret the result, as the variation in the number of primary dealers over the sample is only limited.[15] Except in two instances, the *ex-post* supply always features a (highly) significant negative coefficient estimate, indicating that the *ex-post* bid-to-cover ratio falls as the *ex-post* supply increases. An F-test (not reported) shows that the coefficient on the *ex-post* supply, while negative, is always significantly larger than minus one, suggesting that the DMO indeed lowers its reservation price if it intends to bring more new debt to the market. Finally, we observe that the *ex-post* bid-to-cover ratio of the most recent past auction of the same maturity in most instances enters the regression with a positive sign that is frequently highly significant. In particular, it is always highly significant in the panel regressions, in which case it lies between 0.15 and 0.30, indicating quite substantial persistence. In view of the similarity of the coefficient estimates across the sample countries in many instances, we continue reporting panel estimates only. In particular, coefficient signs are mostly the same across countries, especially when the coefficient estimates are significant. In summary, the theoretical predictions of the effects of volatility and the auction supply on the bid-to-cover ratio are confirmed by our results, whereas we do not find evidence for the effects of risk aversion and weak evidence for the effects of the number of dealers.

In expression (4), the risk aversion η, total dealer wealth W, dealer wealth concentration HHI and volatility σ^2 are the values realized in the auction. However, these values may deviate from the values that are anticipated when the auction is announced. We

[13] When sec referring to a coefficient as "significant", this should be read as significantly different from zero at the 10% or higher level.

[14] A potential explanation is that an increase in Eurozone sovereign debt yields increases the attractiveness of the treasury bond market relative to other markets and generates an extra capital inflow into this market, leading to extra demand at the sovereign debt auctions.

[15] If we drop the aggregate primary dealer wealth and/or the number of primary dealers from the regressions, the estimates of the other coefficient are essentially unchanged.

Table 4
Baseline regression estimates.

$BC^p_{i,t} = c_i + \alpha_1 Y_{i,t-1} + \alpha_2 VOL_{i,t-1} + \alpha_3 CSpread_{i,t-1} + \alpha_4 SUP^p_{i,t} + \alpha_5 log\left(W_{i,t-1}\right) + \alpha_6 N_{i,t} + \alpha_7 BC^p_{i,prev} + \epsilon_{i,t}$

	Germany	France	Belgium	Italy	Spain	Panel
2-year						
Yield	0.075***	0.051***		0.016		0.050***
Volatility	−4.58***	−2.89**		−1.92*		−3.23***
Corporate spread	0.059**	0.047		0.0084		0.0085
Ex-post supply	−0.19*	−0.51***		−0.33***		−0.35***
Log(Wealth)	−0.12***	0.079		−0.069		−0.12***
Number PDs	0.026***	0.00011		−0.016**		0.0085***
Previous BC	0.078	0.27***		0.20***		0.27***
Adjusted R2	0.38	0.74		0.54		0.51
5-year						
Yield	0.11***	0.058***	0.061**	0.033***	0.00006	0.044***
Volatility	−3.52*	−1.95*	−3.47	−1.11	−2.10	−2.13***
Corporate spread	0.083**	−0.0098	0.18**	0.020**	−0.0064	0.011
Ex-post supply	−0.39***	−0.45***	−0.58***	−0.20***	−0.40***	−0.33***
Log(Wealth)	−0.063	0.025	0.31	0.16***	−0.14	−0.00033
Number PDs	0.016**	−0.00074	0.063**	−0.017***	0.047**	0.011***
Previous BC	0.20**	0.011	0.18*	0.11	0.096	0.17***
Adjusted R2	0.39	0.70	0.51	0.48	0.51	0.46
10-year						
Yield	0.070***	0.035**	0.067**	0.017**	0.039***	0.049***
Volatility	−5.09**	−1.84	−0.83	−1.78*	−3.33***	−2.71***
Corporate spread	0.056	−0.020	−0.0036	0.011	0.018	0.00096
Ex-post supply	−0.15	−0.37***	−0.25***	−0.20***	−0.35***	−0.24***
Log(Wealth)	0.018	0.093	0.047	0.038	−0.054	0.021
Number PDs	0.0077	−0.019**	−0.013	−0.0093*	0.081***	0.0021
Previous BC	0.30***	0.13**	0.14**	0.26***	0.047	0.20***
Adjusted R2	0.35	0.58	0.34	0.40	0.48	0.40
30-year						
Yield	0.048	0.088***	−0.0084	0.017	0.038	0.064***
Volatility	−1.79	−2.02	0.76	−3.03	−1.98	−1.61*
Corporate spread	0.024	0.010	−0.079	0.021	0.086***	0.018
Ex-post supply	−0.068	−0.33***	−0.26**	−0.14**	−0.31***	−0.19***
Log(Wealth)	0.044	0.099	0.30	−0.037	0.11	0.066
Number PDs	0.0018	0.024	0.020	−0.0066	0.093**	0.00047
Previous BC	0.16	0.044	−0.0011	0.29***	0.16	0.16***
Adjusted R2	−0.041	0.47	−0.010	0.25	0.43	0.29

Notes: Estimation is for the period January 1, 1999–December 31, 2017. Estimation method is Ordinary Least Squares (OLS) with Newey–West adjusted standard errors. The column under the header "Panel" reports panel OLS regressions estimated with country-fixed effects. Note that the 2-year panel estimates are always without Belgium and Spain. Further, *, ** and *** denote significance at the 10%-, 5%-, and 1%-levels, respectively. Finally, "PDs" = primary dealers.

take the distinction between the effects of the anticipated and unanticipated components of the explanatory variables as follows into account. In the literature (Lou et al., 2013; Beetsma et al., 2016, and Sigeaux, 2017) there is consensus that the auction's impact on secondary market prices starts at most five days in advance of the auction. Also, the DMOs typically announce the exact quantity to be auctioned five days before the auction. Hence, the variables at $t-5$ reflect the expectations of the market in anticipation of the auction and we include these in our next regression. We also include the changes in the yield, aggregate primary dealer wealth and the proxies for risk aversion and volatility from five days before to one day before the auction. These variables capture the news and unanticipated changes in risk aversion and volatility during the run up to the auction. This leads us to the following regression equation:

$$\begin{aligned} BC^p_{i,t} &= c_i + \alpha_1 Y_{i,t-5} + \alpha_2 VOL_{i,t-5} + \alpha_3 CSpread_{i,t-5} + \alpha_4 SUP^p_{i,t} + \alpha_5 log\left(W_{i,t-5}\right) + \alpha_6 N_{i,t} + \\ &\alpha_7 BC^p_{i,prev} + \alpha_8\left(Y_{i,t-1} - Y_{i,t-5}\right) + \alpha_9\left(VOL_{i,t-1} - VOL_{i,t-5}\right) + \alpha_{10}\left(CSpread_{i,t-1} - \right. \\ &\left. CSpread_{i,t-5}\right) + \alpha_{11}\left(log\left(W_{i,t-1}\right) - log\left(W_{i,t-5}\right)\right) + \xi_{i,t} \end{aligned} \tag{6}$$

where $VOL_{i,t-1} - VOL_{i,t-5}$, $log\left(W_{i,t-1}\right) - log\left(W_{i,t-5}\right)$ and $CSpread_{i,t-1} - CSpread_{i,t-5}$ are intended to capture unexpected changes in volatility and market risk aversion between five days and one day before the auction, while $Y_{i,t-1} - Y_{i,t-5}$ is intended to capture other news relevant to secondary market yields during the same period.[16] The mean-zero stochastic variable $\xi_{i,t}$ contains all relevant remaining news not contained in the unexpected changes in the aforementioned variables.

[16] Ideally, we would include $Y_{i,t} - Y_{i,t-5}$ instead of $Y_{i,t-1} - Y_{i,t-5}$, and correspondingly for the volatility and risk aversion variables, but this creates a danger of simultaneity bias.

Table 5
Panel regression 5-day lags and unexpected components of explanatory variables.

$BC^p_{i,t} = c_i + \alpha_1 Y_{i,t-5} + \alpha_2 VOL_{i,t-5} + \alpha_3 CSpread_{i,t-5} + \alpha_4 SUP^p_{i,t} + \alpha_5 log\left(W_{i,t-5}\right) + \alpha_6 N_{i,t} + \alpha_7 BC^p_{i,prev} + \alpha_8\left(Y_{i,t-1} - Y_{i,t-5}\right) + \alpha_9\left(VOL_{i,t-1} - VOL_{i,t-5}\right) + \alpha_{10}\left(CSpread_{i,t-1} - CSpread_{i,t-5}\right) + \alpha_{11}\left(log\left(W_{i,t-1}\right) - log\left(W_{i,t-5}\right)\right) + \xi_{i,t}$

	Unrestricted	Restricted ($\alpha_8 = .. = \alpha_{11} = 0$)	Unrestricted	Restricted ($\alpha_8 = .. = \alpha_{11} = 0$)
	2-year		5-year	
Yield(-5)	0.051***	0.050***	0.044***	0.044***
Volatility(-5)	−3.19***	−3.20***	−2.25***	−2.08***
Corp. spread(-5)	0.0074	0.0075	0.012	0.012
Ex-post supply	−0.36***	−0.36***	−0.33***	−0.33***
Log(Wealth(-5))	−0.12***	−0.12***	−0.0021	−0.0011
Number of primary dealers	0.0085***	0.0085*	0.011***	0.011***
Previous BC	0.27***	0.27***	0.17***	0.17***
Yield(-1) - Yield(-5)	−0.063		0.066	
Volatility(-1) - Volatility(-5)	−2.35		−1.50	
Corp. spread(-1) - Corp. spread(-5)	−0.039		−0.014	
Log(Wealth(-1))- Log(Wealth(-5))	−0.069		0.094	
Adjusted R2	0.52	0.51	0.47	0.46
	10-year		30-year	
Yield(-5)	0.049***	0.050***	0.063***	0.064***
Volatility(-5)	−2.96***	−2.39***	−2.06**	−2.03**
Corp. spread(-5)	0.0025	0.00062	0.020	0.020
Ex-post supply	−0.24***	−0.24***	−0.19***	−0.19***
Log(Wealth(-5))	0.013	0.027	0.031	0.054
Number of primary dealers	0.0019	0.0016	0.0011	0.00058
Previous BC	0.20***	0.19***	0.15***	0.15***
Yield(-1) - Yield(-5)	0.19**		0.21	
Volatility(-1) - Volatility(-5)	−3.26**		2.68	
Corp. spread(-1) - Corp. spread(-5)	0.11		0.32	
Log(Wealth(-1))- Log(Wealth(-5))	0.047		−0.28	
Adjusted R2	0.41	0.40	0.33	0.29

Notes: See *Notes* Table 4.

Note that the estimates of coefficients $(\alpha_1, \ldots, \alpha_7)$ can help to explain the demand in the auction on the basis of information available to the DMO *when* it decides on the details of the auction. Hence, these estimates may help the DMO in devising an optimal strategy for its auction activity, which concerns such choices as the amount of debt to be brought to the market at an auction given the current market conditions.

Table 5 reports the panel estimates of (7). We observe that the estimates of the coefficients of the variables known when the auction details are announced are very similar to the panel estimates in Table 4. The estimates of the coefficients on the unexpected components of the bid-to-cover determinants are always insignificant, except for the case of 10-year debt. Here, a rise in the yield during the run-up to the auction, $Y_{i,t-1} - Y_{i,t-5}$, improves the bid-to-cover ratio, while a rise in volatility during the run up, $VOL_{i,t-1} - VOL_{i,t-5}$, lowers the bid-to-cover ratio. This latter effect is in line with the prediction of our theory. Table 5 also reports the estimates of (7) when we restrict the coefficients on the unanticipated (at the moment of the auction announcement) components of the explanatory variables to zero, i.e. we set $\alpha_8 = .. = \alpha_{11} = 0$. The estimates of the coefficients on the remaining variables are very close to those in the previous column.

In view of the close similarity of the estimates in Table 5 to those of the panel estimates reported in the final column of Table 4, we stick to the model in (6), i.e. the specification with 1-day lagged explanatory variables, as the starting point for the ensuing robustness analysis and the extensions reported later.

5.2. Robustness

Our first robustness variant replaces the *ex-post* bid-to-cover ratio and the *ex-post* supply with their *ex-ante* counterparts, so the estimating equation becomes:

$$BC^a_{i,t} = c_i + \alpha_1 Y_{i,t-1} + \alpha_2 VOL_{i,t-1} + \alpha_3 CSpread_{i,t-1} + \alpha_4 SUP^a_{i,t} + \alpha_5 log\left(W_{i,t-1}\right) + \alpha_6 N_{i,t} + \alpha_7 BC^p_{i,prev} + \varepsilon_{i,t} \quad (7)$$

where $BC^a_{i,t}$ and $SUP^a_{i,t}$ are the *ex-ante* counterparts to $BC^p_{i,t}$, respectively $SUP^p_{i,t}$. Also, a variant of (8) is estimated in which the right-hand side variables dated $t-1$ become dated to $t-5$. The construction of the *ex-ante* measures requires some detailed explanation. Before the auction DMOs announce a target supply or a target range for the supply. In the latter case, our measure of the *ex-ante* supply is always the upper end of the target range. DMOs also often issue debt of more than one maturity on a given auction date. Moreover, we observe that DMOs deploy a large set of different combinations of maturities on auction days. The complication here is that the Belgian and French DMOs announce only target ranges for the total amount of debt to be issued on the auction day, but not

Table 6
Panel estimates with *ex-ante* supply and bid-to-cover ratio.

$BC^a_{i,t} = c_i + \alpha_1 Y_{i,t-l} + \alpha_2 VOL_{i,t-l} + \alpha_3 CSpread_{i,t-l} + \alpha_4 SUP^a_{i,t} + \alpha_5 log\left(W_{i,t-l}\right) + \alpha_6 N_{i,t} + \alpha_7 BC^p_{i,prev} + \epsilon_{i,t}$

	1-day lagged ($l = 1$)	5-day lagged ($l = 5$)
2-year		
Yield	0.052***	0.051***
Volatility	−3.58***	−3.46***
Corporate spread	0.015	0.012
Ex-ante supply	−0.34***	−0.35***
Log(Wealth)	−0.12***	−0.12***
Number of primary dealers	0.011***	0.011***
Previous BC	0.30***	0.30***
Adjusted R2	0.49	0.49
5-year		
Yield	0.058***	0.058***
Volatility	−2.91***	−2.49***
Corporate spread	0.026**	0.026**
Ex-ante supply	−0.26***	−0.26***
Log(Wealth)	0.033	0.042
Number of primary dealers	0.0051	0.0047
Previous BC	0.17***	0.17***
Adjusted R2	0.35	0.34
10-year		
Yield	0.052***	0.052***
Volatility	−3.02***	−2.44***
Corporate spread	−0.00048	−0.0023
Ex-ante supply	−0.22***	−0.23***
Log(Wealth)	0.028	0.042
Number of primary dealers	−0.00027	−0.00086
Previous BC	0.23***	0.23***
Adjusted R2	0.30	0.30
30-year		
Yield	0.083***	0.083***
Volatility	−2.12*	−1.92
Corporate spread	0.024	0.022
Ex-ante supply	−0.21***	−0.21***
Log(Wealth)	−0.0094	−0.0086
Number of primary dealers	−0.0078	−0.0078
Previous BC	0.10	0.099
Adjusted R2	0.24	0.23

Notes: See *Notes* Table 4.

for the individual maturities on issue. Hence, we construct the *ex-ante* supply using information on previous auctions. Specifically, for a particular maturity under consideration (2-, 5-, 10- or 30-year), we calculate the moving-average actual allotment over the past 12 months for auctions of this maturity, which we then divide by the sum of the corresponding moving-average allotments of all maturities on the current auction day. This number is multiplied by the announced target volume (or upper end of the target range) for the current auction day, to get to an estimate of the *ex-ante* supply for that maturity on the current day.[17] The results of this robustness exercise are found in Table 6. The estimates remain rather close to the estimates based on the *ex-post* measures, suggesting that endogenous supply adjustments during the auction in response to developments on the demand side can only be of minor importance. As before, the yields are always highly significant. Again, volatility tends to exert a (highly) significant negative effect on the bid-to-cover ratio and so does the supply, while the previous bid-to cover ratio exerts a highly significantly positive effect, except for 30-year debt for which it now loses significance. Further, the corporate spread now has a significantly-positive coefficient for the 2- and 5-year debt in the panel estimation, a result for which we have no intuitive explanation, suggesting it may be a statistical coincidence. The panel estimates for the 5-day lagged version, reported in the final column of Table 6, are almost perfectly identical to those reported in the previous column.

As our second robustness we estimate equation (6) instrumenting $SUP^p_{i,t}$ with the forecast of the government surplus and the volume of redemptions of the year in which date t falls. We expect both variables to be good instruments for the *ex-post* supply. We might expect that the *ex-post* supply is increasing in the amount of redemptions and decreasing in the government's surplus.

[17] For example, suppose that on a given day t there will be an auction of 5- and 10-year debt, and that the DMO announces a target volume of 10 billion for the two maturities together. The average amount of 5-year debt allotted over all auctions in the past 12 months in which 5-year debt was issued is 2 billion, while the average amount of 10-year debt allotted over all auctions in the past 12 months in which 10-year debt was issued is 6 billion. Then, the estimated *ex-ante* supply of 5-year debt is [2/(2 + 6)]*10 billion = 2.5 billion, while the *ex-ante* supply of 10-year debt is [6/(2 + 6)]*10 billion = 7.5 billion.

Table 7
Panel estimates of further robustness variants on baseline.

	Instrumental variables	PVS replaces corporate spread	Time trends added	As of July 2009	Alternative vol. measure	HHI replaces Number of PDs
2-year						
Yield	0.049***	0.051***	0.0052	0.024*	0.054***	0.048***
Volatility	−3.23***	−3.10***	−2.63***	−2.57***	−0.0075***	−2.92***
Corporate spread	0.0056		0.0024	0.038**	−0.011	0.0018
PVS		−0.063**				
Ex-post supply	−0.26***	−0.38***	−0.42***	−0.38***	−0.36***	−0.34***
Log(Wealth)	−0.12***	−0.084**	−0.099***	−0.13***	−0.079**	−0.11***
Number PDs	0.0065*	0.0099***	0.0030	−0.00090	0.010***	
HHI						0.31
Previous BC	0.30***	0.27***	0.21***	0.052	0.29***	0.28***
Adjusted R2	0.51	0.53	0.57	0.30	0.52	0.51
5-year						
Yield	0.047***	0.044***	0.027***	0.049***	0.047***	0.044***
Volatility	−2.06***	−1.94***	−2.18***	−2.15***	−0.011***	−2.01***
Corporate spread	0.0094		0.018*	0.078***	−0.0064	0.0072
PVS		−0.027				
Ex-post supply	−0.11*	−0.34***	−0.37***	−0.39***	−0.32***	−0.32***
Log(Wealth)	−0.0082	0.030	−0.0081	−0.044	0.00071	0.0057
Number PDs	0.0037	0.011***	0.0060**	0.0013	0.013***	
HHI						−0.089
Previous BC	0.22***	0.18***	0.12***	0.093***	0.18***	0.18***
Adjusted R2	0.35	0.47	0.52	0.49	0.43	0.45
10-year						
Yield	0.050***	0.050***	0.24***	0.032***	0.050***	0.051***
Volatility	−2.78***	−2.76***	−2.33***	−1.31**	−0.011***	−2.55***
Corporate spread	0.00071		−0.00085	0.013	−0.013*	0.00037
PVS		−0.034				
Ex-post supply	−0.14***	−0.24***	−0.29***	−0.25***	−0.26***	−0.23***
Log(Wealth)	0.018	0.057*	0.0078	−0.0017	0.062**	0.028
Number PDs	0.00054	0.0031	−0.0016	−0.0053	0.0077***	
HHI						0.48
Previous BC	0.22***	0.19***	0.18***	0.13***	0.20***	0.19***
Adjusted R2	0.38	0.40	0.44	0.23	0.40	0.40
30-year						
Yield	0.065***	0.064***	0.039*	0.054***	0.067***	0.066***
Volatility	−1.60*	−1.41	−1.38	−1.63	−0.0061	−1.36
Corporate spread	0.019		0.021	0.031	0.013	0.019
PVS		−0.041				
Ex-post supply	−0.20***	−0.18***	−0.22***	−0.26***	−0.20***	−0.18***
Log(Wealth)	0.066	0.12*	0.067	0.059	0.11**	0.072
Number PDs	0.0010	−0.00001	0.00095	0.0063	0.0014	
HHI						0.71
Previous BC	0.15***	0.15***	0.14***	0.17**	0.13***	0.15***
Adjusted R2	0.31	0.26	0.34	0.22	0.30	0.29

Notes: See *Notes* Table 4. In the instrumental variables regression, we instrument $SUP^{p}_{i,t}$ with the surplus and the volume of redemptions (expressed in euros) of the year in which date t falls. "Alternative vol. measure" refers to the measure based on the 20-day rolling standard deviation of daily yield changes.

Moreover, since we confine ourselves to redemptions of bonds with an initial maturity of above one year, the volume of the redemptions for year t is known at the start of year t, and, hence, can be treated as exogenous. Similarly, the government surplus is a slow-moving variable that is unlikely to be affected in the short-run by the bid-to-cover ratio. Moreover, since we use European Commission forecasts from the fall of the year before, the absence of feedback effects from the bid-to-cover ratio to the surplus should be beyond any reasonable doubt. The first column of Table 7 reports the results. These are similar to those for the baseline. Only the number of primary dealers becomes less significant for 2-year debt, while the variable loses significance entirely for 5-year debt. Also, the estimates of the coefficient on the *ex-post* supply are in absolute value slightly smaller for the 5- and 10-year maturities.

Our third robustness variant replaces the corporate bond spread as an indicator of risk aversion by an alternative indicator recently developed by Pflueger et al. (2018), which measures the macroeconomic risk appetite as the difference in stock market valuation between high volatility and low volatility stocks. The measure is labeled the "PVS" ("price volatile stocks").[18] Fig. 10 depicts the PVS. There is a clear downward peak in the first half year of 2009, suggesting a period of particularly low risk appetite. Unfortunately, the PVS is only available at the quarterly frequency and up to the second quarter of 2016, hence the sample is shortened by one-and-a-half years. The results are again reported in Table 7. The coefficient estimates of the baseline variables

[18] As (almost *verbatim*) described in Pflueger et al. (2018), each quarter stocks are classified into quintiles based on their volatility during the quarter. PVS is the difference between the average book-to-market ratio of stocks in the lowest quintile of volatility and that in the highest quintile of volatility. Hence, when market valuations are high, book-to-market ratios are low and, hence, PVS is high when the price of high-volatility stocks is high relative to low-volatility stocks.

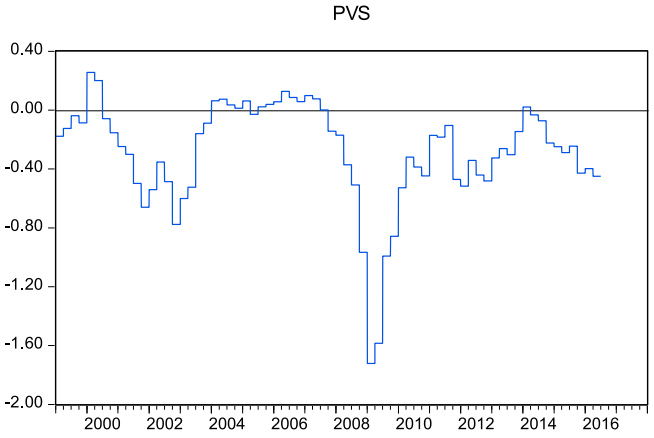

Fig. 10. PVS.

remain essentially the same, while those of PVS are always insignificant, except for two-year debt in which case it is significantly negative at the 5% level, which is counterintuitive, as it predicts that lower risk appetite raises the bid-to-cover ratio. However, overall the role of PVS appears to be only minor in the regressions. The number of primary dealers is highly significant again for the 2- and 5-year debt.

Fourth, we explore whether the significance of the yield in the regressions is not an artifact resulting from simultaneous trend declines in the yield itself and the bid-to-cover ratio. We do this by including a time trend into baseline regression (6). Table 7 shows that the yield is no longer significant for 2-year debt, while it remains (highly) significantly positive for the other maturities. The coefficients of the other variables remain essentially unchanged. Hence, overall the role of the yield weakens, but it remains relevant. The role of the number of primary dealers for 2- and 5-year debt becomes insignificant or also weakens.

As our fifth robustness variant, we investigate whether the results change if we confine the estimation to the period of the Eurozone sovereign debt crisis. The debt crisis erupted in full earnest in April and May 2010. However, this period was preceded by the revelation by Greece that its deficit for 2009 would be substantially higher than what was originally foreseen. Following the revelation, worries about Greece gradually started to mount. Hence, we re-estimate our baseline specification for the period as of July 2009. The results are again found in Table 7. Maybe not surprisingly in view of the lower numbers of observations, the results weaken somewhat, although they generally remain well in line with the baseline estimates. The yield level still has a positive and significant effect, but volatility loses significance for the 30-year debt. The previous bid-to-cover ratio loses significance for the 2-year debt, while the number of primary dealers loses significance for both the 2- and the 5-year debt. The corporate spread becomes significantly positive for the 2-year and the 5-year, a result for which we have no obvious explanation.

In our sixth robustness variant we replace our option-based volatility measure with the alternative measure based on the 20-day rolling standard deviation of daily yield changes. The panel estimates are reported in the next-to-final column of Table 7. The significance of the volatility vanishes for 30-year debt, but overall the results are essentially the same as under the baseline.

In our final robustness variant we replace the number of primary dealers with the (one-period lagged) Herfindahl–Hirschman Index. While the coefficient estimates of the other variables are very similar to those under the baseline, the Herfindahl–Hirschman Index is never significant. This may not be surprising in view of the noise in daily equity market valuations and the incompleteness of the equity data needed to construct the index.

In summary, these robustness checks confirm our main findings: the yield and previous bid-to-cover ratio exert a positive effect on the bid-to-cover ratio, volatility and the auction supply have a negative effect, whereas we do not find evidence for the effects of risk aversion and a weak or no effect for the measures of market concentration.

5.3. Extensions

This subsection explores extensions of the baseline regression. First, we include the most recent foreign bid-to-cover ratio in the regression in order to investigate the potential presence of cross-border spill-overs in auction demand. Second, we control for changes in the national central bank holdings of Eurozone general government debt.

5.3.1. Spillovers of foreign auctions

Previous research (see Beetsma et al., 2018b) has revealed cross-border spill-over effects of Eurozone sovereign debt auctions on secondary markets of other Eurozone countries.[19] It is therefore natural to explore whether a given country's bid-to-cover ratio

[19] There exists a literature on cross-border spillovers in sovereign bond markets. Ang and Longstaff (2013) and Battastini et al. (2014), for example, analyze common risk factors in the euro area, while Baele et al. (2013) demonstrate "flight-to-safety" effects towards countries with solid fundamentals in the euro area. See, further, Bhanot et al. (2014), Claeys and Vašiček (2014) and Brutti and Sauré (2015).

Table 8
Extensions — panel estimates.

	Adding foreign bid-to-cover ratio	Adding central bank gen. govt. debt holdings
2-year		
Yield	0.043***	0.048***
Volatility	−2.99***	−3.14***
Corporate spread	0.0070	0.0074
Ex-post supply	−0.34***	−0.36***
Log(Wealth)	−0.12***	−0.12***
Number of PDs	0.0091***	0.0084**
Previous BC	0.25***	0.27***
Foreign BC	0.090**	
Holdings change lagged		−0.042
Adjusted R2	0.52	0.52
5-year		
Yield	0.041***	0.039***
Volatility	−1.98***	−1.91***
Corporate spread	0.0094	0.011
Ex-post supply	−0.33***	−0.34***
Log(Wealth)	−0.00029	0.011
Number of PDs	0.011***	0.011***
Previous BC	0.17***	0.17***
Foreign BC	0.043	
Holdings change lagged		−0.11*
Adjusted R2	0.47	0.47
10-year		
Yield	0.043***	0.051***
Volatility	−2.47***	−2.76***
Corporate spread	−0.0025	0.0010
Ex-post supply	−0.23***	−0.24***
Log(Wealth)	0.015	0.019
Number of PDs	0.0022	0.0022
Previous BC	0.18***	0.19***
Foreign BC	0.11**	
Holdings change lagged		0.027
Adjusted R2	0.41	0.41
30-year		
Yield	0.065***	0.043***
Volatility	−1.62*	−1.36
Corporate spread	0.018	0.015
Ex-post supply	−0.19***	−0.20***
Log(Wealth)	0.066	0.079
Number of PDs	0.00050	−0.00004
Previous BC	0.16***	0.16***
Foreign BC	−0.0075	
Holdings change lagged		−0.25**
Adjusted R2	0.31	0.33

Notes: See *Notes* Table 4.

depends on the demand in recent auctions in other Eurozone countries. There may be Eurozone common factors underlying the demand in auctions in the Eurozone, e.g. government surpluses may be correlated among countries, and the information contained in these common factors may feed only slowly into the debt markets. Hence, in this subsection we extend the baseline regression by including the *ex-post* bid-to-cover ratio $BC^{p}_{j,prev}$ of the most recent foreign auction of the same maturity:

$$BC^{p}_{i,t} = c_i + \alpha_1 Y_{i,t-1} + \alpha_2 VOL_{i,t-1} + \alpha_3 CSpread_{i,t-1} + \alpha_4 SUP^{p}_{i,t} + \alpha_5 log\left(W_{i,t-1}\right) + \alpha_6 N_{i,t} + \alpha_7 BC^{p}_{i,prev} + \alpha_8 BC^{p}_{j,prev} + \varepsilon_{i,t} \quad (8)$$

where j is used to indicate any country other than i in our sample. We report the panel estimates in Table 8. The coefficient estimates on the baseline variables are similar to those under the baseline regression. Hence, the presence of the foreign bid-to-cover ratio does not come at the cost of the significance of the own bid-to-cover ratio, of which the coefficient hardly changes if at all. The *ex-post* foreign bid-to-cover ratio is significantly positive for the 2-year and 10-year regressions, indicating that if the most recent foreign auction was more successful, the current domestic auction is on average more successful.

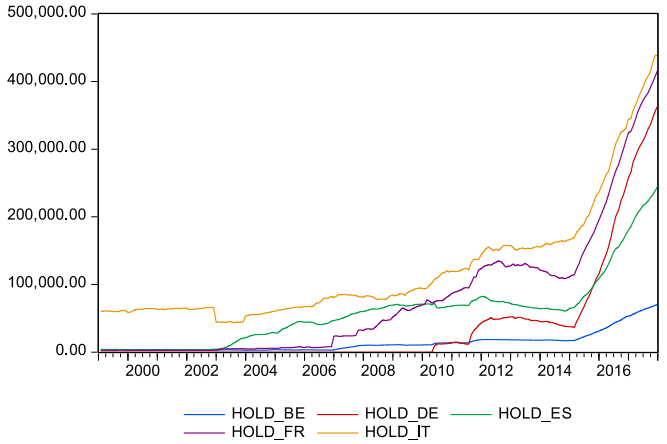

Fig. 11. National central bank holdings of Eurozone general government debt (in millions of euros).

5.3.2. Controlling for national central bank Eurozone general government debt holdings

Since the start of the Eurozone sovereign debt crisis, the European System of Central Banks has engaged in substantial purchases of sovereign debt. The first wave of these purchases was the Securities Markets Program (SMP), which ran from May 2010 until September 2012. The second wave is the Public Sector Purchases Program (PSPP), which started in March 2015 and which is part the ECB's quantitative easing program. It is by far the largest program, which until the end of the sample had accumulated over 2000 billion euros. Net purchases under the PSPP temporarily ended in December 2018,[20] and were resumed in late 2019. The redemptions will for the foreseeable future be reinvested. Central bank sovereign debt purchases in the context of the programs are confined to the secondary market. Fig. 11 depicts the national central banks' holdings of general government debt issued by Eurozone countries. The data is end-of-month holdings and was retrieved from the ECB's Statistical Data Warehouse (2018). For all countries, except Germany, these holdings are already non-zero before the start of the SMP, suggesting that they also contain non-monetary policy holdings that are related to the national tasks of the national central banks and are unlinked to the ECB purchases programs. The data provide no direct indication of what fractions of the holdings have been issued by the own government. However, under the ECB's PSPP, Eurozone central banks mostly purchase the debt issued by their own governments.[21]

It is conceivable that Eurozone governments reacted to the ECB's PSPP with additional long-term debt issuance, thereby undoing part of the fall of the long end of the yield curve. In fact, Andrade et al. (2016, Subsection 6.2) find that "on the quarter of the announcement of the PSPP, the average maturity of issuances was more than 2 years higher than that of redemptions. Moreover, the positive gap between the two measures persisted until the end of the sample". It is also possible that central bank government debt purchases taking place on or around dates of sovereign debt auctions have affected bid-to-cover ratios. This could take place in several ways. One is that the additional demand for debt in the secondary market *prior* to an auction drives up prices not only in the secondary market, but also in the primary market due to the high (or perfect, in case of a re-opening) degree of substitutability of newly-issued debt with the debt traded in the secondary market. This could push down primary dealer demand. It could also push up primary dealer demand if they expect new central bank purchases after the auction. The demand from the central bank could also induce the government to issue more debt as the price against which they can sell is pushed up. This would lower the bid-to-cover ratio.

Here we augment the baseline regression with the one-month lagged change in the national central bank holdings of Eurozone general government debt. We use lagged changes as current-month changes would feed future information into the right-hand side of the regression equation. We spread changes between the end-of-month holdings evenly over the business days in each month, so as to control for variations in the lengths of the months. Hence, the regression equation reads:

$$BC^{p}_{i,t} = c_i + \alpha_1 Y_{i,t-1} + \alpha_2 VOL_{i,t-1} + \alpha_3 CSpread_{i,t-1} + \alpha_4 SUP^{p}_{i,t} + \alpha_5 log\left(W_{i,t-1}\right) + \alpha_6 N_{i,t} + \alpha_7 BC^{p}_{i,prev} + \alpha_8 \Delta DCBH_{i,m(t)-1} + \varepsilon_{i,t} \quad (9)$$

where $m(t)$ is the month in which day t occurs (where we continue counting in a linear fashion, so, for example, January 2000 is month 13, *etc.*) and $\Delta DCBH_{i,m(t)}$ is the daily change in country i's central bank holdings of Eurozone general government debt over month $m(t)$. Precisely,

$$\Delta DCBH_{i,m(t)} = \left(CBH_{i,m(t)} - CBH_{i,m(t)-1}\right) / BD\left(m(t)\right)$$

[20] The end of the net purchases was announced on December 13, see https://www.ecb.europa.eu/press/pressconf/2018/html/ecb.is181213.en.html.

[21] ECB (2015) states that 80% of the PSPP consists of purchases of domestic sovereign bonds by national central banks, and that for this part of the program risk sharing between the national central banks is excluded.

where $CBH_{i,m(t)}$ is end-of-month $m(t)$ country i's central bank holdings of Eurozone general government debt and $BD(m(t))$ is the number of business days in month $m(t)$. Table 8 again reports the panel estimates. The coefficients of the baseline variables are close to those of the baseline regression. Lagged changes in national central bank holdings of Eurozone general government debt have a significantly negative impact on the bid-to-cover ratio for 5- and 30-year debt and are insignificant for the other two maturities. As explained above, a potential explanation of the significant cases is that recent increases in those holdings have pushed up prices of debt, causing the government to issue more and the primary dealers to demand less new debt. These supply and demand channels both suppress the bid-to-cover ratio.

6. Concluding remarks

This paper has explored the determinants of the bid-to-cover ratios of Eurozone public debt issues, which is the most common measure of the demand in such an auction. Our theory suggests that the bid-to-cover ratio should be decreasing in the degree of market risk aversion, market volatility, the amount of debt to be issued and the concentration of primary dealer wealth. The empirical results confirm this partly, with supply and market volatility both exerting a strong negative effect on the bid-to-cover ratio. Essentially no role is found for market risk aversion. The number of primary dealers sometimes exerts a positive effect on the bid-to-cover ratio. However, the sample variation in this variable is rather low. The bid-to-cover ratio in the previous auction of the same maturity tends to have a positive effect on the current bid-to-cover ratio, a persistence that may be accounted for by slow-moving factors determining the demand in the auction. There is an empirically important role for the secondary-market yield, which exerts a positive effect on the bid-to-cover ratio. Finally, lagged changes in national central bank holdings of Eurozone general government debt suppress the bid-to-cover ratio for some debt maturities.

These results are robust to a large set of robustness checks, and also when we lag the explanatory variables by 5 days. In that regression, the factors determining the demand in the auction are all part of the information set of the DMO when it announces the auction and its supply target or range. This is important, because our results can provide the DMO with direct information on when a new debt issue is likely to be successful. In particular, when market volatility is currently relatively high or the last domestic or foreign auction was not very successful, it might be wiser to limit the size of the current auction in favor of a larger future auction size, while in the meantime making use of the money market to bridge temporary funding gaps. In fact, new information becoming available during the run up to the auction has at most only a limited effect on the eventual bid-to-cover ratio.

Our results also suggest that maintaining a relatively large group of primary dealers may be beneficial in terms of being able to place debt at a good price. However, this benefit has to be weighed against the cost of maintaining a larger network of primary dealers.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jempfin.2020.05.005.

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