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THE RELATIVE PRICING OF SOVEREIGN CREDIT RISK AFTER THE EUROZONE CRISIS

Raffaele Corvino
Francesco Ruggiero

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Raffaele Corvino[a,*], Francesco Ruggiero[b]

[a] *Cass Business School, 106 Bunhill Row, EC1Y 8TZ, London*
[b] *Universit di Napoli Federico II, Via Cintia, 80126, Napoli*

Abstract

The paper analyses the relative pricing between sovereign credit default swap (CDS) spreads and sovereign bond yields for European countries during and after the sovereign debt crisis of 2010-2012. We investigate whether riskier countries compensate their debtholders properly by paying out sufficiently higher bond yields compared to those of safer countries. We test whether the differences across countries in terms of the default risk priced in the CDS spreads are consistently priced in the cross section of the bond yields, and we show that an inconsistent cross-sectional relationship between CDS spreads and bond yields emerges during the crisis period for all European countries. However, after the announcement of the Outright Monetary Transaction (OMT) program by the European Central Bank, the consistent cross-sectional relationship between default risk and bond yields is restored for the Eurozone countries only.

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*Corresponding author. *Phone Number*: +39 3465316931
Email addresses: raffaele.corvino.1@cass.city.ac.uk (Raffaele Corvino), francesco.ruggiero@bancaditalia.it (Francesco Ruggiero)

1. Introduction

Credit derivatives and debt securities are strictly related since the pricing of both types of financial assets crucially depends on the risk of default of the reference entity. Credit default swaps (CDS) and bonds issued by the CDS reference entity produce similar exposure to the investor in terms of risk and return. The CDS provides protection to the acquirer in case of default of the reference entity, while the bond pays out yields to the bondholder as long as the reference entity is able to comply with its obligations.

Hull et al. (2004) point out that, under a set of assumptions that ensure the absence of frictions in the market, a portfolio including a bond and the protection on the bond provided by a CDS generates cash flows equal to a riskless bond in all states of the world. Consequently, the CDS premium should be equal to the excess bond yield over the risk-free rate to prevent arbitrage. This equilibrium condition is called the zero-basis condition, where the basis is the difference between the CDS spread and the asset swap spread of the bond.

In this paper, we study the relationship between sovereign CDS and sovereign bonds for European countries during and after the sovereign debt crisis of 2010-2012. In particular, we focus on the cross-sectional relationship between CDS spreads and bond yields across European countries. We investigate whether the differences across countries in terms of default risk, priced in the CDS spreads, are consistently priced in the cross section of the bond yields. Our main finding is the following: an inconsistent cross-sectional relationship between CDS spreads and bond yields emerges during the crisis period for all European countries. However, after the announcement of the Outright Monetary Transaction (OMT) program by the European Central Bank on July 26, 2012, the consistent cross-sectional relationship between default risk and bond yields is restored for the Eurozone countries only.

We start our analysis by documenting that the equilibrium condition between CDS spreads and bond yields is violated before the announcement of the OMT program for all European countries and is restored afterwards for the Eurozone countries only, and in particular for the peripheral countries of the Eurozone. Instead, the deviation from the equilibrium condition persists even after the OMT announcement for the European countries out of the Eurozone.

Since the violation of the equilibrium condition generates arbitrage opportunities, we corroborate the result with a portfolio analysis based on the deviation from the zero-basis condition. We show that arbitrage opportunities are large and persistent before the OMT announcement across all European countries and then quickly disappear after the OMT announcement for Eurozone countries only. Instead, arbitrage opportunities persist even after the OMT announcement for countries outside the Eurozone.

Mispricing has been documented for both corporate (Longstaff et al. (2005), Blanco et al. (2005)) and sovereign securities (Palladini and Portes (2011), Arce et al. (2013), Fontana and Scheicher (2016)). These papers argue that CDS spreads are faster in price discovery, thus reacting more quickly to changes in the credit condition. Consequently, the relationship between CDS spreads and bond yields does not hold in the short term. However, they show that CDS spreads and bond yields exhibit strong co-movements in a long-term perspective. While Palladini and Portes (2011), Arce et al. (2013), and Fontana and Scheicher (2016) provide evidence on the relative pricing of the sovereign credit risk before and during the sovereign crisis, we extend the analysis to the period following the ECB intervention. In addition, we include countries out of the Eurozone, with the aim of highlighting the differential effects of the unconventional monetary policy.

We proceed with our analysis by showing that the deviation from the zero-basis condition does not imply the violation of the expected positive and monotonic relationship across countries between CDS spreads and bond yields. In fact, we show that the cross-sectional rank correlation between CDS spreads and bond yields is always close to 1 for both Eurozone and non-Eurozone countries. This result provides evidence that riskier countries issue debt securities that pay out higher yields.

In general, in a consistent relationship between risk and return, the riskier security should generate a higher expected return compared to a less risky security to induce investors to hold it. Investors are willing to buy risky assets only if they are rewarded with a proper expected return. The higher the risk associated with a given investment, the higher its expected return must be. It turns out that, over a cross section of assets, we should observe a positive and monotonic relationship between the risk and expected return. The empirical contradiction of the positive relationship between the risk and expected return is known in the financial literature as a *distress puzzle*.

The distress puzzle has been widely investigated in the context of corporate securities by studying the relationship between the default risk and expected stock return. The empirical evidence is far from univocal (see, among others, Vassalou and Xing (2004), Campbell et al. (2008), Friewald et al. (2014)). To the best of our knowledge, however, an analysis of the puzzle at the sovereign level is still missing. As countries do not issue equity, we focus on debt securities.

In our framework, the positive risk-return relationship implies that a riskier country should issue debt securities that pay out higher yields. Indeed, we observe a monotonic relationship between CDS spreads, the price of default risk, and bond yields. However, monotonicity is a necessary but not sufficient condition for the consistent relationship between risk and return to hold. The riskier security, in fact, should generate an expected return that is also *sufficiently* higher compared to the safer security. In other words, the difference across securities in terms of expected return should be consistent with the difference in terms of risk. Only a consistent difference compensates the investor properly for the higher level of risk associated with the riskier security.

In our framework, this relationship implies that a riskier country should pay out sufficiently higher bond yields compared to a safer country, that is the difference in terms of bond yields should be consistent with the difference in terms of the default risk priced in the corresponding CDS spreads. We show that an inconsistent cross-sectional relationship between CDS spreads and bond yields emerges during the crisis period for Eurozone countries and is restored after the announcement of the OMT program. Therefore, while the deviation from the zero-basis equilibrium condition does not affect the monotonicity in the cross-sectional relationship between CDS spreads and bond yields, it generates inconsistency in the cross section of the bond yields across countries: the differences across countries in terms of the default risk, priced in the CDS spreads, are not consistently priced in the cross section of the bond yields.

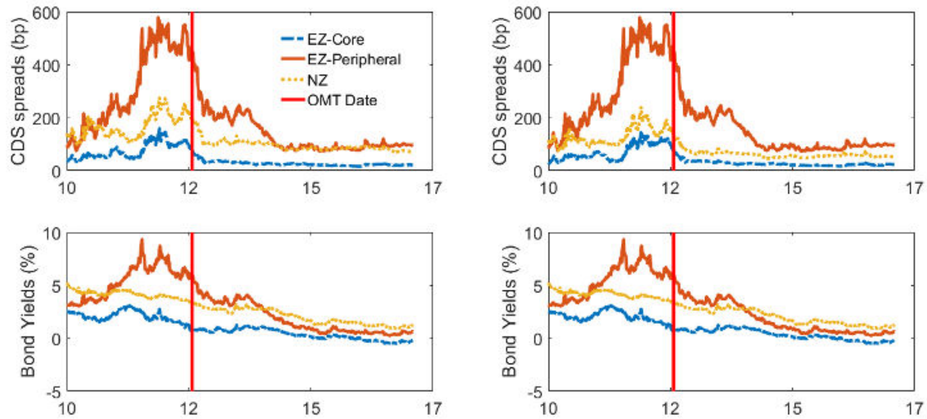
To determine the proper distance between bond yields across countries, we adopt a contingent claim model. In the model, bond and CDS are implicitly related at each point in time, as both the securities are derivative contracts on the same underlying quantity, which are the assets and liabilities of the reference entity. In particular, we adopt a first-passage time model, where the issuer defaults as soon as the value of the assets crosses from above a default boundary, which is assumed to be deterministic and constant. This framework is an extension of the seminal model of Merton (1974), where the issuer may default only at the maturity of the liability. Gapen et al. (2011) introduce a contingent claim analysis to study sovereign credit risk using a Merton model. We estimate the model with a nonlinear Kalman filter using daily data on CDS spreads, and we compute the bond yields implied by the model estimation using Monte Carlo (MC) simulations. These yields are consistent with the default risk of the country priced in the CDS spreads.

We corroborate our results with a portfolio analysis based on the difference between observed and implied bond yields. We show that arbitrage opportunities are large and persistent before the OMT announcement across all European countries, then converge to zero after the OMT announcement for the Eurozone countries only. Arbitrage opportunities do not disappear even after the OMT announcement for the European countries outside of the Eurozone.

Finally, we conjecture that the arbitrage opportunities before the OMT announcement were created by high transaction costs. Therefore, for each country, we estimate the threshold below which arbitrage profits are insufficient to cover the costs to implement the strategy. The idea is that arbitrageurs enter the market only if the arbitrage strategy generates profits above such costs. We show that, before the OMT announcement, the arbitrage opportunities are not cleared because of high transaction costs. Then, we estimate a strong reduction in the transaction costs for the Eurozone countries only, following the ECB intervention. Consequently, the arbitrage opportunities are cleared, and the equilibrium condition in the Eurozone sovereign debt market is restored. However, we do not estimate a similar reduction in the transaction costs for the non-Eurozone countries. Therefore, for those countries, we observe a persistent mispricing even after the OMT announcement.

Our paper is organized as follows. We describe the data in the next section. Then, we provide empirical evidence on the relationship between CDS spreads and bond yields during and after the OMT announcement in Section 3. In Section 4, we focus on the cross-sectional analysis of CDS spreads and bond yields. We detail the underlying credit risk model and our estimation methodology to compute the implied bond yields. In addition, we compare

Figure 1. CDS Spreads and Bond Yields.



The figure reports the mean and median across countries for the sovereign CDS spreads and bond yields between the 1^{st} of January 2010 and the 1^{st} of February 2017, at 5-year maturity for three different groups of countries: Eurozone-core (blue line), Eurozone-peripheral (red line), and non-Eurozone (yellow line). The CDS spreads are expressed in basis points, and the bond yields are expressed in percentage terms. The red line is the OMT announcement date.

observed and implied yields, and we perform the cross-sectional correlation analysis between CDS spreads and bond yields. Finally, we estimate the transaction costs before and after the OMT announcement and compare such costs with the arbitrage profits in Section 5. Section 6 concludes the paper.

2. Data

Our main source of data is Thomson Reuter's Datastream. We download daily data for sovereign CDS spreads and sovereign bond yields for several European countries from January 2010 to February 2017. We collect 1850 daily observations for each country, for both CDS spreads and bond yields, and for three time maturity levels: 1, 5, and 10 years. Datastream provides reference par yields for sovereign bonds at different maturities. The par yield is the internal rate of return (yield to maturity) of a bond traded at par, and it is expressed as an annualized figure. The CDS spread is expressed in basis points and represents the percentage of the CDS notional value that the protection buyer must pay, usually at quarterly frequencies, to the protection seller. Similarly, CDS spreads are expressed in annualized terms.

We use all the maturities of the CDS spreads to implement the estimation methodology.

Table 1. Descriptive Statistics by Country.

Statistics:	CDS Spreads			Bond Yields		
Mean	B/OMT	A/OMT	Diff	B/OMT	A/OMT	Diff
Eurozone						
Core:						
Austria	78.19	20.22	-57.97*	3.14	1.21	-1.93*
Belgium	143.11	33.93	-109.19*	3.77	1.44	-2.33*
Finland	46.50	24.74	-21.76*	2.79	1.14	-1.65*
France	83.17	31.86	-51.31*	3.13	1.37	-1.76*
Germany	39.15	12.58	-26.57*	2.48	0.93	-1.55*
Netherlands	67.26	31.74	-35.53*	7.63	2.31	-5.31*
Peripheral:						
Ireland	485.07	80.00	-405.07*	4.94	2.81	-2.13*
Italy	229.15	138.40	-90.75*	2.80	1.15	-1.65*
Portugal	633.77	247.09	-386.67*	8.85	4.35	-4.49*
Slovakia	136.00	61.90	-74.10*	4.18	1.89	-2.29*
Slovenia	164.69	168.27	3.58	5.10	2.90	-2.20*
Spain	243.27	115.66	-127.62*	5.62	3.07	-2.55*
Non-Eurozone						
Bulgaria	258.99	130.61	-128.39*	6.53	4.28	-2.25*
Croatia	316.38	274.95	-41.43*	3.72	1.30	-2.41*
Czech Republic	98.95	49.67	-49.28*	2.56	1.08	-1.48*
Denmark	60.44	17.83	-42.61*	7.86	4.66	-3.20*
Hungary	353.35	191.21	-162.14*	6.75	6.36	-0.39*
Norway	26.58	16.23	-10.35*	5.17	3.85	-1.32*
Poland	160.49	71.75	-88.74*	5.51	2.47	-3.04*
Romania	301.57	145.09	-156.47*	3.01	1.98	-1.02*
Sweden	36.48	12.96	-23.52*	5.79	3.45	-2.34*
UK	65.54	27.81	-37.73*	7.51	4.49	-3.02*

The table reports the mean over time of the sovereign CDS spreads and bond yields for each country across the periods before (January 1, 2010 - July 25, 2012) and after (July 26, 2012 - February 1, 2017) the OMT announcement date. The CDS spreads are expressed in basis points, and the bond yields are expressed in percentage terms. The third column is the difference between the two periods. The * indicates that the difference is significant at the 5% level.

However, throughout the paper, we focus on the 5-year maturity to show our results in the empirical analysis. We also collect data on the Euribor as a proxy of the European short-term risk-free interest rate. At longer maturities, we proxy the risk-free rate with the euro area yield curve computed exclusively on AAA-rated central government bonds. We use the

Table 2. Descriptive Statistics by Asset.

	Average of Means			Average of Medians		
	B/OMT	A/OMT	Diff	B/OMT	A/OMT	Diff
All Samples:						
CDS	183.10	86.57	-96.53*	125.70	52.40	-73.30*
Yields	4.95	2.66	-2.29*	4.70	0.24	-4.45*
Country Groups:						
Eurozone-core						
CDS	73.23	25.84	-50.39*	70.57	26.24	-44.33*
Yields	3.82	1.40	-2.42*	3.13	0.13	-3.01*
Eurozone-periphery						
CDS	315.33	135.22	-180.11*	239.24	125.14	-114.10
Yields	5.25	2.69	-2.55*	4.84	0.27	-4.58*
Non-Eurozone						
CDS	167.88	93.81	-74.07*	129.99	60.74	-69.24*
Yields	5.44	3.39	-2.05*	5.84	0.36	-5.48*

The table reports statistics of the sovereign CDS spreads and bond yields before (January 1, 2010 - July 25, 2012) and after (July 26, 2012 - February 1, 2017) the OMT announcement date, and the relative difference, across all countries and the three groups of countries. The Average of Means is computed as the mean over time of the cross-sectional average CDS spreads and bond yields across countries. The Average of Medians is computed as the mean over time of the cross-sectional median CDS spreads and bond yields across countries. The CDS spreads are expressed in basis points, and the bond yields are expressed in percentage terms. The * indicates that the difference is significant at the 5% level.

Nelson-Siegel technique to bootstrap the maturities of the risk-free curve needed to obtain the present values of CDS that we use in the arbitrage strategies.

We apply a filter to the sample, excluding countries that report an excessive number of missing data points on bond yields or CDS spreads (more than 40% of the total observations for at least one maturity), thus dropping Cyprus, Luxembourg, and Malta from the sample. We also exclude Greece, which deserves a specific analysis, due to the dramatic turbulence experienced during the sample period. We drop Estonia, Latvia, and Lithuania from the sample because they changed their status from non-Eurozone to Eurozone over the sample period. We end up with a final sample of 22 countries: 12 countries belong to the Eurozone, and 10 countries are outside of the Eurozone. Throughout the analysis, we also divide the sample of the Eurozone countries in two subgroups: core and periphery. The list of countries is reported in Table 1.

Figure 1 shows that bond yields and CDS spreads significantly drop after the announcement of the OMT program for all groups of countries. In Table 1, we report data on CDS spreads and bond yields for each single country in the sample. Table 1 shows that the differences are significant at the 5% level, considering both the mean and median.

In Table 2, we report statistics on the time series of the mean and median across countries before and after July 2012. We also provide a breakdown of the mean and median by different groups of countries. We observe that bond yields and CDS spreads are generally lower for the core Eurozone countries compared to both the peripheral and non-Eurozone countries before and after the OMT announcement. Yet, the reduction in both CDS spreads and bond yields is significant at the 5% level even for the core Eurozone countries.

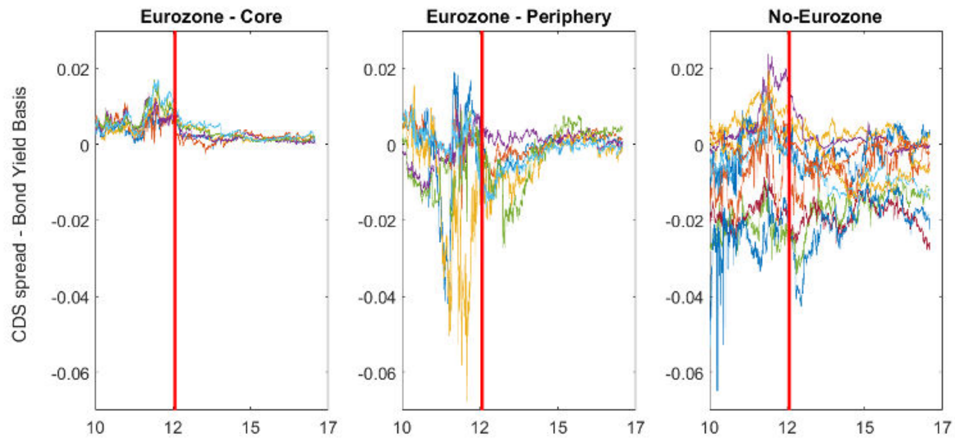
3. The CDS - Bond Basis

In this section, we analyze the theoretical equilibrium condition between CDS spreads and bond yields for each European country over the time series. The CDS spreads and yields on a risky bond issued by the reference entity of the CDS contract are strictly related. The CDS provides protection to the acquirer in case of default of the reference entity, while the bond pays out yields to the bondholder as long as the reference entity is able to comply with its obligations. Hull et al. (2004) have pointed out that, under a given set of assumptions, the T-year CDS spread should be equal to the T-year excess yield on a risky bond issued by the reference entity over the T-year riskless bond:

$$s = y - r, \tag{1}$$

where s is the T-year CDS spread, y is T-year yield on the risky bond, and r is the T-year yield on the riskless bond. The reason is simple: if the assumptions listed by Hull et al. (2004) hold, a portfolio including a T-year CDS and a T-year par yield bond issued by the reference entity generates cash flows equal to a T-year par yield riskless bond in all states of the world. The *basis* is the difference between the T-year CDS spread and the T-year excess yield on a risky bond issued by the reference entity over the T-year riskless bond. In

Figure 2. CDS spreads - Bond Yields Basis.



The figure reports the CDS spread - bond yield basis for each country between the 1st of January 2010 and the 1st of February 2017 at 5-year maturity for the three different groups of countries. The names of the countries belonging to each group are provided in Table 1. The basis is expressed in percentage terms. The red line is the OMT announcement date.

equilibrium, the basis must be equal to zero. Therefore, the basis is a straightforward signal to detect a relative mispricing between CDS spreads and bond yields for a given country that can be analyzed by simply using observed data.

We group our sample countries in three sub-samples: Eurozone-core (EC), Eurozone-peripheral (EP), and non-Eurozone (NZ). Figure 2 shows the dynamics of the basis for each country. The core countries have a substantially lower basis than both the peripheral and non-Eurozone countries. More importantly, the basis of both core and peripheral countries of the Eurozone converge to zero right after the OMT announcement. The non-Eurozone countries, instead, do not show the same pattern, with their basis spread around zero before and after the OMT announcement.

This result is also evident when examining the average of the absolute basis across groups of countries. Table 3 reports that the absolute basis has substantially reduced for the Eurozone countries in the second period of the time series (-65% for the Eurozone-core and -55% for the Eurozone-peripheral, respectively), while the decrease is much less pronounced for the non-Eurozone countries (-10%).

This empirical observation provides evidence on the disequilibrium between CDS spreads and bond yields for all European countries before the OMT announcement, that persists

Table 3. Average Absolute Basis (CDS Spreads - Bond Yields).

	Euro-Core	Euro-Periphery	Non-Eurozone
Before OMT	0.63	0.78	1.05
After OMT	0.22	0.36	0.90

The table reports the average CDS spreads - bond yields basis across countries for the three groups of countries before (January 1, 2010 - July 25, 2012) and after (July 26, 2012 - February 1, 2017) the OMT announcement date. The basis is expressed in basis points. Both CDS spreads and bond yields are at 5-year maturity.

even after the OMT announcement for the non-Eurozone countries only. This deviation from the equilibrium condition should generate arbitrage opportunities in the market before the OMT announcement for all countries in the sample. Next, we compute the potential profits obtained by exploiting the violation of the no-arbitrage condition.

3.1. Arbitrage Strategy

If the basis is different from zero, an arbitrage opportunity arises in the market by trading CDS, risky bonds, and riskless assets, under the set of assumptions exhaustively explained in Hull et al. (2004). Here, we report only the most relevant assumptions that support the flow of our argument:

1. Market participants can short sovereign bonds;

2. Market participants can short the risk-free bonds (they can borrow money at the risk-free rate);

3. The cheapest-to-deliver bond option is ruled out, so that the profit is not affected by the ability of the protection seller to find a cheaper bond to deliver in case of default;

4. The recovery rate of the bond in case of default is equal to zero.

We express all the variables in monetary terms, thus computing the present value of the CDS, risk-free bond, and risky bond using continuous compounding, such that the no-arbitrage condition can be rewritten as follows:

$$P_{CDS} = P_{BY} - P_{RF},$$

where P_{CDS}, P_{BY}, P_{RF} denote the present value of the CDS, risky bond, and riskless bond, respectively. We omit the subscripts i and t to reduce notation.

The arbitrage strategy is based on the CDS spread - bond yield basis. When this relationship is not in equilibrium, there is a signal of an arbitrage opportunity arising on the market. Suppose that, for the i-th country, at time t,

$$P_{CDS} > P_{BY} - P_{RF},$$

then the arbitrageur sells the risk-free asset and purchases the CDS and risky bond issued by the CDS reference entity. The mispricing of the bond generates a positive difference that is exactly the risk-free arbitrage profit. Conversely, if

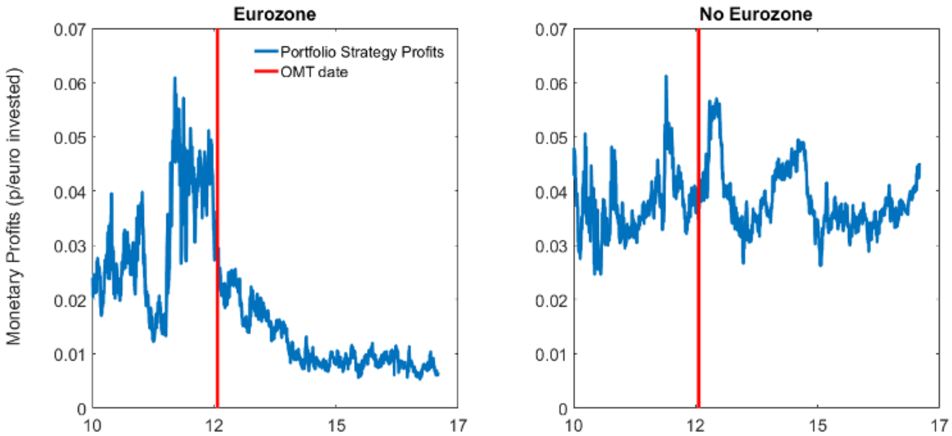
$$P_{CDS} < P_{BY} - P_{RF},$$

then the arbitrageur obtains the same arbitrage profit by reversing the strategy: the arbitrageur purchases the risk-free asset and sells the risky bond and CDS.

Figure 3 shows the arbitrage profits generated by a portfolio equally weighted in terms of countries. The left panel shows the profits that the arbitrageur can obtain by trading assets of the Eurozone countries, and the right panel shows the profits that the arbitrageur can obtain by trading assets of non-Eurozone countries. The profits are large and volatile before the OMT announcement in both Eurozone and non-Eurozone areas. After the announcement, however, the profits drop immediately and start to converge to zero for Eurozone countries. Instead, the riskless profits remain positive and volatile for the countries outside the Eurozone.

Table 4 reports the mean and standard deviation of the potential profits obtained with the arbitrage strategy before and after the OMT announcement and for Eurozone and non-Eurozone countries, respectively. In Table 4, we report a significant difference in the average profits between the two periods for Eurozone countries. Further, the standard deviation drops sensibly after the announcement. For the non-Eurozone area, Table 4 reports results on the means and standard deviations that are very similar across the two periods. The differences are not statistically different from zero.

Figure 3. Arbitrage Profits - Strategy 1.



The figure shows the arbitrage profits on an equally weighted across-country portfolio of sovereign CDSs and bonds using portfolio strategy 1 between the 1^{st} of January 2010 and the 1^{st} of February 2017. The strategy is implemented using either Eurozone sovereign CDSs and bonds only (left panel) or non-Eurozone sovereign CDSs and bonds only (right panel). The profits are expressed in monetary terms assuming a nominal value of 1 for the bonds, and the CDS price is computed as the present value of the CDS spreads expressed in percentage terms. The red line stands for the OMT announcement date.

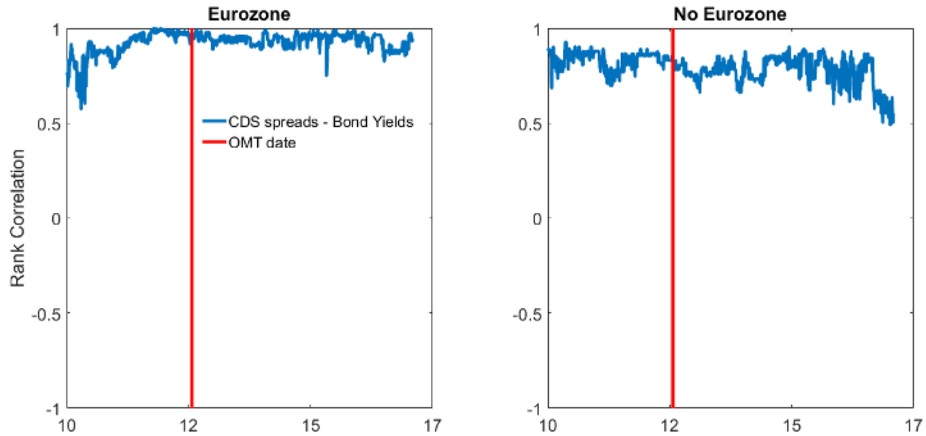
Table 4. Arbitrage Profits - Strategy 1.

Statistic:	Before OMT	After OMT	Difference
Eurozone			
Mean	0.034	0.014	-0.020*
Std. Dev.	0.012	0.005	
Non-Eurozone			
Mean	0.036	0.036	-0.000
Std. Dev.	0.006	0.006	

The table reports the mean and standard deviation of the profits on an equally weighted across-country portfolio of sovereign CDSs and bonds using portfolio strategy 1 before (January 1, 2010 - July 25, 2012) and after (July 26, 2012 - February 1, 2017) the OMT announcement date. The strategy is implemented using either Eurozone sovereign CDSs and bonds only, or non-Eurozone sovereign CDSs and bonds only. The profits are expressed in monetary terms assuming a nominal value of 1 for the bonds, and the CDS price is computed as the present value of the CDS spreads expressed in percentage terms. In the last column, we report the difference across the two periods. The * indicates that the difference is significant at the 5% level.

Therefore, we observe that potential arbitrage profits are large and persistent for all countries before the OMT announcement and quickly converge to zero for the Eurozone countries only. This result is consistent with the evidence on the deviation from the zero-basis condition documented in the previous section.

Figure 4. CDS Spreads - Bond Yields: Cross-sectional Correlations.



The plots show the cross-sectional rank correlation between sovereign CDS spreads and bond yields at 5-year maturity between the 1^{st} of January 2010 and the 1^{st} of February 2017 across Eurozone (left panel) and non-Eurozone countries (right panel). The red line is the OMT announcement date.

4. Cross-Sectional Analysis

The previous section analyses the dynamics of the relationship between CDS spreads and bond yields over time for each country. However, our main target is to investigate the relationship between CDS spreads and bond yields over the cross-sectional dimension. The consistent relationship between CDS spreads and bond yields implies that a riskier country issues debt securities that pay out higher yields. Consequently, we should observe a monotonic and positive relationship between CDS spreads, the price of default risk, and bond yields. We use the Spearman correlation coefficient, which evaluates the rank correlation, to perform our analysis. If a positive and monotonic relationship between CDS spreads and bond yields exists, the rank correlation between CDS spreads and bond yields is equal to 1 over the cross section of countries for any point in time.

Figure 4 shows that the correlation between CDS spreads and observed yields is close to 1 over the time series for both groups of countries. This result implies that the relationship between CDS spreads and observed yields is monotonically positive: the riskier countries pay out higher bond yields compared to the safer countries. This result suggests that the deviation from the zero-basis condition documented in the previous section does not affect the monotonic relationship between CDS spreads and bond yields across countries. In other words, even when the CDS spreads - bond yields bases for single countries are far from zero, the cross-sectional monotonic relationship between CDS spreads and bond yields still holds.

However, the cross-sectional monotonicity between CDS spreads and bond yields is a necessary but not sufficient condition for a consistent relationship. A riskier country, in fact, should pay out bond yields that are not only higher than the bond yields paid out by a safer country, but are also sufficiently higher to compensate the bondholder properly for bearing that higher level of risk. The difference in terms of bond yields between riskier country and safer country should be large enough to be consistent with the difference in terms of the default risk priced in the corresponding CDS spreads. To perform this analysis, we examine the rank correlation over the cross section of countries between CDS spreads and *net yields*. We define net yield as the difference between the actual bond yield and the bond yield implied by the CDS spreads. The latter is the unobservable yield implied by a given level of default risk priced in the CDS spreads of the country.

The idea behind the analysis of the relationship between CDS spreads and net yields should be clear with a simple numerical example. We consider two countries, A and B, and suppose that the CDS spread of A is larger than the CDS spread of B, that is, A is riskier than B. We suppose also that the observed yields are $Y(A) = 0.1$ and $Y(B) = 0.05$, respectively. It turns out that country A is paying out a higher yield, and so the monotonicity condition between CDS spreads and bond yields is verified. However, is $Y(A)$ higher enough to compensate the bondholders for the higher risk associated with the country A? We suppose that the yields implied by the CDS spreads for the two countries are $I(A) = 0.15$ and $I(B) = 0.02$, respectively. Finally, we compute the net yields, which are $N(A) = -0.05$ and $N(B) = 0.03$.

The first consequence is that the bond of country A is overvalued; the actual yield is lower than the risk-implied yield, and the price of the bond is larger than the risk-implied price. On the other hand, the bond of country B is undervalued. Moreover, the monotonicity condition between CDS spreads and net yields is not verified. The difference between the observed bond yields across the two countries is inconsistent with the difference in terms of default risk. The riskier country A, in fact, is paying out an insufficiently higher bond yield compared to the safer country B to compensate the bondholder.

We compute the implied bond yields for each country by estimating a contingent claim model. We adopt a first-passage time model, where the issuer defaults as soon as the value of the assets crosses from above a default boundary, which is assumed to be deterministic and constant. Next, we detail the underlying model and the model estimation procedure and report our results. Then, we describe the MC simulation approach to obtain the implied bond yields, and we compare the implied bond yields with the observed bond yields. Finally, in this section, we implement the cross-sectional correlation analysis between CDS spreads and bond yields, using both the observed and implied bond yields. We also corroborate our findings with a portfolio analysis based on the arbitrage strategy described in the previous section.

4.1. Underlying Model

The asset value of the i-th country is described by a geometric Brownian motion on the filtered probability space $(\Omega, \mathcal{F}, \{\mathcal{F}_t : t \geq 0\}, \mathcal{P})$:

$$dV_{i,t} = \mu_{V_i} V_i dt + \sigma_{V_i} V_i dW_{i,t},$$

where μ_{V_i} and σ_{V_i} are the $\mathcal{P}$-drift and diffusion constant coefficients, and $W_{i,t}$ is a standard Brownian motion under the physical probability measure $\mathcal{P}$.

We define the i-th market value of leverage as $L_{i,t} = \ln\left(\frac{F_i}{V_{i,t}}\right)$, following an arithmetic Brownian motion:

$$dL_{i,t} = \mu_{L_i} dt - \sigma_{L_i} dW_{i,t}, \tag{2}$$

where $\mu_{L_i} = -\left(\mu_{V_i} - \frac{1}{2}\sigma^2_{V_i}\right)$ is the $\mathcal{P}$-leverage drift coefficient, $\sigma_{L_i} = \sigma_{V_i}$ is the leverage diffusion component, and the minus before the diffusion component is the result of the perfect and negative correlation between the Brownian motions of asset and leverage.

In the first-passage time framework, the default occurs as soon as the asset value crosses from above a constant and deterministic barrier C_i that we assume to be below the face value of the debt at any time s with $t \leq s \leq T$, where T is the outstanding debt maturity. The default risk of the country is priced in the CDSs issued with different maturity τ_j, with j going from 1 to J, where the longest maturity τ_J matches the debt maturity T. In a CDS contract, the protection buyer pays a fixed premium at each period until either the default event occurs or the contract expires, and the protection seller is committed to buy back the defaulted bond from the buyer at its par value.

Therefore, the price of the CDS (i.e., the premium paid by the insurance buyer) is defined at the inception date of the contract to equate the expected value of the two contractual legs. By assuming the existence of a default-free money market account appreciating at a constant continuous interest rate r, and M periodical payments occurring over one year, the CDS spread γ with time to maturity τ_j priced at $t = 0$ solves the following equation:

$$\sum_{m=1}^{M} T\frac{\gamma}{M}\exp\left(-r\frac{m}{M}\right)\mathcal{E}_0^{\mathcal{Q}}[1_{t^*>\frac{m}{M}}] = \mathcal{E}_0^{\mathcal{Q}}[\exp(-rt^*)\alpha 1_{t^*<\tau_j}],$$

where t^* stands for the time of default, α is the amount paid by the protection seller to the protection buyer in case of default, and $\mathcal{E}_0^{\mathcal{Q}}$ indicates that the expectation is taken under the risk-neutral measure $\mathcal{Q}$. Therefore, $\mathcal{E}_0^{\mathcal{Q}}[1_{t^*<\tau_j}]$ is the probability that the country defaults at any time before τ_j, which is the probability that the asset value crosses from above the barrier C_i. At t, this probability is equal to the following:

$$PD_{i,t}^{\mathcal{Q}}(\tau_j) = \Phi\left(\frac{K_i + L_{i,t} - \left(r - \frac{1}{2}\sigma_{L_i}^2\right)(\tau_j - t)}{\sigma_{L_i}\sqrt{(\tau_j - t)}}\right) + \exp\left((K_i + L_{i,t})\left(\frac{2r}{\sigma_{L_i}^2} - 1\right)\right)\Phi\left(\frac{(K_i + L_{i,t}) + \left(r - \frac{1}{2}\sigma_{L_i}^2\right)(\tau_j - t)}{\sigma_{L_i}\sqrt{(\tau_j - t)}}\right), \quad (3)$$

if $\tau_j < T$, otherwise

$$PD_{i,t}^{\mathcal{Q}}(\tau_J) = 1 - \Phi\left(\frac{-L_{i,t} + \left(r - \frac{1}{2}\sigma_{L_i}^2\right)(\tau_J - t)}{\sigma_{L_i}\sqrt{(\tau_J - t)}}\right) + \exp\left((K_i + L_{i,t})\left(\frac{2r}{\sigma_{L_i}^2} - 1\right)\right)\Phi\left(\frac{(2K_i + L_{i,t}) + \left(r - \frac{1}{2}\sigma_{L_i}^2\right)(\tau_J - t)}{\sigma_{L_i}\sqrt{(\tau_J - t)}}\right), \quad (4)$$

as $\tau_J = T$. Equation 3 defines the early bankruptcy risk, and equation 4 defines the probability that the country is not able to pay back the outstanding debt F_i at time T, even though the asset value never crossed the default boundary. In the equations (3) and (4), Φ stands for the cumulative distribution function of a standard normal variable, and $K_i = \ln\left(\frac{C_i}{F_i}\right)$. Since the default barrier is below the face value of the debt, K_i assumes only negative values. The larger the absolute value of K_i is, the larger the distance is between the face value of the debt F_i and the default barrier C_i.

4.2. Estimation Methodology

We adopt the following procedure to estimate the model. First, we reconstruct the unobservable dynamics of the leverage, defined as the debt-to-asset ratio, for each country by performing a nonlinear Kalman filter using the CDS spreads as observable variables. The Kalman filter allows to retrieve the dynamics of a latent variable by exploiting the relationship between observable and unobservable variables. The relationship between the observed and unobserved variables forms the *measurement equation*, while the evolution over time of the latent variable is called the *transition equation*. We estimate the model parameters by adopting a quasi-maximum likelihood algorithm, in conjunction with the Kalman filter. Details of the estimation methodology are provided in Appendix A.

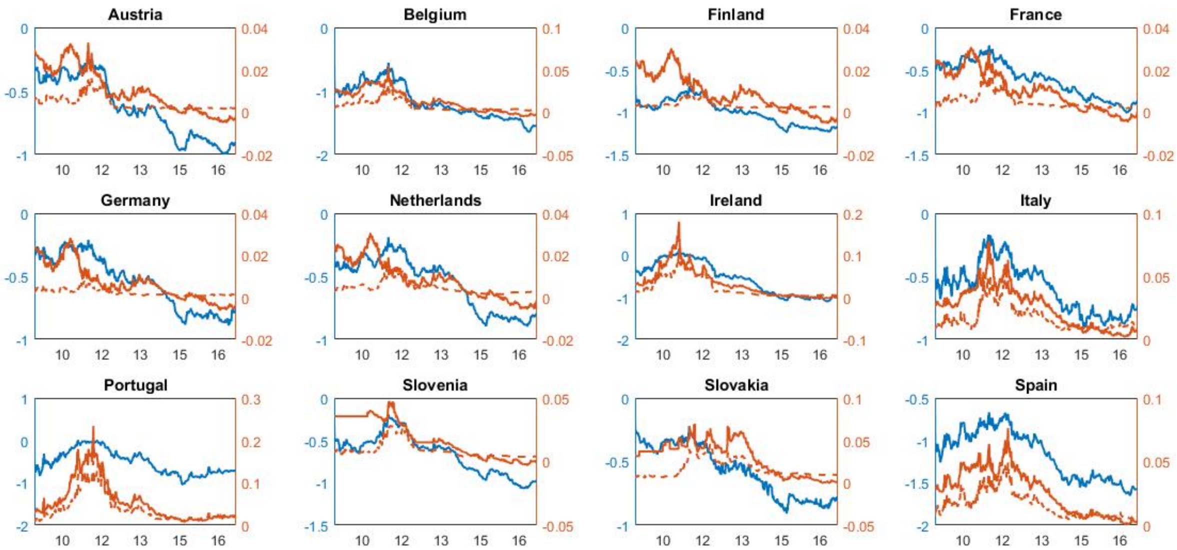
We formulate our problem with a state-space model, where the measurement equations are the equations (3) and (4). The noise terms associated with the CDS implied-default probability for different times to maturity τ_j are assumed to be uncorrelated and to have equal variance:

$$PD^{\mathbb{Q}}_{i,t}(\tau_j) = g\left(L_{i,t}; K_i, \sigma_{L_i}\right) + \epsilon_{i,t}(\tau_j), [j = 1, 5, 10],$$

where the time to maturity is expressed in years, and $j = 10$ stands for the maturity T of the outstanding debt F_i (i.e., 10 years). The function g defines the nonlinear relationships between the observable and latent variables, and $\epsilon_{i,t}(\tau_j)$ is the measurement noise associated with the time horizon j. The measurement noises, for each country i, are assumed to follow a multivariate normal distribution with zero mean and a diagonal covariance matrix R_i. We assume a homoscedastic covariance matrix, which varies by country.

The transition equation describes the evolution of the leverage. It follows from the discretization of the stochastic process defined in (2):

Figure 5. Leverage, CDS Spreads, and Bond Yields: Eurozone Countries.



The plots show the leverage of Eurozone countries (blue line), as defined in equation (2), reconstructed with the nonlinear Kalman filter using the 5-year CDS spreads as the observable variable between the 1^{st} of January 2010 and the 1^{st} of February 2017. Moreover, we report the 5-year CDS spreads (dashed line) and the 5-year bond yields (red line) expressed in percentage terms.

$$L_{i,t+\delta t} = L_{i,t} + \mu_{L_i}\delta t + \eta_{i,t+\delta t},$$

where $\eta_{i,t+\delta t} = \sigma_{L_i}(W_{i,t} - W_{i,t+\delta t}) \backsim \mathcal{N}(0, Q_i)$ is the transition error, and $Q_i = \sigma_{L_i}^2 \delta t$.

The dynamics of $L_{i,t}$ and the parameters of the model, such as μ_{L_i}, σ_{L_i}, and K_i, are estimated by performing a nonlinear Kalman filter in conjunction with a quasi-maximum likelihood algorithm.

Figure 5 provides an idea of the estimation results. In Figure 5, we compare the reconstructed dynamics of the leverage and the observed dynamics of the 5-year CDS spreads and bond yields for our sample countries. The dynamics of both CDS spreads and bond yields are in line with the dynamics of the leverage. When CDS spreads and bond yields approach very low values, such as in the last part of the time series, we estimate a leverage moving far away from zero, toward negative values.

4.3. Implied and Observed Bond Yields

We obtain the implied bond yields for each point in time and for each country by performing an MC simulation analysis. In particular, for each point in time t, and each country i, we simulate the dynamics of the leverage for a time interval going from t to $t + M * 360$, where M is the maturity of the bond expressed in years. The leverage of a country is simulated using the equation (2), where dt is a one-day step. The parameters of the stochastic process are the estimates obtained in the previous step, and we use the estimated leverage at time t as the starting point of the simulated dynamics. We generate $M * 360$ normally distributed random numbers for each country to simulate the daily increment of the Brownian motion, thus finally obtaining the simulated dynamics of the leverage of length $M * 360$.

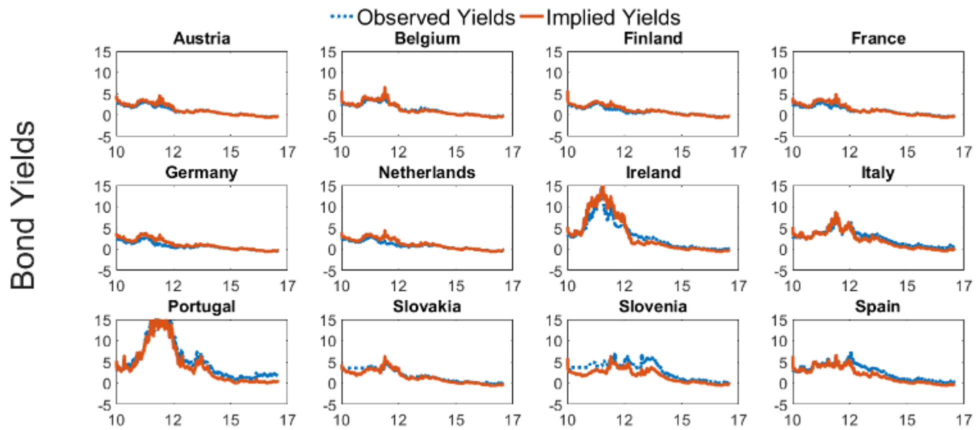
Then, we use the condition of default implied by the model. The country defaults if $V_{i,t} < C_i$, which corresponds to $L_{i,t} > (-K_i)$. Therefore, if the simulated leverage of the country is above $-K_i$, at least for one point in time over the time horizon, we impose that the bond defaults, and the t-value of the bond is zero. Otherwise, the t-value of the bond is equal to the risk-free discount factor using the risk-free rate at time t. We compute the bond price for each time t as an average over 10,000 simulations, and the corresponding yield by simple inversion. If we define B the price of the bond obtained with the MC simulations, then the implied yield Y is equal to the following:

$$Y = \log\left(\frac{1/B}{M * 360}\right).$$

The difference between observed and implied yields should be zero for each country and each point in time, if the observed risky yields of a country are consistent with the default risk priced in the CDS spreads. Indeed, the maintained assumption behind this statement is that the model-implied yields are well estimated, and the model is able to fully capture whatever drives the relationship between default risk and bond prices. With these caveats in mind, we compare observed and implied yields for each country over the sample time-series.

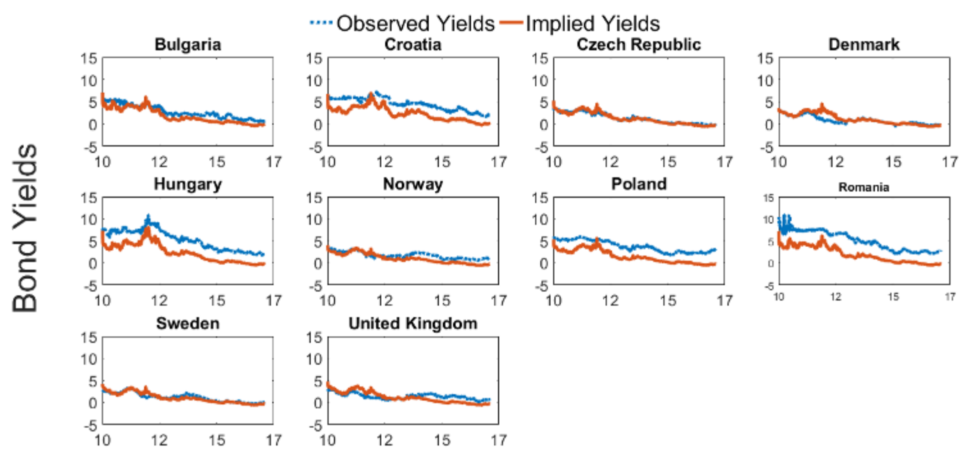
Figures 6 and 7 show that the implied yields are generally closer to the observed yields for the Eurozone countries compared to those of the non-Eurozone countries. Within the Eurozone group, we obtain implied yields that are very close to the observed yields for the

Figure 6. Implied Versus Observed Yields: Eurozone.



The plots show the observed (blue line) and the model-implied (red line) bond yields at 5-year maturity for Eurozone countries between the 1^{st} of January 2010 and the 1^{st} of February 2017. Bond yields are expressed in percentage terms. We compute the model-implied yields using the estimation methodology described in Section 4.

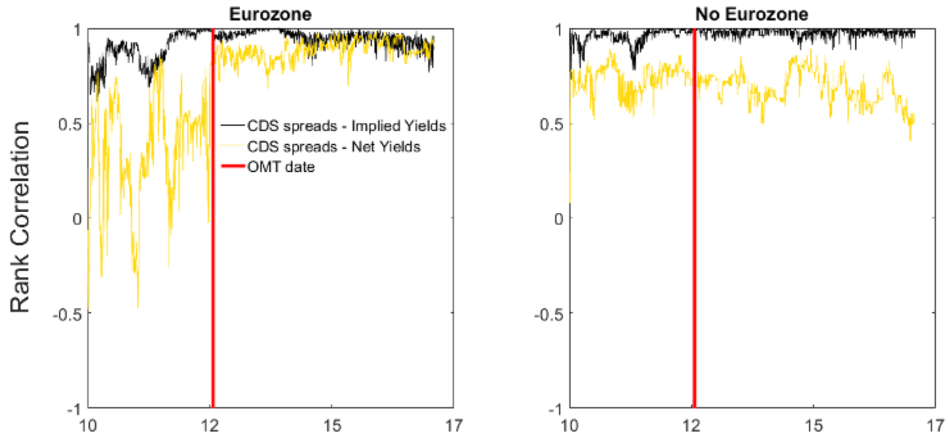
Figure 7. Implied Versus Observed Yields: Non-Eurozone.



The plots show the observed (blue line) and model-implied (red line) bond yields at 5-year maturity for the non-Eurozone countries, between the 1^{st} of January 2010 and the 1^{st} of February 2017. Bond yields are expressed in percentage terms. We compute the model-implied yields using the estimation methodology described in Section 4.

core countries in the second part of the time series. At the opposite, the non-Eurozone countries show a persistent distance between implied and observed yields over the entire time series.

Figure 8. CDS Spreads - Net Yields: Cross-sectional Correlations.



The top plots show the cross-sectional rank correlation between sovereign CDS spreads and model-implied yields (black line), and between sovereign CDS spreads and net yields (yellow line) at 5-year maturity across Eurozone (left panel) and non-Eurozone countries (right panel) between the 1^{st} of January 2010 and the 1^{st} of February 2017. We compute the model-implied yields using the estimation methodology described in Section 4, and we compute the net yields as the difference between observed and model-implied yields.

4.4. Correlation Analysis

We now focus on the main result of the paper: computing the cross-sectional correlation for each point in time between CDS spreads and net bond yields across our sample countries. For each point in time, we compute the Spearman correlation coefficient between CDS spreads and bond yields using both implied and net yields across the sample countries. The next figure graphically represents the main result of the paper. Figure 8 shows the dynamics of the cross-sectional correlations between the 5-year CDS spreads and the implied bond yields, and between the 5-year CDS spreads and the net yields for the Eurozone and non-Eurozone countries, respectively.

The plots show that the correlation between CDS spreads and implied yields is close to 1 over the entire time series and for both groups of countries. This result is natural since the implied yields are estimated using the CDS spreads. Moreover, the correlation is not perfectly equal to 1, as the model is subject to error. The yields obtained by MC simulations are also subject to error.

More importantly, the yellow line 8 shows the dynamics of the cross-sectional correlation between CDS spreads and net yields. The correlation randomly moves around zero for the

Table 5. Correlation CDS spreads - Bond Yields.

	Eurozone			Non-Eurozone		
	Obs Yields	Imp Yields	Net Yields	Obs Yields	Imp Yields	Net Yields
Before OMT	0.883	0.938	0.367	0.956	0.895	0.737
	(0.003)	(0.000)	(0.275)	(0.000)	(0.002)	(0.026)
After OMT	0.951	0.927	0.885	0.978	0.818	0.683
	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.044)

The table reports the cross-sectional rank correlation between sovereign CDS spreads and observed bond yields, between sovereign CDS spreads and model-implied bond yields, and between sovereign CDS spreads and net yields at 5-year maturity across Eurozone and non-Eurozone countries before (January 1, 2010 - July 25, 2012) and after (July 26, 2012 - February 1, 2017) the OMT announcement date. We compute the model-implied yields using the estimation methodology described in Section 4, and we compute the net yields as the difference between observed and model-implied yields. We report p -values in parentheses.

Eurozone countries before the OMT announcement, then approaches 1 right after the OMT announcement, and remains stable afterwards. It turns out that, before the OMT announcement, the differences between sovereign bond yields across the Eurozone countries are not consistent with the cross-sectional differences in terms of default risk, and this consistency is restored right after the announcement.

This result is even more interesting if we compare Eurozone and non-Eurozone countries. In fact, non-Eurozone countries do not show any change over time in the cross-sectional correlation between CDS spreads and net yields. The correlation is stable over the entire time series, never approaching 1.

Table 5 reports the average correlation between CDS spreads and the different measures of bond yields across countries in each group for the two periods (i.e., before and after the OMT announcement). The average correlation between CDS spreads and both actual and implied yields is very close to 1 for both groups in each period. The average correlation across Eurozone countries between CDS spreads and net yields is more than double in the second period compared to the first period. This correlation, instead, is very similar across the two periods for non-Eurozone countries and is even lower after the OMT announcement.

4.5. Net Yields and Arbitrage Strategy

To corroborate our findings, we construct long-short portfolio strategies based on the net yields to exploit the deviation of the observed yields from the model-implied yields that are consistent with the default risk priced in the CDS spreads. For each point in time, we classify the sample countries as *undervalued* when the net yield is positive and as *overvalued* when the net yield is negative.

If the i-th country is undervalued, the arbitrageur sells the risk-free asset and purchases the CDS and risky bond issued by the CDS reference entity. Otherwise, if the i-th country is overvalued, the arbitrageur purchases the risk-free asset and sells the risky bond and CDS to obtain the risk-free profit.

The implementation of this strategy works exactly as for the arbitrage strategy described in Section 3. The difference between the two strategies is only given by the signal of the riskless profit opportunity arising on the market. In the first strategy, the signal is the zero-basis condition. In this strategy, the signal is the distance between the observed and implied yields.

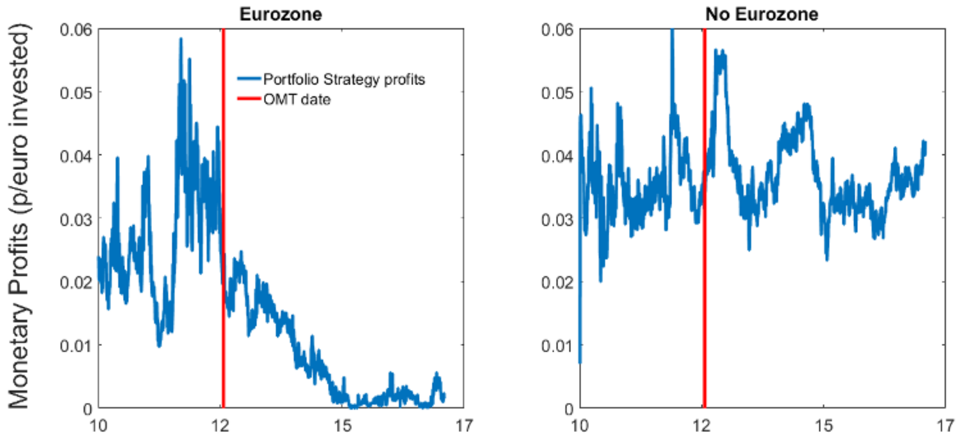
In Figure 9, we compare the profits obtained on an equally weighted portfolio across countries by trading assets of Eurozone and non-Eurozone countries, respectively, using the arbitrage strategy described in this section. The profits reported in Figure 9 are very similar to those presented in Figure 3. Arbitrage opportunities are persistent for both groups of countries before the OMT announcement; however, they quickly converge to zero for the Eurozone countries after the announcement of the OMT program.

Table 6 reports the mean and standard deviation of the arbitrage profits before and after the OMT announcement for the Eurozone and non-Eurozone countries, respectively. Table 6 shows a pronounced difference in the average profits between the two periods for the Eurozone countries. Further, the standard deviation drops sensibly after the OMT announcement. Such numbers indicate that, after the OMT announcement, the arbitrage opportunities are approximately zero. Instead, for the non-Eurozone area, Table 6 reports similar figures for the mean and standard deviation between the two periods. The differences between the two periods, in fact, are not statistically different from zero.

5. Arbitrage and Transaction Costs

Arbitrage opportunities can persist in the market if the riskless profits are insufficient to cover the costs to implement the arbitrage strategy. The idea is that arbitrageurs enter

Figure 9. Arbitrage Profits - Strategy 2.



The figure shows the arbitrage profits on an equally weighted across-country portfolio of sovereign CDSs and bonds using portfolio strategy 2 between the 1^{st} of January 2010 and the 1^{st} of February 2017. The strategy is implemented using either Eurozone sovereign CDSs and bonds only (left panel), or non-Eurozone sovereign CDSs and bonds only (right panel). The profits are expressed in monetary terms assuming a nominal value of 1 for the bonds, and the CDS price is computed as the present value of the CDS spreads expressed in percentage terms. The red line stands for the OMT announcement date.

Table 6. Arbitrage Profits - Strategy 2.

Statistic:	Before OMT	After OMT	Difference
Eurozone			
Mean	0.029	0.003	-0.027*
Std. Dev.	0.012	0.005	
Non-Eurozone			
Mean	0.020	0.012	-0.008
Std. Dev.	0.013	0.017	

The table reports the mean and standard deviation of the profits on an equally weighted across-country portfolio of sovereign CDSs and bonds using portfolio strategy 2 before (January 1, 2010 - July 25, 2012) and after (July 26, 2012 - February 1, 2017) the OMT announcement date. The strategy is implemented using either Eurozone sovereign CDSs and bonds only, or non-Eurozone sovereign CDSs and bonds only. The profits are expressed in monetary terms assuming a nominal value of 1 for the bonds, and the CDS price is computed as the present value of the CDS spreads expressed in percentage terms. In the last column, we report the difference across the two periods. The * indicates that the difference is significant at the 5% level.

the market only if the arbitrage strategy still generates profits once the transaction costs have been paid. Therefore, we control for transaction costs in two ways. First, we use bid and ask prices of sovereign bonds and CDS for our sample countries to compute the performance of the two arbitrage strategies, and we check whether the strategies are still

Table 7. Bid-Ask Spreads.

	Bond		
	Euro-Core	Euro-Periphery	Non-Eurozone
Before OMT	2.55	22.83	7.02
After OMT	0.87	8.46	9.10
	CDS		
	Euro-Core	Euro-Periphery	Non-Eurozone
Before OMT	5.20	14.95	7.82
After OMT	4.01	10.56	7.82

The table reports the average bid-ask spread for bonds and CDSs across countries for the three groups of countries before (January 1, 2010 - July 25, 2012) and after (July 26, 2012 - February 1, 2017) the OMT announcement date. The spreads are expressed in basis points. Both CDSs and bonds are at 5-year maturity.

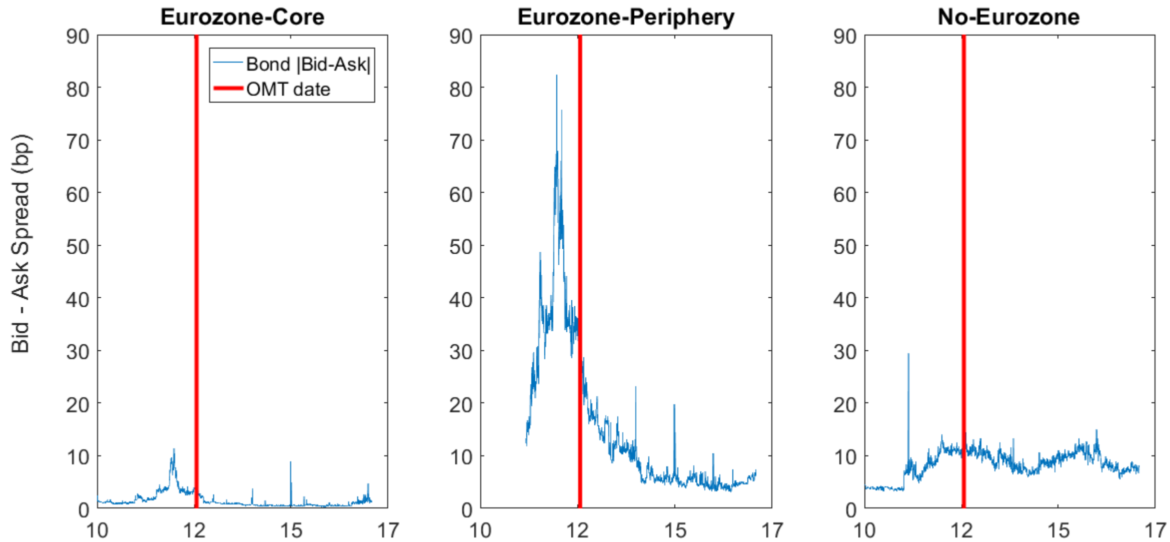
profitable. Second, we estimate the threshold beyond which the riskless trading gains become sufficiently profitable.

5.1. Bid-Ask Prices

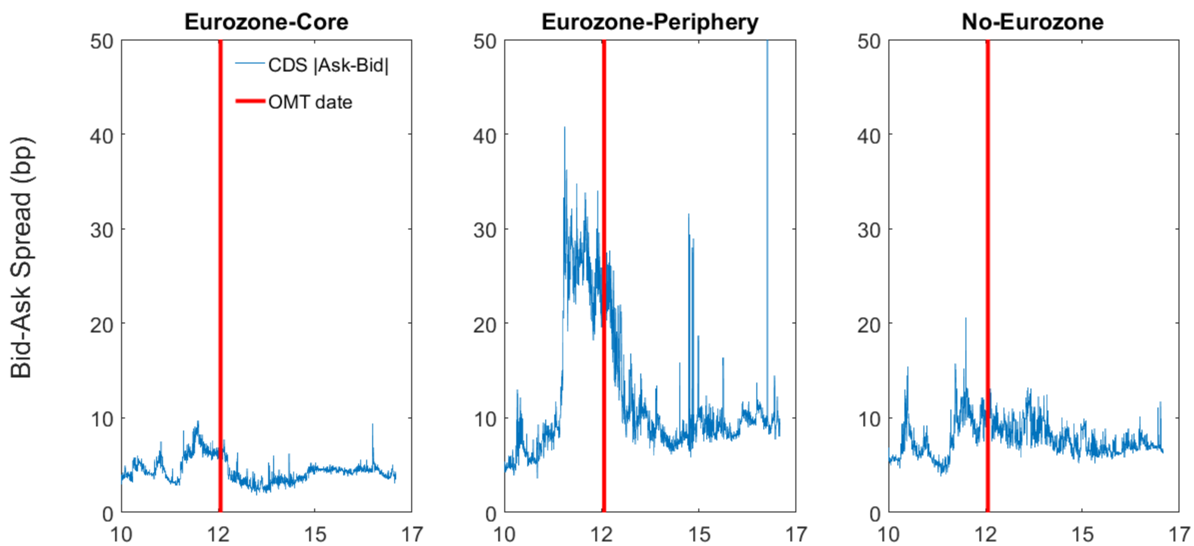
In this section, we use bid and ask prices for CDS and bonds between January 2010 and February 2017. We compute the bid-ask spread for our sample countries at each time t for both assets. Figure 10 shows the average bid-ask spread across countries on the 5-year maturity bond (top panel) for Eurozone-core, Eurozone-periphery, and non-Eurozone countries, respectively. The plots show that, for both the Eurozone groups, the average spread has a spike during the sovereign debt crisis followed by a strong and persistent reduction over the subsequent years. Albeit the two Eurozone groups show similar dynamics, the average spread across the peripheral countries is higher in magnitude compared to the average spread across the core countries, in particular before the OMT announcement. The average bid-ask spread across the non-Eurozone countries, instead, is substantially persistent across the two periods. Similar discussion applies to the CDS (bottom panel). However, the reduction in the average bid-ask spread for both the Eurozone groups occurs right after the OMT announcement. In Table 7, we report the average bid-ask spread across countries for bonds (top panel) and CDS (bottom panel) for the three groups of countries before and after the OMT announcement date.

Using data on bid-ask spreads, we compute the riskless profits generated by the two

Figure 10. Bid-Ask Spreads.



The figure shows the average 5-year maturity bond bid-ask spread across countries for the three groups of countries between the 1st of January 2010 and the 1st of February 2017. The spreads are expressed in basis points. The red line stands for the OMT announcement date.

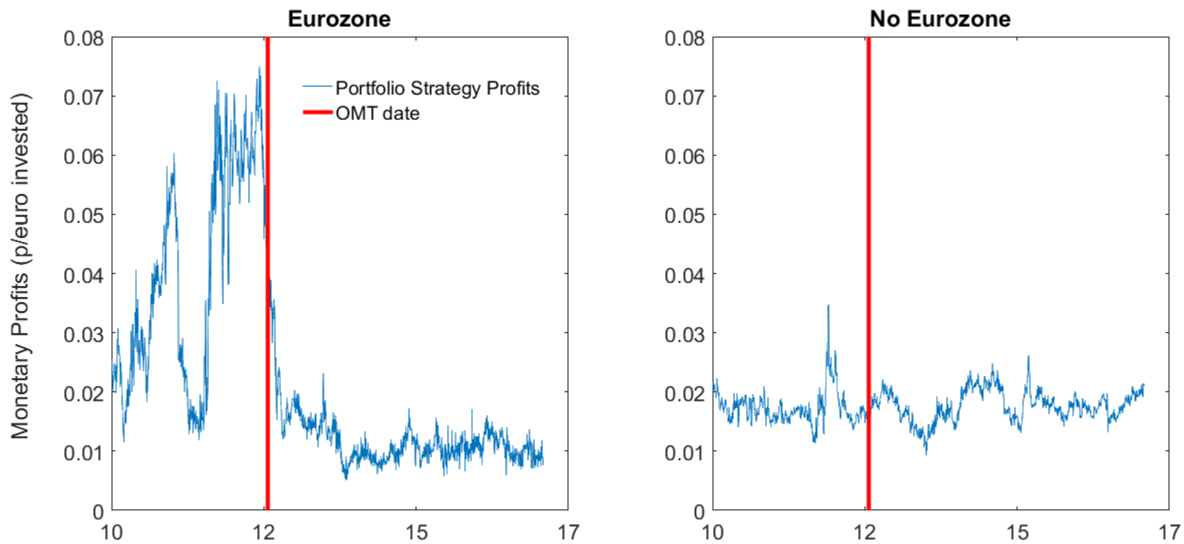


The figure shows the average 5-year maturity CDS bid-ask spread across countries for the three groups of countries between the 1st of January 2010 and the 1st of February 2017. The spreads are expressed in basis points. The red line stands for the OMT announcement date.

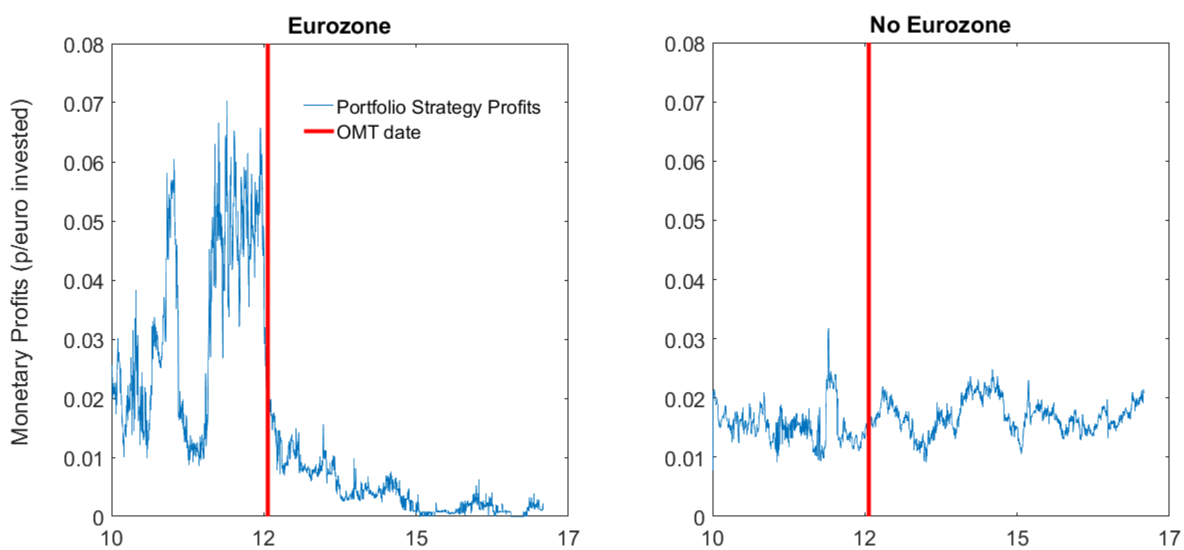
arbitrage strategies described in the previous sections. By doing that, we use the actual price that an arbitrageur should pay to implement the strategy: the bid price, when the arbitrageur sells the asset, and the ask price, when the arbitrageur buys the asset. In Figure 11, we plot the profits generated by arbitrage strategy 1 (top panel) and arbitrage strategy 2 (bottom panel), described in Sections 3 and 4, respectively. The plots show that the arbitrage profits computed with bid and ask prices have very similar patterns to the arbitrage profits computed using only one price for each asset.[1]

[1]Differences in magnitude between the profits computed in this section compared to those calculated in Sections 3 and 4 are due to the different data sources of the CDS prices. The CDS market is an over-the-counter market; therefore, different data providers may report different prices. We use Datastream-Thomson Reuters in Sections 3 and 4, and we use Bloomberg in this section.

Figure 11. Arbitrage Profits.



The figure shows the arbitrage profits on an equally weighted across-country portfolio of sovereign CDSs and bonds between the 1^{st} of January 2010 and the 1^{st} of February 2017 using portfolio strategy 1, for which each transaction occurs at the quoted bid or ask price. The strategy is implemented using either Eurozone sovereign CDSs and bonds only (left panel), or non-Eurozone sovereign CDSs and bonds only (right panel). The profits are expressed in monetary terms assuming a nominal value of 1 for the bonds, and the CDS price is computed as the present value of the CDS spreads expressed in percentage terms. The red line stands for the OMT announcement date.



The figure shows the arbitrage profits on an equally weighted across-country portfolio of sovereign CDSs and bonds between the 1^{st} of January 2010 and the 1^{st} of February 2017 using portfolio strategy 2, for which each transaction occurs at the quoted bid or ask price. The strategy is implemented using either Eurozone sovereign CDSs and bonds only (left panel), or non-Eurozone sovereign CDSs and bonds only (right panel). The profits are expressed in monetary terms assuming a nominal value of 1 for the bonds, and the CDS price is computed as the present value of the CDS spreads expressed in percentage terms. The red line stands for the OMT announcement date.

The persistence of riskless profits across Eurozone countries before the OMT announcement date and across non-Eurozone countries before and after the OMT announcement date suggests that there are costs to implement the strategies not explained by the bid-ask spread. These costs, which prevent investors from exploiting the mispricing in the sovereign bond market, are not observable. Therefore, in the next section, we estimate such costs.

5.2. Estimating Transaction Costs

For each country, we estimate a vector error correction model (VECM) that includes CDS spreads and bond yields in excess of the risk-free rate adjusted for the nonlinearity due to the transaction cost threshold (TVECM). In a linear VECM, any deviation from the long-run equilibrium (zero-basis condition) would trigger trades leading the market back to the equilibrium. It turns out that, in absence of frictions, such as transaction costs, we should observe a basis moving around zero. Instead, when frictions arise in the market, we expect to observe a persistent deviation from the equilibrium. In particular, with non-zero transaction costs, the deviation should persist as long as the magnitude of the deviation is below a given threshold, which introduces nonlinearity in the error correction model.

Following Gyntelberg et al. (2017), we model CDS spreads and excess risky bond yields in vector form as follows:

$$\Delta y_t = [\lambda^L ec_{t-1} + \Gamma^L(\ell)\Delta y_t] d_{Lt}(\beta, \theta) + [\lambda^U ec_{t-1} + \Gamma^U(\ell)\Delta y_t] d_{Ut}(\beta, \theta) + \epsilon_t,$$

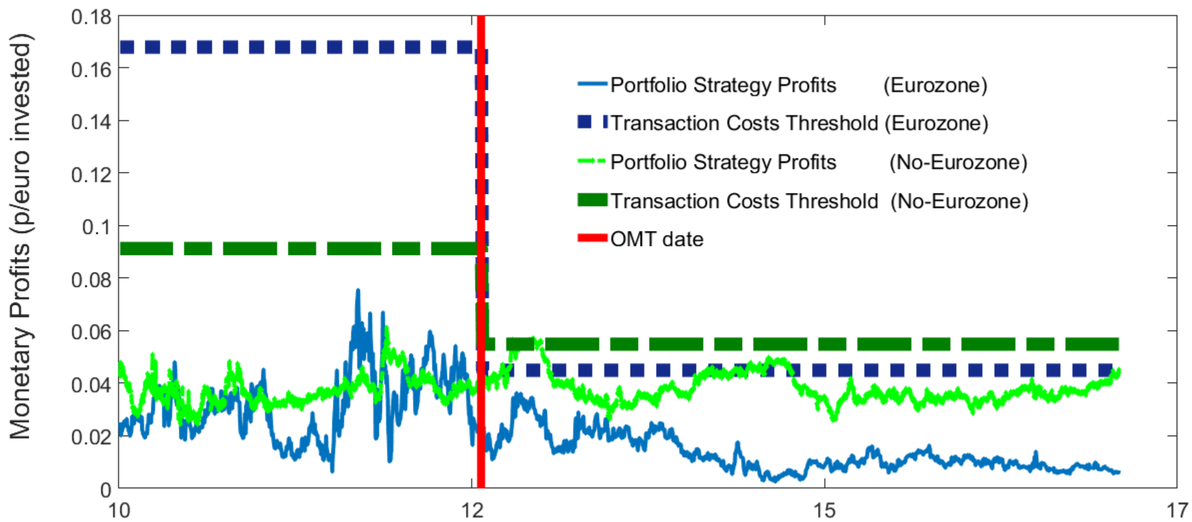
where $ec_{t-1} = CDS_{t-1} - \beta_0 - \beta_1 ER_{t-1}$ is the error correction term with ER standing for the excess risky bond yield, $\Gamma(\ell)\Delta y_t$ is the VAR term of order ℓ, and ϵ_t are white noise shocks. Moreover, d_{Lt} and d_{Ut} are defined as follows:

$$d_{Lt} = I(ec_{t-1} \leq \theta)$$

$$d_{Ut} = I(ec_{t-1} > \theta),$$

where I is an indicator function, and θ is the threshold to be estimated. We force β_1 to be equal to 1, and we estimate β_0. An estimate of β_0 different from zero stands for a persistent non-zero basis. Therefore, the average transactions costs faced by the arbitrageurs are given

Figure 12. Arbitrage Profits and Transaction Costs.



The figure shows the profits generated by arbitrage strategy 1 for Eurozone countries (blue line) and non-Eurozone countries (green line) against the average transaction costs across Eurozone countries (blue dotted line) and non-Eurozone countries (green dotted line), respectively, between the 1^{st} of January 2010 and the 1^{st} of February 2017. The red line stands for the OMT announcement date.

by $\theta + \beta_0$. We estimate the model following the approach of Hansen and Seo (2002), who estimated a two-regime TVECM using a maximum likelihood algorithm. We also estimate the model for two periods: before and after the OMT announcement. As result, we obtain an estimate of the average transaction costs for each country and for each period. Table 8 reports our results.[2]

We find that, in general, the key threshold is substantially higher before the OMT announcement (the average transaction costs across countries is 922 bp) compared to the second period (384 bp). This result is consistent with the findings of Gyntelberg et al. (2017), who estimate a threshold more than twice higher during the Eurozone sovereign debt crisis compared to that of the pre-crisis period. Moreover, we find that the drop in the average transaction costs across the two periods is much more pronounced for Eurozone countries

[2]The statistical significance of the thresholds is evaluated following the approach of Hansen and Seo (2002), who calculate standard errors by means of both parametric and non-parametric bootstrap analysis. Gyntelberg et al. (2017) provide a short description of the two alternative bootstrap procedures and the decision criterion for the threshold statistical significance.

Table 8. Average Transaction Costs.

Countries	Before OMT	After OMT	% Diff
Austria	0.0152	0.0025	-83
Belgium	0.0468	0.0073	-84
Finland	0.0105	0.0036	-66
France	0.0131	0.0060	-54
Germany	0.0133	0.0013	-90
Netherlands	0.0098	0.0059	-40
Average Core	**0.0181**	**0.0044**	**-75**
Ireland	0.2466	0.0312	-87
Italy	0.1255	0.0508	-59
Portugal	0.4179	0.0897	-78
Slovakia	0.0723	0.0131	-81
Slovenia	0.0321	0.0368	+14
Spain	0.1123	0.0479	-57
Average Peripheral	**0.1678**	**0.0449**	**-73**
Average Eurozone	**0.0930**	**0.0247**	**-73**
Bulgaria	0.1132	0.0542	-52
Croatia	0.1958	0.1161	-40
Czech Republic	0.0303	0.0084	-72
Denmark	0.0152	0.0044	-71
Hungary	0.2156	0.0975	-54
Norway	0.0111	0.0407	+268
Poland	0.1170	0.0789	-32
Romania	0.2012	0.1034	-48
Sweden	0.0070	0.0109	+56
United Kingdom	0.0057	0.0340	+495
Average Non-Eurozone	**0.0912**	**0.0548**	**-39**
All Countries	**0.0922**	**0.0384**	**-58**

The table reports the average transaction costs ($\theta + \beta_0$) for each country before (January 1, 2010 - July 25, 2012) and after (July 26, 2012 - February 1, 2017) the OMT announcement date. The average transaction costs are expressed in percentage terms. The last column reports the variation in percentage terms across the two time periods for each country. We also report the mean across groups of countries (Eurozone core, Eurozone-peripheral, and non-Eurozone).

(from 930 bp to 247 bp), and in particular for the peripheral countries (from 1678 bp to 449 bp), with respect to non-Eurozone countries (from 912 bp to 548 bp).

Next, we compare the estimated transaction costs with the potential arbitrage profits across groups of countries by splitting our sample in two groups (Eurozone and non-Eurozone). However, our results hold if we again split the Eurozone countries in two subsamples (core and peripheral). The plot in Figure 12 offers a straightforward interpretation of our results.

Before the OMT announcement, we estimate similar average transaction costs across groups of countries, and transaction costs are above the arbitrage profits for both groups of countries. Therefore, the arbitrageurs do not have an incentive to intervene and clear the arbitrage opportunities, as the riskless profits are not even sufficient to cover the costs to implement the strategy. Consequently, over this period, there is a persistent deviation from the zero-basis equilibrium condition.

After the OMT announcement, we estimate a strong reduction of the average transaction costs across the Eurozone countries. Then, the arbitrageurs find it profitable to enter the market and take advantage of the deviation from the equilibrium condition. Consequently, the arbitrage profits quickly converge to zero. In other words, the lower transaction costs have created the condition for the traders to profit from the arbitrage opportunities generated by the relative mispricing between CDS spreads and bond yields, thus leading the sovereign debt market back to equilibrium (zero basis).

On the other hand, this condition does not occur for the non-Eurozone countries. The reduction in the threshold, in fact, is not enough to create the condition for the traders to clear the arbitrage opportunities. Therefore, we observe a persistent mispricing between CDS spreads and bond yields even after the OMT announcement.

6. Conclusion

In the paper, we conduct an empirical investigation of the relationship between sovereign CDS spreads and sovereign bond yields. In summary, we document that, after the announcement of the OMT program by the ECB, the consistent cross-sectional relationship between CDS spreads and bond yields across Eurozone countries is restored.

We document a deviation from the no-arbitrage theoretical relationship between CDS spreads and bond yields over the time series for our sample countries. However, we show that such deviation does not affect the monotonicity in the cross-sectional relationship between CDS spreads and bond yields. Then, we show that the violation of the zero-basis equilibrium condition generates instead inconsistency in the cross section of the bond yields across countries with respect to the differences in terms of default risk priced in the CDS spreads. The differences across countries in terms of default risk, which is priced in the CDS spreads, are not consistently priced in the cross section of the bond yields. This inconsistent cross-sectional relationship vanishes after the OMT announcement for the Eurozone countries only.

Further investigation should focus on the big challenge of isolating the long-term effects of the OMT program on the relative pricing of the sovereign credit securities to prove and identify a robust causal relationship. The main issue in a sovereign analysis is created by the unavoidable interaction between external and internal factors that are simultaneously at work. With this paper, we want to highlight crucial evidence for the analysis of the risk-return relationship, linking this cornerstone of the financial theory with macro-economic and monetary events, awaiting further and deeper research.

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A. Kalman Filter and Quasi-Maximum Likelihood Estimation

In a general formulation with a nonlinear relationship between the measurement and the state variables, the state-space model is defined by two sets of equations: the transition and measurement equations, respectively:

$$X_{i,t+\delta t} = X_{i,t} + c_i + \epsilon_{i,t+\delta t},$$

$$Y_{i,t+\delta t} = \psi(X_{i,t+\delta t}) + u_{i,t+\delta t},$$

where $X_{i,t+\delta t}$ is the i-th observation of the state variable at time $t+\delta t$, c_i is the time-invariant component driving the evolution of the state variable, and $\epsilon_{i,t+\delta t}$ is the transition error on the i-th observation of the state variable at time $t+\delta t$. On the other hand, $Y_{i,t+\delta t}$ is the i-th observation of the measurement variable at time $t+\delta t$, ψ is the measurement function that links the observable and latent variable, and $u_{i,t+\delta t}$ is the measurement error.

For a Gaussian state-space model, under standard assumptions, the discrete Kalman filter is proved to be the minimum mean squared error estimator. However, in the case of a nonlinear relation between the measurement and state variable, the classic linear Kalman filter is no longer optimal. One possible solution is to linearize the estimation around the current estimate using the partial derivatives of the process and measurement functions. To linearize the measurement process, we must compute the derivatives of ψ with respect to the following:

(a) the state variable: $H_{i,j} = \frac{\partial \psi_i}{\partial X_j}(\tilde{X}_t, 0)$,

where H is the Jacobian matrix of partial derivatives of the generic measurement function $\psi(\cdot)$ with respect to the state variable X, and $\tilde{X}_t$ is the current estimate of the state.

(b) the measurement noise: $\breve{H}_{i,j} = \frac{\partial \psi_i}{\partial \nu_j}(\tilde{X}_t, 0)$,

where $\tilde{H}$ is the Jacobian matrix of partial derivatives of $\psi(\cdot)$ with respect to the noise term ν.

Once the linearization has been completed, we can implement the discrete Kalman filter in the usual steps. First, we must set the *initial conditions*:

$$\lambda_{i,0} \quad P_{i,0},$$

where $P_{i,t} := var[X_{i,t} - \lambda_{i,t}]$ is the variance of the estimation error, and $\lambda_{i,t}$ is the estimate of the state at time t based on the information available up to time t. Then, the filter implementation is based upon two sets of equations, the *predicting* equations and the *updating* equations, which must be repeated for each time step in the data sample.

- *State Prediction*

$$\lambda_{i,t+\delta t/t} = \lambda_{i,t} + c_i,$$

and

$$P_{i,t+\delta t/t} = P_{i,t} + Q_i,$$

where $\lambda_{i,t+\delta t/t}$ is the estimate of the state at time $t+\delta t$ based on the information available up to time t, and Q_i is the covariance of the transition noise.

- *Measurement Update*

$$\lambda_{i,t+\delta t} = \lambda_{i,t+\delta t/t} + P_{i,t+\delta t/t} H^{'}_{i,t+\delta t} Z^{-1}_{i,t+\delta t} \left(Y_{i,t+\delta t} - \psi(\lambda_{i,t+\delta t/t}) \right)$$

$$P_{i,t+\delta t} = P_{i,t+\delta t/t} - P_{i,t+\delta t/t} H^{'}_{i,t+\delta t} Z^{-1}_{i,t+\delta t} H_{i,t+\delta t} P_{i,t+\delta t/t}$$

$$Z_{i,t+\delta t} = H_{i,t+\delta t} P_{i,t+\delta t/t} H^{'}_{i,t+\delta t} + R_i,$$

where H stands for the Jacobian matrix of partial derivatives of the generic measurement function ψ with respect to the state variable X, and $Z_{i,t+\delta t}$ is the covariance matrix of the prediction errors at time $t+\delta t$. The prediction errors are defined as $v_{i,t+\delta t} = Y_{i,t+\delta t} - \psi(\lambda_{i,t+\delta t/t})$, where $Y_{i,t+\delta t}$ is the observation of the measurement variable at time $t+\delta t$.

The parameters that describe the dynamics of the transition and the measurement equations (i.e., *hyperparameters*) are unknown and must be estimated.

We rewrite the state-space model as follows:

$$(y_{t+\delta t}, x_{t+\delta t}) = (x_t, \{\theta\}), \quad \{\theta\} = \{\theta^{(f)}; \theta^{(g)}\}$$

, where $y_{t+\delta t}$ is the observable variable at time $t+\delta t$, $x_{t+\delta t}$ is the state variable at time $t+\delta t$, $\{\theta^{(f)}\}$ is the set of unknown parameters in the transition equation, and $\{\theta^{(g)}\}$ is the set of unknown parameters in the measurement equation. The measurement and transition equations of the system are as follows:

$$g(y_{t+\delta t}, \alpha) = \varphi(x_{t+\delta t}, \beta) + \epsilon_{t+\delta t}, \quad \epsilon_t \backsim \mathcal{N}(0, \sigma^2_\epsilon)$$

$$x_{t+\delta t} = f(x_t, \gamma) + \eta_{t+\delta t}, \quad \eta_t \backsim \mathcal{N}(0, \sigma^2_\eta).$$

Then,

$$\{\theta^{(f)}\} = \{\gamma, \sigma_\eta^2\}$$

$$\{\theta^{(g)}\} = \{\alpha, \beta, \sigma_\epsilon^2\}.$$

We assume that the nonlinear regression disturbance ϵ_t is normally distributed:

$$f(\epsilon_t) = \frac{1}{\sqrt{2\pi\sigma_\epsilon^2}} \exp\left[-\frac{\epsilon_t^2}{2\sigma_\epsilon^2}\right].$$

By transformation of the variable, the density of y_t is given by the following:

$$f(y_t) = f(\epsilon_t)\left|\frac{\partial \epsilon_t}{\partial y_t}\right|, \quad \frac{\partial \epsilon_t}{\partial y_t} = \frac{\partial g(y_t, \alpha)}{\partial y_t}.$$

Then, the density of y_t is as follows:

$$f(y_t) = \frac{1}{\sqrt{2\pi\sigma_\epsilon^2}} \exp\left[-\frac{(g(y_t,\alpha) - \varphi(x_t,\beta))^2}{2\sigma_\epsilon^2}\right]\left|\frac{\partial g(y_t,\alpha)}{\partial y_t}\right|.$$

The log-likelihood function for observation t is the following:

$$\ln \Omega_t\left(y_t; \{\theta\}\right) = -\frac{1}{2}\ln(2\pi) - \frac{1}{2}\ln(\sigma_\epsilon^2) - \frac{(g(y_t,\alpha) - \varphi(x_t,\beta))^2}{2\sigma_\epsilon^2} + \ln\left|\frac{\partial g(y_t,\alpha)}{\partial y_t}\right|,$$

and the log-likelihood function for $t = 1, 2, ..., T$ observations (i.e., $\delta t = 1$) is as follows:

$$\ln \Omega = \sum_{t=1}^{T} \ln \Omega_t\left(y_t; \{\theta\}\right) = -\frac{T}{2}\ln(2\pi) - \frac{T}{2}\ln(\sigma_\epsilon^2) - \frac{1}{2\sigma_\epsilon^2}\sum_{t=1}^{T}(g(y_t,\alpha) - \varphi(x_t,\beta))^2$$

$$+\sum_{t=1}^{T}\ln\left|\frac{\partial g(y_t,\alpha)}{\partial y_t}\right|.$$

As long as $g(y_t, \alpha) = y_t$, then we obtain the following:

$$f(y_t) = f(\epsilon_t) \Rightarrow \ln \Omega_t\left(y_t; \{\theta\}\right) = \ln \Omega_t\left(\epsilon_t; \{\theta\}\right).$$

The last term in the log-likelihood function is equal to zero, and the space of the hyper-parameters to be estimated is reduced to the following:

$$\{\theta^{(f)}\} = \{\gamma, \sigma_\eta^2\}$$

$$\{\theta^{(g)}\} = \{\beta, \sigma_\epsilon^2\}.$$

In practice, the iteration of the filter generates a measurement-system prediction error and a prediction error variance at each step. Under the assumption that measurement-system prediction errors are Gaussian, we can construct the log-likelihood function as follows:

$$\ln \Omega(y_t; \{\theta\}) = \ln \prod_{t=0}^{T-\delta t} p\left(y_{t+\delta t/t}\right) = \sum_{t=0}^{T-\delta t} \ln p\left(y_{t+\delta t/t}\right) =$$

$$= -\frac{N}{2}\ln(2\pi) - \frac{1}{2}\sum_{t=0}^{T-\delta t} \ln|Z_{t+\delta t}| - \frac{1}{2}\sum_{t=0}^{T-\delta t} v_{t+\delta t}{}' Z_{t+\delta t}^{-1} v_{t+\delta t},$$

where N is the number of time steps in the data sample. Finally, this function is maximized with respect to the unknown parameter vector $\{\theta\}$. This is known as the *quasi-maximum likelihood* estimation, in conjunction with the nonlinear Kalman filter.

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