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Three essays on the interest rate cruve multiplicity in the interbank market

Tres ensayos sobre la multiplicidad de curvas de tipos de interés en el mercado interbancario

MEMORIA PARA OPTAR AL GRADO DE DOCTOR

PRESENTADA POR

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THREE ESSAYS ON THE INTEREST RATE CURVE MULTIPLICITY IN THE INTERBANK MARKET

TRES ENSAYOS SOBRE LA MULTIPLICIDAD DE CURVAS DE TIPOS DE INTERÉS EN EL MERCADO INTERBANCARIO

MEMORIA PARA OPTAR AL GRADO DE DOCTOR EN BANCA Y FINANZAS CUANTITATIVAS PRESENTADA POR

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Bajo la supervisión de
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To my family

”Your time is limited, so don’t waste it living someone else’s life. Don’t be trapped by dogma - which is living with the results of other people’s thinking. Don’t let the noise of others’ opinions drown out your own inner voice. And most important, have the courage to follow your heart and intuition. They somehow already know what you truly want to become. Everything else is secondary.”

Steve Jobs

Preface

This doctoral dissertation is composed of three independent essays focused on the analysis of interbank market spreads in the Euro-area during the post-crisis period and studying the fundamental variables explaining the interbank market interest rate curves multiplicity under different approaches. First, according to a practitioners perspective. Secondly, following asset pricing valuation techniques. Finally, considering econometric methods.

This dissertation consists of five chapters:

Chapter 1: Introduction. This chapter introduces the main chapters of the dissertation and explains the motivation and main contributions.

Chapter 2: Determinants of the multiple-term structures from interbank rates. This chapter, containing the first essay, studies the dynamic properties of interbank market spread curves considering a practitioners approach and emphasizes the role of credit and liquidity variables as determinants of these dynamics. The information content of the model residuals is also considered.

Chapter 3: The term structure of interbank counterparty risk. This chapter, containing the second essay, focuses on counterparty risk and also counterparty risk-premia information embedded in interbank spread quotes. The estimation is performed following asset pricing valuation techniques. The chapter analyzes the main sources of counterparty risk compensation.

Chapter 4: Interbank spreads permanent and transitory components and their relationship to credit and liquidity risks. This chapter, containing the third essay, studies the importance of the nature of shocks in the characterization of the asset pricing implications of credit and liquidity risks decomposing the interbank market spread series into transitory and permanent components using an econometric approach.

Chapter 5: Conclusions. This chapter summarizes the most relevant results and outlines future areas of research.

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Resumen

Esta tesis lleva por título ”Tres ensayos sobre la multiplicidad de curvas de tipos de interés en el mercado interbancario” y está compuesta por tres artículos de investigación independientes en los que se analiza la evolución de los diferenciales del mercado interbancario del Euro en el periodo post-crisis. El objetivo es obtener información embebida en las cotizaciones de estos diferenciales emplenado distintas metodologías e identificar las variables que subyacen al fenómeno de la multiplicidad de curvas, caracterizando el papel que juegan a la hora de explicar esta evolución. El análisis se realiza según una aproximación cercana a la práctica de mercado (Capítulo 2), siguiendo técnicas de valoración de activos (Capítulo 3) y finalmente considerando métodos econométricos (Capítulo 4).

El Capítulo 2, que incluye el primer ensayo, se centra en la evolución dinámica de las distintas curvas de tipos de interés surgidas a raíz de la crisis -diferenciadas por la periodicidad de pago del tipo de interés subyacente- a través del estudio de sus diferenciales respecto a la curva *overnight*. La metodología empleada es similar a la de Diebold and Li (2006) y se resume en tres factores principales que se interpretan como nivel, pendiente y curvatura. El análisis de componentes principales de estos factores para distintas periodicidades muestra que existen patrones comunes entre los factores de las diferentes curvas, en particular el primer componente principal explica el 90% de su variación. El estudio de los determinantes de estos factores revela importantes conclusiones sobre las fuentes de este patrón. En concreto, se observa que el nivel tiene una relación muy importante con el riesgo de crédito. Asimismo, el estudio del contenido informacional de los errores residuales del modelo -mediante el cómputo de la medida de ruido de Hu et al. (2013)- nos lleva a concluir que estos residuos tienen relación con la liquidez. El análisis de estos datos empleando téncicas VAR refuerza estos resultados.

En el segundo de los ensayos incluido en el Capítulo 3 se estudia la estructura temporal del riesgo de contrapartida asociada a prestar o pedir prestado a distinta periodicidad en el mercado interbancario. Motivados por los resultados del Capítulo 2 consideramos una única fuente de incertidumbre para el riesgo de contraparte y seguimos la metodología de Pan y Singleton (2008) para inferir esta información de las cotizaciones de spreads interbancarios. Realizamos este ejercicio

para las distintas periodicidades de spreads y comparamos los resultados, observando la importancia del riesgo de contraparte, que se relaciona con el riesgo de crédito, y encontrando importantes patrones comunes entre las distintas periodicidades. También se estudian las razones por las cuales los agentes piden compensación por riesgo de contraparte mediante la consideración de varias variables explicativas y su relación con las primas de riesgo. Este análisis revela que la incertidumbre sobre el crédito en el mercado financiero, la liquidez y el nivel de aversión al riesgo de los agentes juegan un papel importante a la hora de explicar por qué el mercado está reflejando estas primas.

En el tercer ensayo, incluido en el Capítulo 4 y motivado por resultados del Capítulo 2 y 3, se descompone las series de diferenciales de las curvas interbancarias en dos factores latentes, un componente transitorio y otro permanente, con el objetivo de tener en cuenta la distinta naturaleza de las fuentes de la multiplicidad de curvas. Empleamos el modelo de Adolfatto et al. (2008) para la especificación de la ecuación de estado y el método de Filtro de Partículas para resolverla. Se observa la relación de estos componentes con el riesgo de crédito y liquidez a fin de caracterizar más detalladamente el impacto de estas variables sobre los diferenciales interbancarios. Los resultados obtenidos demuestran que los *shocks* de crédito y liquidez son de distinta naturaleza. Tomar en cuenta esta distinción introduce elementos nuevos que ayudan a identificar fuentes de heterogeneidad en el efecto de estas variables para las distintas curvas y vencimientos. En particular, concluimos que los *shocks* de crédito tienen un poder explicativo más importante que los *shocks* de liquidez. Para curvas con periodicidades cortas, los *shocks* de liquidez y crédito tienen un impacto permanente y su mayor efecto es en el corto y largo plazo, respectivamente. Sin embargo, para curvas con periodicidades largas, el impacto de los *shocks* de crédito se vuelve transitorio mientras que los *shocks* de liquidez siguen siendo permamentes y pasan a tener un mayor efecto sobre todos los vencimientos de la curva.

Finalmente, como conclusiones, destacar la importancia del riesgo de crédito como variable de primer orden a la hora de explicar el fenómeno de la multiplicidad de curvas y los fuertes patrones comunes en su impacto sobre las distintas curvas. En cuanto a fuentes de segundo orden enfatizar el papel nada desdeñable que juega la liquidez a través de su efecto en las primas de riesgo de los spreads interbancarios y la distinta naturaleza de su impacto respecto a los *shocks* de crédito. Tomar en consideración estas variables de segundo orden resulta de utilidad a la hora de observar ciertas heterogeneidades en el comportamiento de las curvas para distintos tenores y vencimientos.

Summary

This dissertation is entitled ”Three essays on the interest rate curve multiplicity in the interbank market” and it is structured in three independent research articles devoted to the analysis of Euro interbank market spreads in the post-crisis period. The goal is deriving information from spreads quotes considering different methodologies and identifying the underlying sources of the curve multiplicity phenomena, characterizing their explanatory role. The analysis is performed following different approaches. According to a practitioners perspective (Chapter 2), following asset pricing valuation techniques (Chapter 3) and finally considering econometric methods (Chapter 4).

Chapter 2 includes the first essay and studies the dynamic evolution of the different tenor curves emerged after the start of the crisis focusing on their differentials with respect to the overnight curve. The method that we consider is similar to Diebold and Li (2006) and it is summarized in three main factors interpreted as level, slope and curvature. The principal component analysis of these factors across tenors show important commonalities. More concretely, the first principal component accounts for 90% of these factors fluctuations across tenors. The study of these factors determinants yields important conclusions about the commonality sources. In particular, the level factor strongly relates to credit risk. Also, the study of the information content of the model residuals through the computation of the Hu et al. (2013) noise measure allows us to conclude that these residuals relate to liquidity. The analysis of the data considering VAR techniques confirms these results.

The second essay, contained in Chapter 3, studies the term structure of counterparty risk associated to borrowing and lending at different tenors in the interbank market. Motivated by Chapter 2 results we consider a single source of uncertainty to model counterparty risk and, following Pan and Singleton (2008) methodology, we infer counterparty risk information from interbank spread quotes. We apply the same methodology to different tenor spreads and compare the results noticing the important commonalities between different tenors counterparty risk intensities and their relationship to credit risk. The determinants of agents' risk compensation for counterparty risk uncertainty are also studied considering different explanatory variables. This study reveals that financial sector credit risk, liquidity and agents' level of risk aversion play an important role in order to explain interbank spreads counterparty risk-premium components.

In the third essay, included in Chapter 4 and motivated by Chapter 2 and 3 results, we decompose interbank market spread series into two latent, transitory and permanent, factors with the goal of accounting for the different nature of multi-curves drivers. We follow the specification of Adolfatto et al. (2008) for the state-space equation and the Particle-Filter methodology to solve it. We observe these components relationship to credit and liquidity variables in order to characterize more deeply their impact on interbank spreads. The results show evidence of the different nature of credit and liquidity shocks. Taking into account these components introduces new elements that help identifying sources of heterogeneity in the effect of credit and liquidity across tenors and maturities. In particular, we conclude that credit shocks display more important explanatory power compared to liquidity shocks. For shorter tenor curves, liquidity and credit shocks have a permanent impact and they have a more important effect at shorter and longer maturities, respectively. However, for longer tenor curves, credit shocks change their nature and become transitory while liquidity shocks remain permanent but in this case their impact is on the entire term structure.

Finally, to conclude, we would like to emphasize the importance of credit risk as first order effect variable explaining the curves multiplicity phenomena and the strong commonalities of its impact on the different curves. Concerning second order effect sources, it is worth highlighting the significant role of liquidity through its effect on risk premiums and the different nature of its impact compared to credit shocks. Taking into account these second order drivers is certainly useful in order to identify certain heterogeneities in the behaviour of the curves across tenors and maturities.

Chapter 1

Introduction

This dissertation, composed of three independent essays, deals with the interbank market interest rate multiplicity that has emerged since August 2007. In particular, we extract information embedded in interbank market spreads considering different methodologies with the purpose of shedding light on the main drivers behind interbank multiple curves.

This research is motivated by a set of important empirical facts that have affected the interbank market in recent times.

Since the start of the crisis, a market change of perceptions about the risks inherent in borrowing and lending operations between banks at different tenor has been reflected on deposit rates and also on the quotes of interest rate derivatives - whose payments are linked to these rates-.

The multiple curve framework appeared as a new practice followed by market makers given that the pre-crisis single-curve replication strategies were not supported by market derivatives quotes in the presence of these differential risks across tenors. This framework was an extension of the pre-crisis set-up where curves differentiated by tenor were considered and constructed with different tenor sets of derivative instruments. It is believed that interbank market fundamentals have changed since the beginning of the crisis and that the multiple-curve practice -prevalent since then- will be the new paradigm for interest rate derivatives valuation for the years to come.

Despite this evidence, literature about the topic has been very scarce, particularly among academics. In particular, little research has been devoted to a deep study and quantification of the sources of the multiple curves differentials. This dissertation tries to bridge a gap on this issue between academics and practitioners. We consider this research very relevant given the importance of over-the-counter interest rate transactions and the financial and economic implications of the interbank market.

In our analysis, we consider Basis Swap spreads, which are float-to-float interest rate swaps capturing the differences between the distinct tenor curves. In particular, we focus on Basis Swaps of the Euro interbank market corresponding to different tenor deposit rates with respect to the overnight rate, Eonia, which is considered an interbank market risk-free rate proxy. The consideration of Basis Swaps spreads term structures allows us to analyze the asset pricing implications of different sources comparing their role across tenors and also across maturities, providing a more complete analysis of the multiple-curve phenomena. Among these sources, we emphasize the role of credit and liquidity risks, disentangling their effect from other economic and financial explanatory drivers.

Each of the essays of this dissertation approaches this topic under a different perspective. The first essay, contained in Chapter 2, considers a practitioners perspective. The second essay, included in Chapter 3, follows an asset pricing valuation methodology. Finally the third essay, in Chapter 4, takes into account econometric techniques.

The practitioners approach followed in Chapter 2 is useful to study the dynamic evolution of the different interbank curves. This exercise is performed applying the Diebold and Li (2006) model and estimating the Nelson and Siegel (1987) level, slope and curvature factors associated to each tenor curve. The study of the commonalities of these factors across tenors and their relationship to credit and liquidity risks allows to compare the different curves pattern. The reasoning behind model price deviations is considered in the computation of the Hu et al. (2013) noise measure for different tenors and the analysis of its information content.

This chapter contributions emphasize the important commonalities behind the level, slope and curvature factors summarizing the distinct curves dynamics. In particular, the principal component analysis shows that there exists a single driver explaining the majority of these factors fluctuations across tenors and the analysis of their information content reveals that credit risk is the main source of the level changes. The information content behind the model residuals is also linked to a single variable, liquidity.

Chapter 3, focuses on counterparty risk information embedded in interbank spread curves, motivated by Chapter 2 results concerning the leading role of a single factor explaining spread curves level and its relationship to credit risk. In particular, we notice that the distinct tenor curves contain information about the term structure of counterparty risk associated to borrowing and lending at different frequency in the interbank market. Following an asset pricing valuation methodology, in particular Pan and Singleton (2008), we set up a one-factor affine continuous time model to estimate the different tenor curves counterparty risk intensities. In addition, modeling these intensities under risk-neutral and real world measures allows us to infer the interbank spreads risk-premium component that reflects agents' compensation for the counterparty risk uncertainty of spreads' underlying rates. This approach is useful to discriminate counterparty risk from risk-premium effects on interbank spreads. Studying the impact of different explanatory variables on these two components permits improving our understanding about the sources of interbank spreads fluctuations. Along the lines of Chapter 2, model residuals are analyzed in order to keep track of the information left unexplained by the model.

This chapter contributions highlight the magnitude of counterparty risk intensities and the important commonalities across tenors. Their relationship to credit variables is noticeable, particularly to German CDS spreads, which can be interpreted as a state variable summarizing the level of risk agents are willing to bear in interbank deposit borrowing and lending transactions. Risk-premium commonalities are also important reflecting that the same explanatory variables underlie their changes, particularly financial sector specific variables -credit and liquidity- and also risk aversion. The analysis of the determinants of the model residuals yields similar results to Chapter 2 as we find that they relate to liquidity.

The econometric approach considered in Chapter 4 separates the fluctuations in the interbank spread series into two distinct latent components. Chapter 4 motivations depart from Chapter 2 and Chapter 3 results concerning the relationship of model price deviations, which a priori may be expected to be transitory, to liquidity. Chapter 4 goal is accounting for the different nature of multi-curves drivers. This goal is achieved by formulating a state-space equation problem following the specification of Adolfatto et al. (2008). Under this specification the transitory factor is modeled as an stationary autoregressive process while the permanent factor changes its level according to a Bernoulli process. The state-space equation is solved with the Particle-Filter method, which is a Monte Carlo sequential approach. The study of the relationship of these components to different economic and financial explanatory variables is useful to observe whether the impact of credit and liquidity shocks -apart from other explanatory variables- depends on the factor. It is also helpful to derive conclusions about the explanatory power of the different components and shocks, across tenors and maturities. This allows to characterize more deeply the impact of credit and liquidity shocks on interbank spreads and understanding the reasons for the different behaviour of the distinct tenor curves.

This chapter contributions shed light on the importance of considering the nature of credit and liquidity shocks in order to explain the multiple curve phenomena. The heterogeneity of the effect of these shocks across tenors and maturities can be explained by the different nature of their impact. These heterogeneities also help to explain the differences in the distinct tenor curves behaviour. In particular, credit shocks explanatory power is more important compared to liquidity shocks and the nature of their impact changes from permanent to transitory as tenors increase. Remarkably, liquidity shocks impact is always permanent and more significant across maturities as tenors increase.

All these considerations and contributions over the different chapters may prove to be relevant to have a better understanding of the interbank curves multiplicity and interbank market fundamentals, but also in the design of financial market intervention policies and the planning of investors hedging strategies.

The rest of the dissertation is organized as follows. Chapter 2 studies the main determinants of multi-curve dynamics. Chapter 3 focuses on the estimation of counterparty risk and risk-premium components embedded in interbank spreads. Chapter 4 shows the importance of analyzing the nature of credit and liquidity shocks to explain their role on the interbank spread evolution and the different behaviour of the curves. Finally, Chapter 5 summarizes the main conclusions and outlines the areas of future research.

Chapter 2

Determinants of the multiple-term structures from interbank rates

The classic relationship between deposit rates and interest rate derivatives has been fractured since August 2007. Uncertainty in the interbank money market has increased the risk premia differentials on unsecured deposits rates of different tenors, such as Euribor, leading to a new pricing framework of interest rate derivatives based on multiple curves. This article analyzes the economic determinants of this new multi-curve framework. We employ Basis Swap (BS) spreads –floating-to-floating interest rate swaps– as instruments for extracting the interest rate curve differentials. Our results show that the multi-curve framework mirrors the standard single-curve setting in terms of level, slope and curvature factors. The level factor captures 90% of the total variation in the curves, and this factor significantly covaries with a proxy for systemic risk. Moreover, the curve residuals are significantly correlated with interbank liquidity. Our empirical findings also show unidirectional causality running from risk (and liquidity) to level (and noise) factors.

2.1 Introduction

The risk of losses resulting from lending in the interbank money market, or interbank risk, is a recent phenomenon in financial markets (Filipovic and Trolle, 2013). The financial distress that began in August 2007 resulted in a preference for cash flows receiving payments with shorter maturities, increasing the spreads on unsecured deposits, such as Libor or Euribor rates, of different tenors. This uncertainty in unsecured deposit rates has been transmitted to derivative markets because many interest rate–linked instruments, such as forward rate agreements (FRAs) and interest rate swaps (IRSs), reference those interbank rates. This new scenario is characterized by the rupture of classic relationships between deposit rates and interest rate derivatives. For example, deposit rates and Overnight Indexed Swap (OIS) rates of the same maturities, which historically evolved with negligible spreads, started to diverge. Similarly, the spreads between the forward rates implied by consecutive deposits and those implied by market FRAs have been significantly different from zero since August 2007. Furthermore, Basis Swap (BS) spreads and floating-to-floating IRS instruments, traditionally close to zero, have increased to unprecedented levels.

These non-negligible discrepancies between the implicit rates of deposit and market instruments have led to a novel multi-curve framework, where the assumption of an unique zero-coupon curve as benchmark for pricing derivative instruments suddenly does not hold. Investors and practitioners now select suitable term structures according to the tenor of the interbank reference. For instance, IRSs indexed to the three-month Euribor must employ a different curve than those indexed to the six-month Euribor. The interest rate derivatives market is one of the largest markets worldwide – in terms of notional outstanding, the market accounts for more than 80% of the total amount outstanding of over-the-counter (OTC) derivatives[1]. However, the academic literature on the multi-curve framework is still sparse; see, for example, recent papers by Mercurio (2009), Henrard (2014) and Filipovic and Trolle (2013).

This paper analyzes the dynamics of the multi-curve framework, searching for economic drivers that could illuminate this new scenario. We exploit the informational content of BS spreads, a type of IRS in which the parties exchange two floating rate interests. BS spreads are suitable instruments to study how investors price liquidity and credit risks in the interbank market, and they are employed to extract the different interest rate curves differentials in the multi-curve framework. Our sample focuses on the BS spreads written on Euribor against Eonia. Because Eonia is commonly accepted as the risk-free reference rate in the interbank market, the BS spread can be considered a direct measure of the liquidity/credit premium embedded in the multiple curves. Not surprisingly, these BS spreads, which were negligible before August 2007, subsequently increased to unprecedented levels.

BS spreads are used as instruments to determine interest rate curve differentials. Along these lines, this paper adopts an orthodox procedure to analyze the term structure following the approach

[1]For instance, the notional outstanding of IRS (FRA) contracts was USD 461.3 (82.3) trillion in December 2013, according to the September 2014 BIS Quarterly Review.

in Diebold and Li (2006). This methodology extracts the curves at different tenors using the spline fitting of Nelson and Siegel (1987). When applied to BS data, we are able to identify the multiple-curve (main) factors, which eases the process of comparing sets of curve dynamics while taking advantage of the goodness of fit properties of this model. Then, the methodology of Diebold and Li (2006) is used to characterize the information contained in each curve into three parameters that evolve dynamically. These parameters are interpreted as the level, slope and curvature factors of the term structure (Nelson and Siegel, 1987), providing an extensive analysis of the determinants of these curve factors and their relationships to various macroeconomic and financial variables. Additionally, our approach considers the information content of the model residuals, similarly to Hu et al. (2013), Berenguer et al. (2013) or Rubia et al. (2014). The dataset employed here is composed of weekly BS spreads from the Euro interbank market, and it corresponds to different maturities and tenors underlying the Euribor rates. The BS spread market data period ranges from June 2008 to August 2013, including the recent European sovereign debt crisis.

The main contributions of this article to the financial literature are threefold. First, this paper shows that the multi-curve framework mirrors the single-curve framework. We find that information in the multi-curve setting can be divided into three factors explaining the level, slope and curvature, and this information accounts for approximately 97% of the total variation in the spreads. Furthermore, we explore the different sources of commonality among these curves, studying each factor's behavior.

Second, a projection of the time series coefficients onto a set of economic variables shows the role of credit and liquidity risk as determinants of the multi-curve framework. The time series of the factor levels covaries significantly with a proxy for systemic risk, the spread between AAA EUR Financial sector and German sovereign yields. Analogously, illiquidity in the market, proxied by the ECB liquidity indicator, is statistically significant in explaining the model residuals. Finally, a VAR approach shows not only that the empirical errors that arise from the fitted curves are mainly explained by liquidity in the money market for the euro area but also that systemic risk is the main economic driver of interest rate factors for levels.

This paper belongs to the growing literature on interbank risk. Our work is most closely related to Filipovic and Trolle (2013), who employ a similar dataset but consider a different methodological approach. Additionally, Filipovic and Trolle (2013) focus on understanding the roles of credit and liquidity in explaining interbank spreads in risk premiums, while we seek to characterize the dynamic properties of the multi-curve setting. This strategy permits us to draw important conclusions about the commonalities in the behavior of interest rates in the multi-curve framework beyond examining their sources. A recent series of papers has also analyzed Libor-overnight spreads as measures of interbank risk, emphasizing their credit and liquidity risk components; see, for instance, Michaud and Upper (2008), Schwartz (2010), Eisenschmidt and Tapking (2009) or McAndrews et al. (2008). Our research also employs interbank spreads but extends its analysis to the entire term structure of these spreads captured by BS quotes. This strategy allows us to explore a more complete set of information regarding interbank risk because BSs contain information concerning market expectations of future Libor-overnight spreads. In addition, we consider several term structures of BS spreads associated with interbank rates of different tenors. To the best of our knowledge, this paper represents the first attempt to model the multiple curves using the methodology in Diebold and Li (2006).

This article is also related to the body of literature devoted to term structure modeling, especially to studies attempting to fit observed yield curves. The academic literature on this topic focuses on two main types of models: Nelson and Siegel (1987) models and affine term structure models. Nelson-Siegel models rely on three latent factors (interpreted as level, slope and curvature) and postulate a particular form of the term structure of interest rates that does not depend on the existence of arbitrage opportunities. Affine term structure models depend on assumptions concerning the absence of arbitrage opportunities and postulate that the unobservable factors underlying the term structure follow a stochastic process. A non-exhaustive review of this literature includes Vasicek (1977), Cox et al. (1985), Chan et al. (1992), Duffie and Kan (1996), Dai and Singleton (2000), Dai and Singleton (2002), and Piazzesi (2005), among many others.

Thus, this article seeks to characterize the economic determinants of the multi-curve framework using the informational content of BS spreads. The structure of the paper is as follows. Section 2.2 presents the multi-curve framework and its connection to BSs. Section 2.3 introduces the structure of the market and the dataset. Section 2.4 develops the estimation, and Section 2.5 analyzes the determinants. Some conclusions are provided in Section 2.6.

2.2 One curve, multiple curves and Basis Swap spreads.

Next, we review the classic link between forward and implicit rates and its connection to the existence of a unique curve for valuation. As is conventional in the interest rate derivative market, we consider simple compounded interest rates.

2.2.1 The replicating portfolio

The departures of interest rate derivatives market quotes from the classic single-curve framework can be illustrated using the replicating strategy of an FRA, an interest rate derivative contract that guarantees the interest rate on an obligation that will be lent or borrowed in the future. This agreement starts at future date T_i, finalizing at maturity date T_j, where $\tau(T_i,T_j)$ is the time elapsed. Within an FRA, one party decides to exchange a variable or reference interest rate $L(t,T_x)$ with tenor T_x, usually an interbank market reference such as Euribor. Accordingly, her counterparty interchanges a fixed interest rate $F(t,T_i,T_j)$ that is determined at the beginning of the contract. Because FRAs are liquidated at time T_i, the cash flow of an FRA at maturity is the spread among variable and fixed interest rates. The rate $F(t,T_i,T_j)$ is fixed to equalize the present value of one Euro at time T_i and the present value of a deposit of one Euro from time T_i until T_j,

$$P(t,T_i) - (1 + F(t,T_i,T_j)\tau(T_i,T_j))P(t,T_j) = 0, \quad \text{with } i < j \tag{2.1}$$

considering as discount factors the prices at time t of zero-coupon bonds with maturity T_x, i.e., $P(t,T_x) = 1/(1+L(t,T_x)\tau(t,T_x))$.

The cash flows of an FRA can be replicated by combining a long position in a bond with maturity T_i and face value one Euro and a short position in a bond with maturity T_j and face value $(1+F(t,T_i,T_j)\tau(T_i,T_j))$. Therefore, there exists an equivalence between i) entering into an FRA and ii) obtaining funding at different periods. This previous expression may be restated to represent the well-known non-arbitrage relationship between forward and FRA rates. In other words, ignoring that credit and liquidity issues may affect the funding that can be obtained at different periods, the implicit forward rate from deposits and the FRA rate should be equal. This replicating portfolio argument holds regardless the tenor of the FRA, implying that there should be consistency between the value of a particular tenor FRA rate and the capitalization of shorter tenor forward rates. In this way, the forward curve is *unique* because for a given maturity, financing at any tenor is equivalent.

Equivalence between the rate from FRAs and the implicit rate from deposits changed after August 2007, leading to inconsistent FRA rates at different tenors. As noted by Filipovic and Trolle (2013), the lack of confidence in the balance sheets of many financial institutions moved market makers to assign credit and liquidity risk premiums to different tenor (deposit) financing operations in the interbank market. Then, deposit rates started to reflect credit and liquidity risks.[2] In this situation, borrowing for a given maturity at different tenor floating rates is not equivalent. Consequently, the above-mentioned replication strategy for valuing interest rate derivatives does not yield a unique valuation after August 2007.

To reconcile post-crisis derivative market prices with classic single-curve replicating strategies, market makers have mainly adopted a solution based on a multiple curve, or multi-curve, framework. The existence of a multi-curve framework has been previously noted in the literature in, for instance, Mercurio (2009) and Henrard (2014). In this new setting, agents discriminate among the term structures of interest rates differentiated by the underlying interbank market reference rates according to their tenor. Denoting the Euribor rate associated with tenor x as $L_x(T_{i-1},T_i)$ (note the subscript x), where $x = \{1M, 3M, 6M, 12M\}$, the price of the zero-coupon bond associated with this

[2]In parallel to the recognition of the credit and liquidity risks, the perception of higher counterparty risk resulted in the establishment of clauses and collateral agreements, such as CSAs, in interbank market contracts to mitigate the consequences associated with counterparty defaults. Although these clauses helped mitigate the counterparty risk concerning the derivative contracts themselves, the credit and liquidity risks embedded in the instrument reference rates still had effects on these derivatives quotes.

Euribor rate with tenor x is,

$$P_x(T_{i-1},T_i) = \frac{1}{1+L_x(T_{i-1},T_i)\tau_x(T_{i-1},T_i)} \quad . \tag{2.2}$$

Because the multi-curve framework arises as a consequence of curves differentiated by tenor, the curve construction uses distinct sets of instruments linked to different tenor rates. For instance, only FRAs and IRSs associated with a 6-month payment frequency are used in deriving the curve associated with the Euribor 6M frequency. To value an interest rate instrument, the curve associated with a particular tenor underlying rate is used to estimate the instrument future rates, and a unique discounting curve is considered in the computation of the present value of these flows. Presently, FRA rates are themselves considered building blocks, and they are valued either directly from market quotes or implicitly as forward rates from the curve associated with its corresponding tenor.

Another aspect to be revisited is the concept of the risk-free rate. The appearance of the multi-curve framework poses some questions about the risk-free instruments employed for discounting derivatives (see Hull and White, 2013). There seems to exist a consensus in the market on using the curve of the overnight tenor Eonia rate as a discounting curve because most interbank derivative contracts are collateralized through CSAs, which implies that the collateral is capitalized at the Eonia rate. To avoid no-arbitrage opportunities, this rate curve must be considered in the discounting process. In the following, the discount factors associated with the OIS curve are denoted as $P_d(t,T)$.

2.2.2 The Basis Swap and its relationship to multiple curves

The lack of consistency between the post-crisis market quotes and the single-curve framework was particularly evident for certain instruments such as the BS, which is an interest rate derivative that involves the exchange of two floating rates at different tenors. BSs are OTC instruments, and they are mainly used by counterparties to swap interest rate payments linked to short-term reference rates of different tenor for a given period – the maturity of the contract. Therefore, these BS quotes reflect the premium that exists for term lending compared to rolling funding at shorter intervals in the Euro (Libor) interbank money markets, as longer tenor Euribor rates involve higher risk compared to shorter tenors. The BS spread reflects the difference between lending at compound shorter tenor rates compared to longer tenor rates in the Euro interbank money market. Then, the BS term structure captures the spread between the tenor IRS curves and the differential costs of funding at distinct tenors.[3]

The BS contract may be quoted as a portfolio of two standard floating versus fixed swaps with

[3]Consider, for example, the 3-month Euribor versus the 6-month Euribor BS. In this contract, one of the counterparties makes payments linked to the 3-month Euribor and, in exchange, receives the 6-month Euribor rate. If the 6-month Euribor rate is expected to be greater than the 3-month Euribor compounded quarterly, then the longer tenor leg of the swap involves a basis spread over the value of the shorter tenor leg that is necessary to be considered for the contract to be in equilibrium at inception.

two different floating rates and coincident fixed leg tenors.[4] The BS spread is the difference between the two equilibrium fix-to-float swap rates, and hence, it has the same payment frequency as the embedded swap's fixed leg. Then, the value of the BS contract is

$$\begin{aligned}\Delta_{x,y} &= IRS\left(t;T_x,T_z\right) - IRS\left(t;T_y,T_z\right) \\ &= \frac{\begin{pmatrix} E_t\left(\sum_{j=1}^{n_x} e^{-\int_t^{T_{x,j}} r(s)ds}\tau_x\left(T_{x,j-1},T_{x,j}\right)L_x\left(T_{x,j-1},T_{x,j}\right)\right) \\ -E_t\left(\sum_{j=1}^{n_y} e^{-\int_t^{T_{y,j}} r(s)ds}\tau_y\left(T_{y,j-1},T_{y,j}\right)L_y\left(T_{y,j-1},T_{y,j}\right)\right)\end{pmatrix}}{\sum_{j=1}^{n_z} P_d\left(t,T_{z,j}\right)\tau_z\left(T_{z,j-1},T_{z,j}\right)},\end{aligned} \tag{2.3}$$

where $IRS\left(t;T_x,T_z\right)$ and $IRS\left(t;T_y,T_z\right)$ link the equilibrium swap rates of fixed versus floating IRS contracts and the floating legs, respectively, to the x- and y-tenor Euribor reference rates.

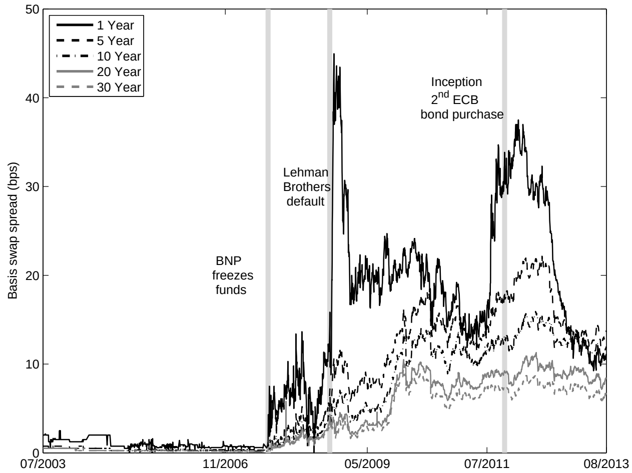
If the pricing formula (2.3) is considered under the classic interest rate framework, the existence of a unique riskless curve implies that the IRS floating leg would be replicated by a portfolio of two single zero-coupon bonds irrespective of the floating reference rate tenor. This is because the IRS floating leg represents the sum of discounted expected values of FRA rates. Under the single-curve framework, such a net present value would be equivalent to the sum of implicit forward rates and may be replicated by the value of two zero-coupon bonds with the same maturity as the contract start and maturity dates. This would imply that the value of the IRS rate would not depend on the tenor of the underlying FRA rates, and consequently, the BS spreads would be zero, that is, $\Delta_{x,y} = 0$, as occurred before August 2007. This fact is shown in Figure 2.1, which displays the time series of the Euribor 6M versus 3M BS spread from July 2003 until August 2013. According to the single-curve framework, before August 2007, BSs exhibited a low volatility pattern with quotes that were close to zero. However, since the credit crunch, BS spreads have increased to unprecedented levels and have become extremely volatile.

2.3 The structure of the Basis Swap market

BS contracts are mainly used for hedging and speculative purposes. Entities use a BS as a hedging instrument for basis risk, for instance, in situations where assets and liabilities are tied to rates

[4]There exist two types of single-currency BS contracts exchanged in the interbank market. On the one hand, a BS can be constituted by two vanilla swaps, which is called the first type here. On the other hand, single line items, the second type, consist of the interchange of two floating rates, the longer tenor Euribor rate against the shorter tenor rate plus a spread. The choice of the contract type depends on the infrastructure capability of the financial entities. In any case, there are negligible differences between the quotes of both type of swaps, mainly due to the frequency of compounding and day count conventions. This paper employs the first type of BS contract, providing a complete description of the second type in B.

Figure 2.1: Euribor 6M vs Euribor 3M Basis Swap spread corresponding to different maturities.



Time series of the Euribor 6M versus 3M Basis Swap spread. Data period ranges from July 28th, 2003 to August 30th, 2013.

of different tenor. Similarly, entities are exposed to basis risk when the underlying and hedging instruments are linked to different tenor Euribor rates. Moreover, because BSs reflect short-term expectations about market credit and liquidity conditions, these derivative contracts can also be used to speculate about future levels of basis spreads.

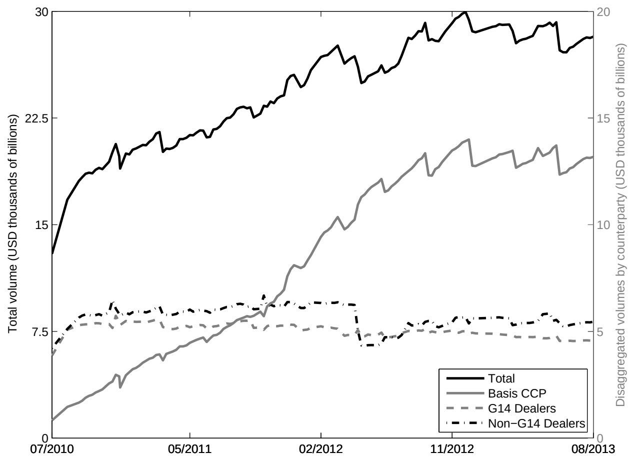
Figure 3.4, which depicts the evolution of BS aggregated transaction data in terms of outstanding trades gross notional, shows the increment of trading operations with BS contracts during recent years. The BS notional outstanding is the total amount of open interest that the clearing house has in these swaps. The BS trades are disaggregated by the type of counterparty: a) central clearing counterparties (CCP); b) G-14 dealers, and c) non-G-14 dealers. The data are collected from fourteen financial entities' interest rate derivative transactions reports and published by TriOptima and DTCC.[5] As shown in Figure 3.4, we observe that trading with central clearing counterparties has dramatically contributed to increased BS turnover.[6]

Figure 3.3 depicts the gross notional evolution of Basis Swap trades with respect to other interest rate–linked products. Data on IRSs, FRAs, Swaptions and Caps/Floors comprises from July 2010 until July 2013. Data from OIS starts in April 2012. Records before those dates are not available to us. As observed, trading activity with interest rate derivatives is heavily concentrated in IRS. However, its relative size has decreased in the recent years in favor of FRA and BS trading

[5]The G-14 financial entities include Bank of America-Merrill Lynch, Barclays Capital, BNP Paribas, Citi, Credit Suisse, Deutsche Bank AG, Goldman Sachs & Co., HSBC Group, JP Morgan, Morgan Stanley, The Royal Bank of Scotland Group, Societe Generale, UBS AG and Wells Fargo Bank. For more details, see http://www.trioptima.com/repository.html.

[6]This pattern is corroborated by our conversations with traders, who highlight that BS contracts exchanged in the interbank market are commonly cleared through central clearing houses of which one of the most important is the London Clearing House (LCH).

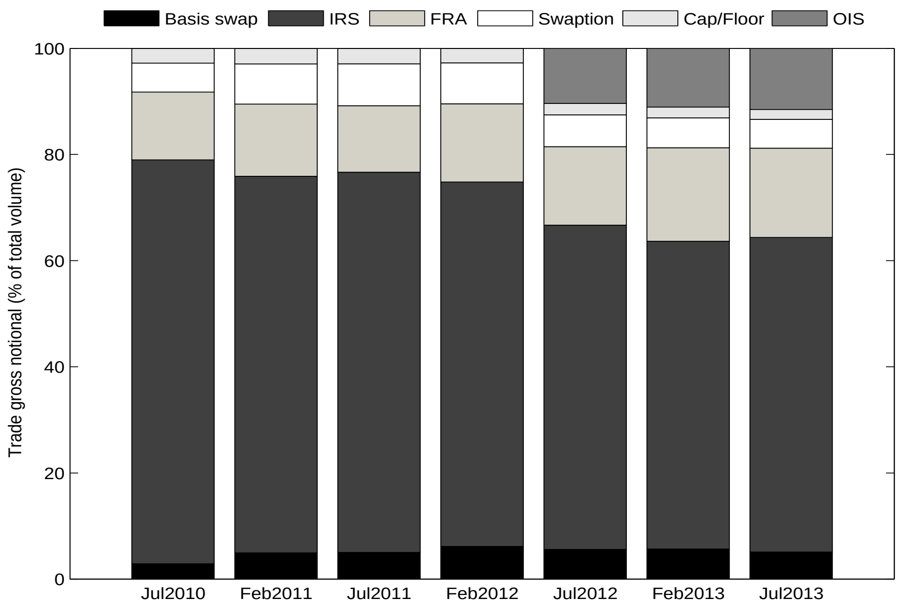
Figure 2.2: Basis swap trades gross notional disaggregated by the type of counterparty.



Basis swap trades gross notional disaggregated by the type of counterparty. Basis swap outstanding trades gross notional data correspond to left axis. Basis swap disaggregated by type of counterparty are in right axis. Outstanding trades gross notional data are in billions of USD and it is based on 14 financial entities interest rate derivatives transaction weekly reports. Data are disaggregated by the type of counterparty: G14 dealers, non-G14 dealers and central clearing counterparties (Basis CCP). The sample period ranges from July 30th, 2007 to August 30th, 2013. Data have been extracted from DTCC and TriOptima.

operations. The BS volume accounts for approximately 6% of the total volume, and this percentage remains stable during the period analyzed.

Figure 2.3: Gross notional in percentage of the traded total volume for different Interbank Market instruments



Each bar contains the BS, IRS, FRA, Swaption, OIS and Cap/Floor Trades Gross Notional. Data ranges from July 2010 until July 2013, with the exception of OIS series, which starts in April 2012. Data are extracted from DTCC and Trioptima.

2.3.1 Data and descriptive statistics

The dataset comprises BS spread market quotes from June 2nd, 2008 to August 30th, 2013. The data frequency is weekly, and they have been drawn from Bloomberg. We are interested in the BS spreads of different Euribor tenors with respect to Eonia, which is the underlying rate of OISs. We focus on the BS contracts whose payments are associated with Euro interbank deposit rates for tenors of 1, 3, 6 and 12 months (from now onwards we denote them as BS1M, BS3M, BS6M and BS12M, respectively). In addition, each BS contract based on Euribor rates is traded for maturities from 1 to 10, 12, 15, 20, 25 and 30 years. Given that market does not provide quotes for these BS spreads for all tenors, we synthetically build those BS spreads by non-arbitrage when they are not available. This procedure requires the use of the BS pricing formulas stated in Section 2.2. Information and details about the BS contracts are reported in Table 2.1, which summarizes the available BS market quotes (Panel I) and the synthetically obtained BS spreads (Panel II). As an example of our procedure, consider, for instance, the series of Euribor 6M vs Eonia spreads, which are not directly available in the market. We add Euribor 6M vs Euribor 3M to Euribor 3M vs Eonia BS quotes, having previously transformed the latter from type 2 into type 1 swap contracts. As a robustness check, we confirm that this methodology matches the quotes for existing data.

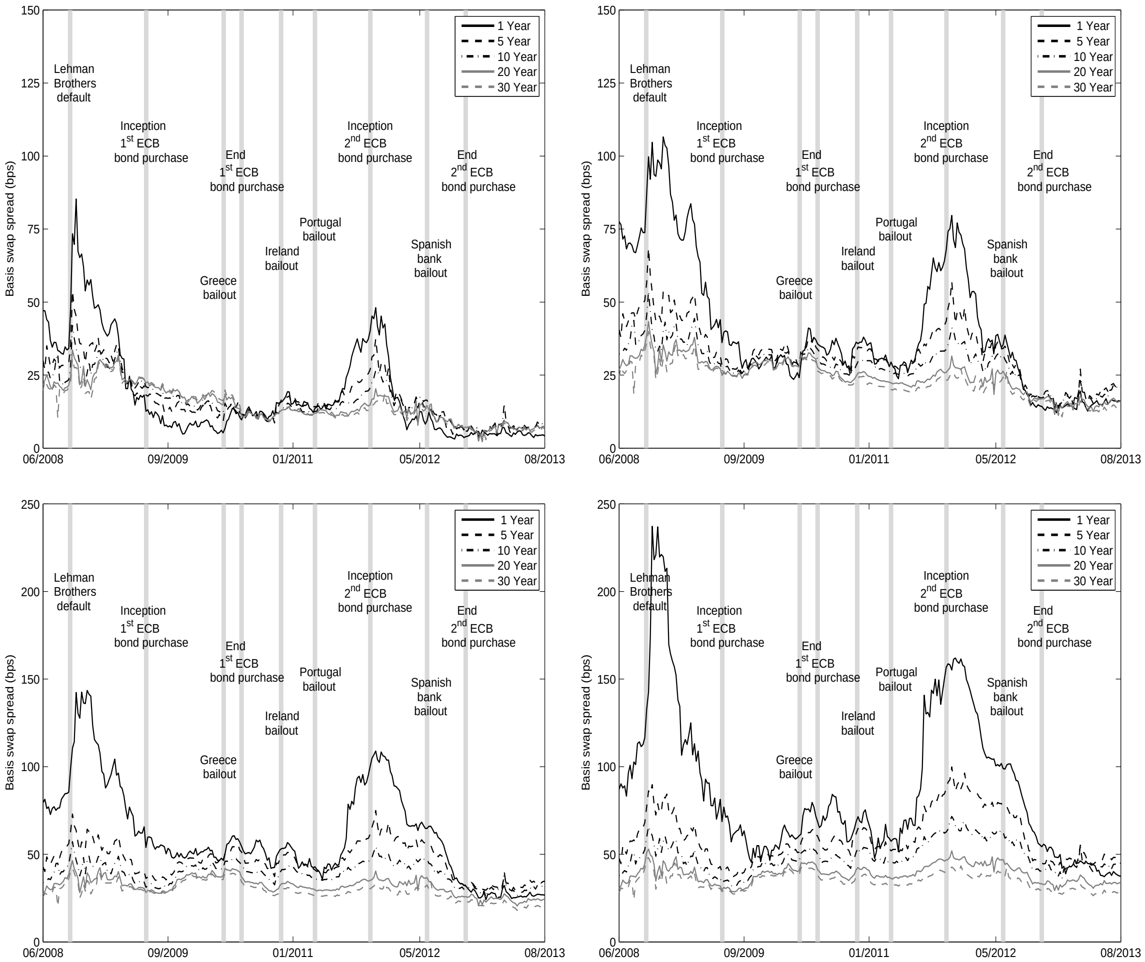
Table 2.1: Contract details concerning Basis Swap spread market quotes.

Interest rates	Tenors	Type of contract	Payment Frequency	Calculation basis
Panel I.- Contract details concerning Basis Swap spread Market quotes				
Euribor vs. Eonia	3M vs overnight	2 swaps	Annually	Act/360
Euribor vs. Eonia	3M vs 1M	2 swaps	Annually	30/360
Euribor vs. Eonia	6M vs 3M	1 swap	Quarterly	Act/360
Euribor vs. Eonia	6M vs 1M	2 swaps	Annually	30/360
Euribor vs. Eonia	12M vs 3M	2 swaps	Annually	30/360
Euribor vs. Eonia	12M vs 6M	2 swaps	Annually	30/360
Panel II.- Derivation details concerning Euribor vs Eonia Basis Swap spreads				
Euribor vs. Eonia	1M vs overnight	(1) Euribor 3M vs Eonia - Euribor 3M vs Euribor 1M		
		(2) Euribor 6M vs Eonia - Euribor 6M vs Euribor 1M		
Euribor vs. Eonia	3M vs overnight	Direct Market Quote		
Euribor vs. Eonia	6M vs overnight	Euribor 3M vs Eonia + Euribor 6M vs Euribor 3M		
Euribor vs. Eonia	12M vs overnight	(1) Euribor 3M vs Eonia + Euribor 12M vs Euribor 3M		
		(2) Euribor 6M vs Eonia + Euribor 12M vs Euribor 6M		

Figure 2.4 shows the evolution of the BS time series used. Some interesting aspects are illustrated in this Figure. First, BS premiums tend to increase in the presence of risk uncertainty. For example, Figure 2.4 shows that the Lehman Brothers bankruptcy in September 2008 resulted in a sharp increase in BS spreads that lasted several months. Analogously, BS spreads rose significantly during the European sovereign debt crisis, for instance, during the government bailouts of Greece in May 2010, Ireland in November 2010, and Spain in June 2012. Second, the term structure of BS spreads is consistently downward sloping, especially at longer tenors (3, 6 and 12 months). This effect is also observable at 1-month BS spreads during times of financial distress. Finally, BS spreads seem to react to the special measures undertaken by the ECB during the crisis.[7] The implementation of these actions appears to be correlated with a gradual decrease in BS spreads. In sum, BS spreads seem to capture liquidity shortages within the financial sector and perceptions of the default risk associated with lending in the interbank market, as noted by Filipovic and Trolle (2013).

[7]To enable banks to access funding just after the Lehman collapse, the ECB conducted massive injections of liquidity on October 8th, 2008 and special term refinancing operations on September 29th, 2008. Additionally, the ECB intervened in debt markets to prevent government borrowing costs from increasing to prohibitively high levels and ensure depth and liquidity in certain dysfunctional market segments. The first goal was achieved by the Securities Markets Programme, introduced in May 2010, and its successor, Outright Monetary Transactions, launched in August 2012. The second objective was pursued by the purchase of Euro-denominated covered bonds under two programs introduced on June 30th, 2010 and October 31st, 2012. Through the long-term refinancing operations conducted in fall

Figure 2.4: Euribor versus Eonia Basis Swap spreads at different maturities.



Time series of the Euribor versus Eonia Basis Swap spreads. The distinct figures correspond to the different Euribor tenors Basis Swap spreads: 1-month (top, left), 3-months (top, right), 6-months (bottom, left) and 12-months (bottom, right). Data period comprises weekly data from June 2nd, 2008 to August 30th, 2013.

Table 2.2 provides some descriptive statistics. We observe that BS curves are, on average, downward sloping and convex. Moreover, the volatility of BS spreads tends to be higher for short term maturities. A cross-sectional inspection of the BS spread shows that i) long-term BS spread tenors are higher than short-term tenors and that ii) long-term tenors are more volatile than shorter ones. In addition, the median is generally lower than the mean, signaling that the distribution is skewed to the right, particularly for shorter maturities. Finally, the autocorrelation coefficients reveal that shorter maturities exhibit more persistence, and this persistence is declining with the time horizon over the long-run.

Table 2.2: Basis Swaps summary statistics

									ρ_N			
		Mean	Std.	Median	Min	Max	Skew.	Kurtosis	4	12	24	N
BS1M	1y	18.31	15.99	12.43	3.10	85.30	1.47	4.66	0.91	0.69	0.33	274
	5y	16.92	9.24	14.60	2.70	53.85	1.01	3.67	0.90	0.75	0.46	274
	10y	16.02	7.21	14.78	3.35	41.95	0.76	3.18	0.89	0.77	0.56	274
	20y	15.03	6.47	13.38	2.50	33.60	0.55	2.66	0.92	0.81	0.65	274
	30y	14.54	6.28	12.80	2.20	30.90	0.47	2.47	0.92	0.81	0.68	274
BS3M	1y	40.79	22.98	34.10	12.10	106.55	0.95	3.04	0.95	0.76	0.40	274
	5y	32.61	10.10	31.85	13.30	68.45	0.34	2.94	0.91	0.72	0.39	274
	10y	28.66	6.95	28.90	13.95	53.65	0.08	3.11	0.88	0.70	0.42	274
	20y	24.80	5.93	25.35	12.20	43.30	-0.09	2.66	0.90	0.75	0.55	274
	30y	23.11	5.81	23.57	10.65	39.90	-0.11	2.41	0.91	0.76	0.61	274
BS6M	1y	61.20	27.33	53.95	24.10	143.50	0.90	3.42	0.95	0.71	0.31	274
	5y	46.29	9.86	46.33	29.10	74.95	0.17	2.42	0.90	0.66	0.22	274
	10y	39.10	6.21	40.00	25.54	57.25	-0.05	2.25	0.84	0.55	0.16	274
	20y	32.02	5.04	32.13	20.50	46.35	-0.06	2.50	0.85	0.58	0.28	274
	30y	29.04	5.17	28.88	18.00	42.25	0.04	2.53	0.86	0.63	0.41	274
BS12M	1y	86.49	42.50	71.40	37.25	237.20	1.35	4.58	0.93	0.64	0.22	274
	5y	59.61	14.37	55.29	37.10	99.85	0.72	2.48	0.93	0.70	0.27	274
	10y	48.81	8.61	46.95	31.90	71.60	0.42	2.52	0.88	0.65	0.26	274
	20y	38.86	5.25	38.60	28.60	52.95	0.18	2.28	0.83	0.52	0.11	274
	30y	34.74	4.62	35.01	24.00	48.05	0.15	2.32	0.79	0.46	0.12	274

Descriptive statistics for different Euribor tenor versus Eonia Basis Swap spreads term structures. The table presents the mean, standard deviation, median, minimum, maximum, skewness, kurtosis and 4, 12 and 24 lag autocorrelations of the term structures whose selected maturities are 1, 5, 10, 20 and 30 years. The distinct Euribor tenors are 1, 3, 6 and 12 months. The historical series are expressed in basis points and correspond to weekly data from June 2nd, 2008 to August 31st, 2013.

2.3.2 Commonality analysis

As an initial exercise to address the nature of comovements in the BS time series, we perform a principal components analysis (PCA) of the entire sample of (standardized) Euribor tenor BS

2011, the ECB also intended to enable banks to access long-term funding.

spreads. The results show strong commonality in the data, where a first principal component accounts for 73.36% of the total explained variance in the BS series. This percentage increases to 89.41% and 96.84% when incorporating the information from the second and third components, respectively. An inspection of the loading coefficients (not reported here but available upon request) shows that the first principal component can be understood as an equally weighted portfolio of the BS series. The second component loadings clearly disentangle the short-term tenors (1M and 3M) from long-term tenors (6M to 1 year). While the first component represents a level factor, the second component reflects a slope factor. Finally, the third component could be interpreted as a curvature factor embedded in the cross-section of BS spreads. Further inspection of the first principal component loading coefficients reveals that the medium-term tenors are representative of the joint behavior of the level factor, while the 1- and 12-month tenors, particularly the latter, may display slight heterogeneity with respect to the medium-term tenor spreads.

To further be sure of the interpretation of the term structure components, we perform a PCA for each tenor; then, we execute four different PCAs. The results are consistent across tenors, and they are consistent with the standard interest rate term structure assessment. The first component clearly captures most of the variation in BS spreads; for example, the lowest (highest) explained variance for this first component is 87.72% (92.66%). Moreover, the loading coefficients of first principal components are approximately equal, reinforcing the view that first components behave as level factors. We also observe that medium-term maturities (from 5 to 10 years) present slightly higher loading coefficients. This may indicate that medium-term maturities act as level benchmarks.

The second principal component could be interpreted as a slope factor: the loading coefficients are statistically significant for shorter and very long-term maturities, differing in their sign. The explained variance is 7.14%, on average. Finally, the third principal components clearly represent curvature factors, and their explained variance is nearly residual – on average, 2.15%.

From the previous results, we conclude that the different BS spread curves have strong commonalities and that their term structures exhibit similar level, slope and curvature patterns. Heterogeneity in the joint BS behavior may arise across maturities, over the short- and very long-run, and across tenors, at shorter and longer tenors.

2.4 An analysis of the multiple-term structures

2.4.1 Curve fitting

There exist several approaches for fitting the term structure in the unique curve setting that are of potential interest in the analysis of the multi-curve framework.[8] This article focuses on the Nelson and Siegel (1987) model, which imposes a parametric structure on the interest rate curve at different

[8]See Diebold and Li (2006) for a discussion of the different methods available.

maturities that is flexible enough to generate a variety of time-varying curve shapes as follows,

$$s_t(\theta;\tau) = \beta_{1t} + \beta_{2t}\left(\frac{1-e^{-\lambda_t\tau}}{\lambda_t\tau}\right) + \beta_{3t}\left(\frac{1-e^{-\lambda_t\tau}}{\lambda_t\tau} - e^{-\lambda_t\tau}\right), \quad (2.4)$$

where $s_t(\theta;\tau)$ is the zero-coupon Basis Swap (ZCS) spread at time t with maturity τ and θ is a four-parameter vector, $\theta = (\beta_{1t}, \beta_{2t}, \beta_{3t}, \lambda_t)$, to be estimated. In particular, parameter β_{1t} is usually interpreted as a level factor because $s_t(\theta;\infty) \rightarrow \beta_{1t}$. Parameter β_{2t} is a decreasing function of τ, and it is usually intended as a slope factor; and parameter β_{3t} is the curvature factor, which is a concave function of τ. The λ_t parameter determines both the maturity at which the curvature loading is maximized and the exponential decay rate associated with the term $e^{-\lambda_t\tau}$. This parameter λ_t is usually fixed in the estimations (see Diebold and Li, 2006). The model generates BS spreads that approach the instantaneous rate $\beta_{1t} + \beta_{2t}$ when maturity τ approaches zero and the value β_{1t} when maturity τ tends to infinity in the limit. Notice that, although the Nelson and Siegel (1987) model is presented as a static model, Diebold and Li (2006) interpret their parameters as dynamic latent factors, where β_{1t}, β_{2t} and β_{3t} are level, slope and curvature factors, respectively. Then, the time series statistical properties of these factors capture the underlying dynamic patterns of the curve. All parameters in vector θ have a subscript t because they are estimated at each point in time.

The Nelson and Siegel (1987) model is formulated in terms of continuous forward and zero-coupon yield curve rates. Unlike in the Nelson-Siegel model, market BS spreads are quoted as simply compounded swap rates instead of zero-coupon continuously compounded interest rates. Thus, to apply this model, we transform those BS spreads into zero-coupon rates by bootstrapping, a standard approach for constructing interest rate curves. We next present our procedure, which builds on the relationship between swap BS spreads, and simple forward spreads associated with BS for future periods. This relationship is an artificial construct that allows us to derive the zero-coupon BS curve by applying bootstrapping. In this way, we first recursively infer simple forward spreads using the following formula:

$$\Delta_{x,y} = \frac{\sum_{j=1}^{n_x} P_d\left(t, T_{x,j}\right)\tau_x\left(T_{x,j-1}, T_{x,j}\right) Fwdspread\left(T_{x,j-1}, T_{x,j}\right)}{\sum_{j=1}^{n_z} P_d\left(t, T_{z,j}\right)\tau_z\left(T_{z,j-1}, T_{z,j}\right)}, \quad (2.5)$$

where the information about the discount rate curve $P_d(.)$ is obtained from OIS quotes and the forward spread curve is simply extracted from equation (2.5), possibly by a non-linear technique. Then, the ZCS are recursively calculated using the relationship

$$\left(1 + ZCSpread_S\left(t, T_{x,j}\right)\left(T_{x,j} - t\right)\right) = \prod_{i=1}^{j}\left(1 + FwdSpread\left(T_{x,i-1}, T_{x,i}\right)\tau_x\left(T_{x,i-1}, T_{x,i}\right)\right). \quad (2.6)$$

Finally, simple ZCS spreads are transformed into continuous spreads taking into account the relationship between simple and continuously compounded rates as follows:

$$ZCSpread_C\left(t,T_{x,j}\right)=\frac{\ln\left(1+ZCSpread_S\left(t,T_{x,j}\right)\left(T_{x,j}-t\right)\right)}{\left(T_{x,j}-t\right)}. \tag{2.7}$$

This procedure is applied to each BS spread term structure associated with a given Euribor underlying tenor. Finally, the model parameter vector θ is estimated by OLS regressions for each point in time. The parameter λ_t is fixed at 0.206, the value that maximizes the loading on the medium-term factor at 9 years. [9]

2.4.2 Parameter estimates

Figure 2.5 depicts the time series of the estimated Nelson-Siegel model factors. Some interesting conclusions arise from the inspection of this figure. For example, the evolution of the level factor β_{1t} (upper graph) shows that, overall, the term structure exhibits a downward trend beginning in September 2008. This observation is extensible to all tenors, suggesting a reduction of financial tensions in the eurozone. Notably, financial crisis events, such as the collapse of Lehman Brothers in September 2008 and the worsening of the European sovereign debt crisis around November 2011, are associated with remarkable peaks of the β_{1t} coefficient around those dates, reflecting an increment of the interbank risk level. As expected, the BS spreads level factor increases monotonically with the tenor.

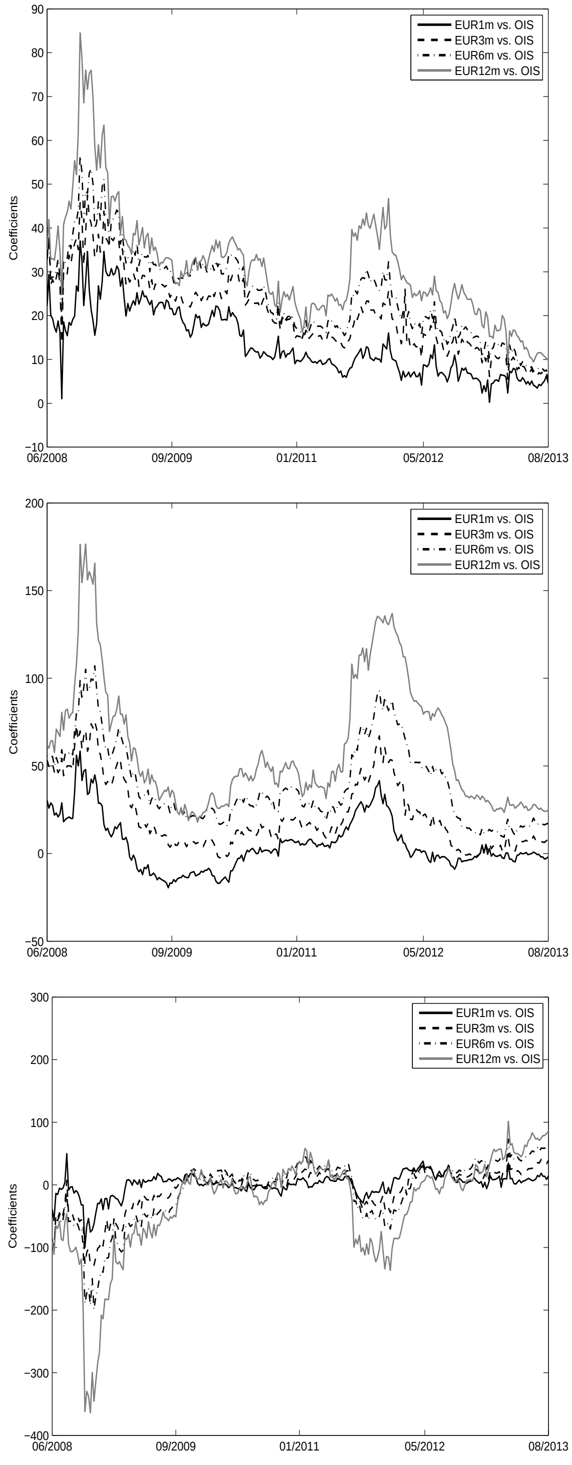
The evolution of the β_{2t} coefficient (Figure 2.5, middle graph) also exhibits significant increases during times of financial distress. At a first glance, this pattern seems counterintuitive because higher slopes in the term structure are not linked to distress periods. This puzzle is solved by Diebold and Li (2006), who notice that an increment in β_{2t} reflects an increment in short-term yields more than long-term yields because the short-term rates rely on β_{2t} more heavily. In this way, higher values of β_{2t} during distress periods are reflecting an increment of compensation at shorter maturities. Finally, the time series of parameter β_{3t} are displayed in the bottom graph of Figure 2.5. Parameter β_{3t} remains close to zero most of the time; however, some isolated and extremely high departures are observed when unexpected crisis events take place.

An additional summary of the descriptive statistics of the factors is shown in Table 2.3. The beta coefficients increase in size and volatility as the tenors increase. Moreover, the evolution of the β_{1t} coefficient exhibits lower volatility than the β_{2t} or β_{3t} coefficients, reflecting that slope and curvature react more intensively to financial distress situations. Additionally, the autocorrelation coefficients of the β_{1t} factor reveal that persistence in the level series is high.

In accordance with the empirical findings for BS spreads reported in Section 2.3.2, Figure 2.5 suggests the existence of commonalities among the time series of estimated factors. To assess this

[9] The choice of this maturity coincides with the point at which the BS data curvature component expressed with respect to maturity is maximized.

Figure 2.5: Time series of Nelson and Siegel (1987) model coefficients for different Basis Swap instruments



Time series of the Nelson and Siegel (1987) coefficients for Basis Swap spreads at different tenors. β_1 coefficient is upper graph. β_2 and β_3 are middle and lower graphs, respectively. Data frequency is weekly and ranges from June 2nd, 2008 to August 30th, 2013.

Table 2.3: Summary statistics of the Basis Swaps Nelson and Siegel (1987) factors

	BS Tenor (months)	Mean	Std.	Median	Min	Max	Skew.	Kurtosis	ρ_N 4	12	24	N
β_1	1	13.64	7.67	11.05	0.23	37.04	0.67	2.59	0.90	0.78	0.67	274
	3	20.82	8.86	20.21	5.50	47.51	0.47	2.71	0.93	0.80	0.60	274
	6	24.76	10.23	24.93	6.69	56.49	0.49	2.96	0.92	0.77	0.53	274
	12	31.05	12.95	29.88	9.41	84.51	1.25	5.59	0.91	0.65	0.29	274
β_2	1	5.05	15.35	0.96	-19.49	58.40	1.01	3.72	0.92	0.67	0.26	274
	3	21.73	19.67	14.68	-2.43	75.16	0.96	2.78	0.94	0.74	0.35	274
	6	39.43	23.40	31.30	9.33	107.14	0.90	2.88	0.94	0.71	0.30	274
	12	60.57	36.86	46.87	17.95	176.52	1.13	3.44	0.94	0.67	0.27	274
β_3	1	0.70	18.17	4.20	-99.65	49.93	-1.69	8.76	0.75	0.38	0.04	274
	3	-5.61	35.18	8.36	-129.31	49.99	-1.43	4.78	0.90	0.68	0.38	274
	6	-9.82	52.46	8.27	-199.02	73.11	-1.25	4.49	0.92	0.70	0.42	274
	12	-30.52	81.79	-4.15	-363.83	101.48	-1.63	6.62	0.91	0.63	0.29	274

Descriptive statistics for the Nelson-Siegel model factors corresponding to different Euribor tenor BS spread curves. The table presents the mean, standard deviation, median, minimum, maximum, skewness, kurtosis and 4, 12 and 24 lags autocorrelations of the BS spreads term structures. The distinct BS Euribor tenors are 1, 3, 6 and 12 months. The historical series correspond to weekly data from June 2nd, 2008 to August 31st, 2013.

aspect, we perform a PCA of the standardized parameter time series. Table 2.4 summarizes the nature of the principal component structure. We observe that factors strongly comove across BS tenors, as indicated by the fact that only one component tends to explain almost the entire joint variability (92.73%, 91.74% and 89.74%, respectively, for the level, slope and curvature factors). Regarding the loadings, the first principal component arises from an equally weighted average, which could be interpreted as a level factor. The second and third principal components capture the slope and concavity of the Nelson-Siegel parameter curves across different reference rate tenors, respectively.

2.4.3 Residuals and noise measure

According to Hu et al. (2013), the abundance of liquidity in credit markets tends to smooth out the Treasury yield curve because arbitrage forces minimize deviations between fundamental and market prices. During times of distress, liquidity shortages can lead to price deviations from fundamental values. These deviations, or noise, seem to contain valuable information, especially about liquidity issues (see, for example, Berenguer et al. (2013) and Rubia et al. (2014)). Interested in this issue, we implement the noise measure of Hu et al. (2013), the RMSE between the market observed BS

Table 2.4: PCA of the Basis Swaps Nelson and Siegel (1987) factors

	β_{1t}			β_{2t}			β_{3t}		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
BS1M	-0.49	-0.69	-0.52	-0.48	-0.78	-0.35	0.45	-0.87	0.14
BS3M	-0.51	-0.11	0.74	-0.51	-0.13	0.70	0.52	0.09	-0.70
BS6M	-0.52	0.10	0.14	-0.51	0.41	0.21	0.51	0.36	-0.11
BS12M	-0.49	0.71	-0.41	-0.50	0.46	-0.59	0.51	0.32	0.70
Variance (%)	92.93	5.86	0.88	91.76	6.02	2.12	89.80	8.64	1.25

PCA results for the Nelson-Siegel level, slope and curvature factors. The table presents the factor loadings of the first three principal components and the percentage variance explained by each component. These figures are computed by performing a principal component analysis separately for the level, slope and curvature factors associated to the distinct Euribor tenor vs Eonia Basis Swap spread term structures. The distinct Euribor tenors are 1, 3, 6 and 12 months. The historical series of the factors correspond to weekly data from June 2nd, 2008 to August 31st, 2013.

quotes and the Nelson and Siegel (1987) model-implied spreads,

$$Noise_t = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[BS_t^{market} - BS_t^{model}\right]^2}, \tag{2.8}$$

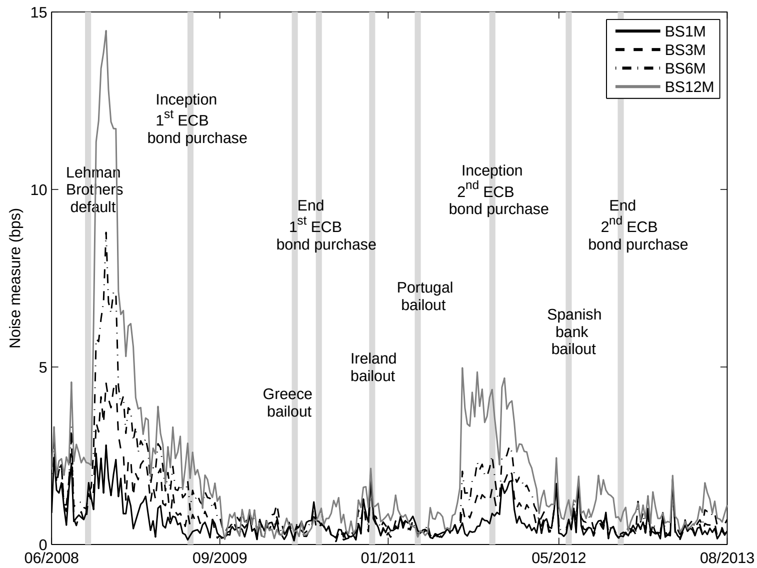
where N is the number of maturities in the BS spread curve, BS_t^{market} is the BS quote, and BS_t^{model} is the model-implied BS spread corresponding to maturity i and time t.

Figure 3.8 displays the time series of the noise measure for different tenors. Noise is time-varying, exhibiting remarkable increases during periods of financial distress and liquidity/credit crises, such as the Lehman Brothers collapse and European sovereign debt crisis. Notably, changes in noise are relatively more intense for longer BS tenors. This is consistent with the idea that longer maturities are more sensitive to changes in monetary policy, financial distress and market conditions, such as the exit of arbitrage capital from the marketplace (see Hu et al. (2013) and Rubia et al., 2014).

2.5 The determinants of the multiple-term structures

This section develops a regression analysis to explore the economic covariates of the Nelson and Siegel (1987) factors previously estimated.

Figure 2.6: Time series of Hu et al. (2013) noise measure



Time series of the Hu et al. (2013) noise measure applied to the Basis Swap spreads at different tenors. Data period ranges from June 6th, 2008 to August 30th, 2013.

2.5.1 Variable descriptions

The number of variables that are potentially linked to the term structure is initially unbounded. Following the research design in Longstaff et al. (2011) and Groba, Lafuente and Serrano (2013), we focus on a panel of economic variables that are grouped into four categories: money and interest rate, stock market, credit market and risk aversion variables. Descriptions of the variables employed are provided here.

Money and interest rate market variables. The multi-curve setting is clearly linked to the risk of lending in the interbank market or interbank risk (Filipovic and Trolle, 2013). Therefore, the money and interest rate variables are the first group that draws our attention. This group includes the i) interest rate level in the euro area, as denoted by *IR Level*. The interest rate is the risk-free lending rate in the euro area, and it is proxied by the Eonia Index, which is computed as a weighted average of all actual overnight lending transactions executed by the Eonia panel of banks in the Euro money market [10]. The interest rate data are calculated and provided by the ECB.

The ii) interest rate slope (*IR Slope*) is usually considered an indicator of overall economic health (see Collin-Dufresne et al. (2001) and Groba, Diaz and Serrano, 2013). The risk-free interest rates slope in the euro area is proxied by the spread between 10- and 2-year Eonia swap quotes. Eonia swaps or, alternatively, OIS are similar to vanilla IRS transactions – they both are exchanges of a

[10]Euribor and Eonia rates were contributed by the same panel of banks until June 1st 2013 but since then the Eonia and Euribor panels are allowed to be different.

fixed and variable interest rates, where the variable rate is linked to the Eonia Index. The data are taken from Bloomberg. Finally, we use the iii) ECB liquidity indicator for the euro area money market (*ECB Liq*) published by the ECB. The composite indicator includes arithmetic averages of individual liquidity measures. The data sources for these measures are the ECB, Bank of England, Bloomberg, JPMorgan Chase & Co., Moody's KMV and ECB calculations.

Stock market variables. This group includes the iv) Euro Stoxx Banks Price Index, a capitalization-weighted index that reflects the stock performance of companies in the European Monetary Union (EMU) that are involved in the banking sector. The data source is Bloomberg. The time series of this variable is considered in *logs*. Additionally, we use the v) Euro Stoxx VIX Index, a market estimate of future volatility based on a weighted average of implied volatilities of options written on Euro Stoxx 50 stocks. It captures implied volatility on Eurex traded options with a rolling 30-day expiry. The source is also Bloomberg.

Credit market variables. The list includes the vi) Itraxx Senior Financials, an index that comprises 25 equally-weighted 5-year maturity credit default swaps (CDS) on investment grade European entities involved in the financial sector. The index is from Markit. Then, we consider vii) German CDS, the Federal Republic of Germany Senior CDS quotes in USD and 5-year maturity and is drawn from Bloomberg. This variable is named *German CDS*. Finally, the viii) AAA Fin - German Government yield (*FG Spread*), is the spread between 1-year maturity AAA EUR Financial Sector and the 1-year maturity German Government yields. Each yield is calculated as a composite yield of representative securities around the 1-year maturity. The source is Bloomberg.

Risk aversion variables. Finally, we include a risk aversion variable, the ix) ECB Risk Aversion Indicator, an euro area global risk aversion indicator published by ECB and denoted as *ECB RA*. The indicator is constructed as the first principal component of five risk aversion indicators, namely, the Commerzbank Global Risk Perception, UBS FX Risk Index, Westpac's Risk Appetite Index, BoA ML Risk Aversion Indicator and Credit Suisse Risk Appetite Index. An increase in the indicator denotes an increase in risk aversion. This indicator comes from Bloomberg, Bank of America Merrill Lynch (BoA ML), UBS, Commerzbank and ECB calculations.

To avoid the risk of using variables with similar information content, we compute the correlation matrix for all candidate variables to be included in our regression analysis, which is reported in Table 3.3. We observe that the Euro Stoxx Banks and Euro Stoxx VIX are highly correlated with the Itraxx Financial and ECB risk aversion indexes. Additionally, the Itraxx Financial index exhibits a strong correlation with the German CDS. To avoid collinearity problems, we exclude the stock market variables and the Itraxx Senior Financial index. Standard stationarity tests systematically reject the existence of a unit root for the increments.

Table 2.5: Pairwise correlations of increments of explanatory variables

	IR Level	*IR Slope*	*ECB Liq*	*EuroStoxxBanks*	*EuroStoxxVix*	*Itraxx Fin.*	*German CDS*	*FG Spread*	*ECB RA*
IR Level	1.00								
IR Slope	0.03	1.00							
ECB Liq	0.12	-0.18	1.00						
EuroStoxxBanks	-0.00	-0.06	0.10	1.00					
EuroStoxxVix	0.12	0.18	-0.19	-0.67	1.00				
Itraxx Fin.	0.05	-0.16	-0.03	-0.71	0.46	1.00			
German CDS	0.04	-0.06	-0.16	-0.51	0.37	0.60	1.00		
FG Spread	0.13	0.22	-0.37	-0.19	0.26	0.23	0.23	1.00	
ECB RA	0.11	0.17	-0.17	-0.66	0.82	0.54	0.43	0.26	1.00

2.5.2 The determinants of curve factors and residuals

To study the determinants of the multi-curve framework, we develop a regression analysis of the factor coefficients and noise residuals from the Nelson and Siegel (1987) model previously estimated in Section 2.4. Let $\Delta\beta_{it}$ denote the increments of the factor i coefficients at time t; we model the conditional mean of this process. In particular, we consider the following OLS regression specification:

$$\begin{aligned}\Delta\beta_{it} = \alpha_i \quad &+ \quad \gamma_{1i}\Delta IRLevel_t + \gamma_{2i}\Delta IRSlope_t + \gamma_{3i}\Delta ECBLiq_t \\ &+ \quad \gamma_{4i}\Delta GermanCDS_t + \gamma_{5i}\Delta FGSpread_t + \gamma_{6i}\Delta ECBRA_t + \varepsilon_{it}, \end{aligned} \tag{2.9}$$

where $\theta_i = (\alpha_i, \gamma_i')'$ denotes the main parameters of interest and ε_i denotes random disturbances.

Tables 2.6 and 2.7 report the resulting OLS estimates from projecting the respective factor and noise increments onto a set of regressors for each of the tenors BS spreads. We report the estimated parameters, White (1980) robust standard errors for individual significance, and adjusted R^2 coefficients. The results in Table 2.6 show that the bond spread between the AAA Financial and German government plays a leading role in explaining fluctuations in the level factor β_{1t}; when the financing costs of the financial sector increase, investors concerns' about market-wide credit conditions translate into higher BS spreads. Notably, this pattern remains qualitatively unchanged across maturities.

The β_{1t} level factor also accounts for the risk perceived by investors in the euro area when lending to financial institutions compared to more secure investment alternatives. Not surprisingly, the ECB risk aversion index is also statistically significant for longer tenors. In the case of higher tenor Euribor BS curves, changes in the level factor also appear related to the level of instability in economic conditions, as captured by the interest rates slope. Indeed, the adjusted R^2 shows that the explanatory ability of the model is clearly higher for the 6- and 12-month tenors.

Regarding the main drivers of fluctuations in the slope factors β_{2t}, we highlight the role of economic agents' perception of future uncertainty, as proxied by the ECB Risk Aversion indicator. This variable is statistically significant at conventional confidence levels for all tenors. While the

Table 2.6: OLS robust regressions of the BS Nelson and Siegel (1987) factors

	Level				Slope				Curvature			
Variables	1M	3M	6M	12M	1M	3M	6M	12M	1M	3M	6M	12M
Constant	-0.0425	-0.0856	-0.1005	-0.1019	-0.0343	-0.1285	-0.0892	-0.0742	0.0449	0.3481	0.4417	0.5122
	(0.1549)	(0.1594)	(0.1454)	(0.1807)	(0.1988)	(0.2054)	(0.1908)	(0.2863)	(0.5292)	(0.5432)	(0.5975)	(0.9081)
IR Level	0.9901	0.7989	0.9001	1.7358	4.3208***	2.4105	3.5688**	6.0949**	-9.3117**	-7.4823**	-12.1386***	-19.3707***
	(1.0387)	(0.7169)	(0.7563)	(1.2578)	(1.6330)	(1.6795)	(1.4325)	(2.3812)	(4.2381)	(3.3987)	(3.8524)	(7.2879)
IR Slope	2.4664	3.6731	6.8222***	13.7108***	-1.9503	-0.1594	6.2614**	21.0284***	-14.9685	-20.7851**	-41.1972***	-81.7927***
	(2.7391)	(2.3779)	(2.3399)	(3.0256)	(2.8339)	(2.8960)	(2.7022)	(4.2956)	(9.7135)	(9.1292)	(11.2563)	(16.3723)
ECB Liq	-1.0556	-0.5716	-0.1768	-2.0453	-1.0465	-0.5955	-4.2867*	-9.8534**	8.6292	12.3584*	16.4656**	31.0617***
	(1.7978)	(1.5557)	(1.3917)	(1.8769)	(2.5872)	(2.4005)	(2.2162)	(3.8199)	(7.4693)	(6.6060)	(6.7528)	(11.6305)
German CDS	-0.0322	-0.0481	-0.0482	-0.0760*	0.0919**	0.1757***	0.1602***	0.1108	0.1180	0.0803	0.1231	0.2616
	(0.0316)	(0.0317)	(0.0312)	(0.0433)	(0.0441)	(0.0438)	(0.0447)	(0.0873)	(0.1093)	(0.1084)	(0.1150)	(0.2262)
FG Spread	6.0817**	7.5278**	7.6327***	9.0437***	4.6584	3.7101	5.6403	10.0496	-13.5029	-13.9832	-14.0002	-21.0975
	(3.0825)	(3.1519)	(2.7486)	(3.0838)	(4.8579)	(4.6758)	(4.3733)	(6.2942)	(10.2093)	(10.1273)	(8.8135)	(14.8808)
ECB RA	-0.1723	0.0107	0.4072**	0.8657***	0.6822*	0.9194**	1.2510***	2.8271***	-0.9310	-1.3510*	-3.2001***	-6.2824***
	(0.2461)	(0.2554)	(0.2008)	(0.2859)	(0.4112)	(0.3553)	(0.3340)	(0.5760)	(0.8516)	(0.7629)	(1.1275)	(1.8527)
Adj-R^2	4.75	7.18	15.02	28.33	15.11	16.79	33.68	46.06	11.67	16.49	30.79	41.04
N	273	273	273	273	273	273	273	273	273	273	273	273

OLS robust regressions of the Basis Swap Nelson-Siegel factors. The table reports the OLS results from regressing changes in the different Euribor tenor Basis Swap spreads Nelson-Siegel parameters against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 percentage values. The Nelson-Siegel parameters are associated with level, slope and curvature factors, and the distinct Euribor tenors are 1, 3, 6 and 12 months. The sample period corresponds to weekly data from June 2nd, 2008 to August 31st, 2013. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

explanatory ability of interest rate levels is important, the slopes only predict future movements for the 6- and 12-month tenors. Compared with the empirical findings for levels, the explanatory power of the linear model also increases with the tenor, but it is clearly higher for each tenor. Indeed, the adjusted R^2 reaches 46% for the 12-month maturity. Finally, as for the curvature, our results are qualitatively similar to those previously reported for the slope.

To complete our study, we develop an analysis to identify the explanatory variables for the noise measures underlying our linear regressions. Table 2.7 summarizes our empirical results. The key role in explaining departures from fitted curves is clearly played by liquidity. With the exception of the 1-month tenor, liquidity is statistically significant at standard confidence levels. Consistently, the adjusted R^2 increases with tenor, reaching its highest value for the 12-month case. ECB liquidity coefficients are negative, indicating that increments in price deviations are related to decreases in market liquidity. This result is remarkable, and it is fully consistent with previous literature regarding the information content embedded in this model's residuals (see Hu et al. (2013) and Rubia et al., 2014).

2.5.3 The joint dynamics of factors

As previously reported, empirical evidence about the determinants of the evolution of factors reveals that global credit and liquidity market conditions in the financial sector play significant roles in explaining the dynamics of levels and noises, respectively. To assess the relative importance of these two explanatory variables, we explore the nature of the joint dynamics for all tenors using a vector autoregression (VAR) model. Initially, we estimate a five-variable VAR for the first differences of levels (1, 3, 6, and 12 months), including changes in the spread between 1-year maturity AAA EUR Financial Sector and the 1-year maturity German Government yield. The lag length is chosen in accordance with the Hannan-Quinn information criterion, and we consider two lags in all cases.

For the sake of exposition, we limit the VAR analysis to Granger causality and some impulse-response functions. Table 2.8 reports the empirical values of the Wald statistic for testing the exclusion of groups of regressors for each equation in the VAR. We can observe two clear patterns: First, financial risk cannot be statistically excluded to anticipate futures movements of the level factor, regardless of the tenor considered. However, causality running from level factors to credit risk arises only for the 1- and 12-month tenors. Second, as for cross interactions between level factors, only the 1-month BS could be better predicted using the information content of the 3-month rates.

Next, we examine the nature of the feedback effects within the VAR system through impulse-response functions. Taking into account the previous results concerning causality, we focus on the responses of level factors to a shock in credit market conditions. The Figure 2.7 depicts the estimated responses based on a Cholesky decomposition of the variance-covariance matrix; we assume that the level factor have no contemporaneous effects on changes in the spread between the 1-year AAA Financial and German Government yields. Additionally, we report standard error bands at the 95%

Table 2.7: OLS robust regressions of noise components

	Noise			
Variables	1M	3M	6M	12M
Constant	0.0032	-0.0007	0.0040	0.0069
	(0.0257)	(0.0261)	(0.0296)	(0.0397)
IR Level	0.1512	0.1782	0.2526	0.3494*
	(0.1397)	(0.1373)	(0.1569)	(0.2007)
IR Slope	-0.1119	0.1807	0.3980	1.4760**
	(0.4378)	(0.4209)	(0.5257)	(0.6569)
ECB Liq	-0.2590	-0.5136**	-0.8924***	-1.6557***
	(0.2620)	(0.2411)	(0.2940)	(0.3691)
German CDS	-0.0005	0.0007	-0.0004	-0.0135
	(0.0053)	(0.0064)	(0.0072)	(0.0112)
FG Spread	0.2756	0.1930	0.4869	0.4505
	(0.4259)	(0.4432)	(0.3991)	(0.6493)
ECB RA	-0.0187	-0.0059	0.0085	0.1922**
	(0.0458)	(0.0433)	(0.0644)	(0.0830)
Adj-R^2	-0.09	3.39	11.42	26.06
N	273	273	273	273

OLS robust regressions of noise components. The table reports the OLS results from regressing changes in the different Euribor tenor Basis Swap spread curves noise components against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 percentage values. The noise components are computed as the RMSE between the different Euribor tenor market observed basis spreads and the Nelson-Siegel model implied spreads. The distinct Euribor tenors are 1, 3, 6 and 12 months. The sample period corresponds to weekly data from June 2nd, 2008 to August 31st, 2013. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

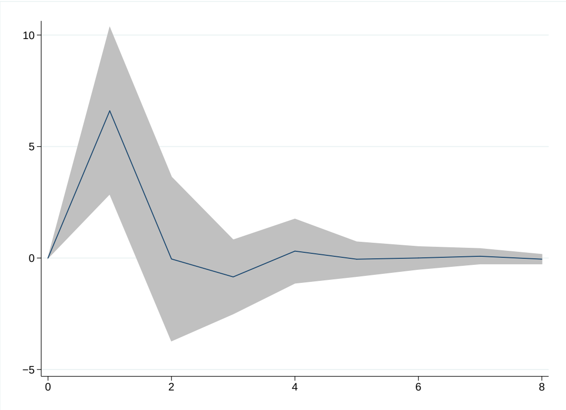
Table 2.8: Granger causality tests for Nelson and Siegel (1987) level factors VAR models

Equation	Excluded	χ^2 statistic
$\Delta\beta_{1M}$	$\Delta\beta_{3M}$	6.0882**
	$\Delta\beta_{6M}$	0.7929
	$\Delta\beta_{12M}$	2.6568
	Δ FG Spread	14.7710***
	All	44.6680***
$\Delta\beta_{3M}$	$\Delta\beta_{1M}$	0.0879
	$\Delta\beta_{6M}$	0.7399
	$\Delta\beta_{12M}$	2.2869
	Δ FG Spread	12.4420***
	All	37.8740***
$\Delta\beta_{6M}$	$\Delta\beta_{1M}$	0.4588
	$\Delta\beta_{3M}$	2.2925
	$\Delta\beta_{12M}$	4.1712
	Δ FG Spread	12.905***
	All	31.0430***
$\Delta\beta_{12M}$	$\Delta\beta_{1M}$	2.8670
	$\Delta\beta_{3M}$	3.2928
	$\Delta\beta_{6M}$	0.0423
	Δ FG Spread	16.3660***
	All	30.3140***
$\Delta FGSpread$	$\Delta\beta_{1M}$	1.7249
	$\Delta\beta_{3M}$	5.3141*
	$\Delta\beta_{6M}$	3.6336
	$\Delta\beta_{12M}$	9.9698***
	All	19.1720**

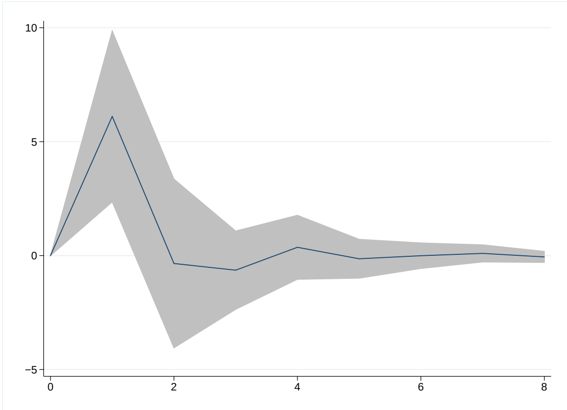
Granger causality Wald tests on the significance of all the lags from the excluded variable. Variables β_{1M}, β_{3M}, β_{6M} and β_{12M} are the level coefficients of Nelson and Siegel (1987) model. The variable FG Spread stands for spread between the 1-year maturity AAA EUR Financial Sector and the 1-year maturity German Government yield. The model lags have been selected according to the Bayesian Information Criterion. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

confidence level, computed using Monte Carlo methods, to enable a visual check for significance. We observe a similar pattern of responses for all tenors, and the initial reaction of the 12-month is slightly larger. While the point estimated responses converge to zero after six weeks, the confidence interval at the 95% confidence level confirm that the transitory shock only produces significant contemporaneous responses. In all cases, such a reaction is positive, indicating that increases in the spread between 1-year AAA EUR Financial Sector and the 1-year German Government yield systematically produce and increase in BS levels for all maturities. This is consistent with the idea that higher uncertainty in euro area financial sector conditions is transferred to higher BS premiums.

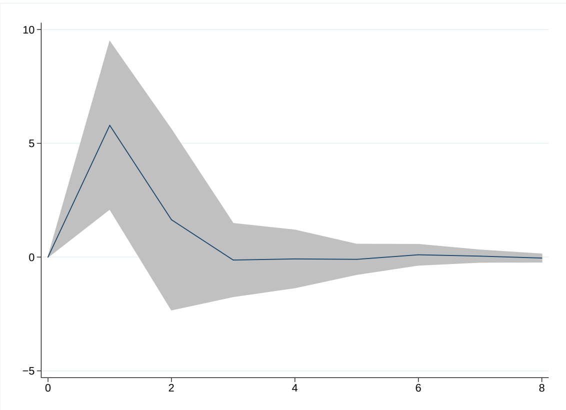
Figure 2.7: Impulse-response functions for increments of level factors in 5-variable VAR



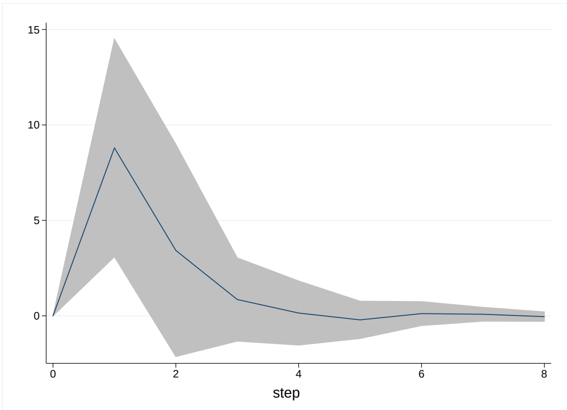
Response of 1-month level to shock in FG spread



Response of 3-month level to shock in FG spread



Response of 6-month level to shock in FG spread



Response of 12-month level to shock in FG spread

A five-variable VAR is estimated with the increments of level factors of four tenors (1, 3, 6 and 12 months) and the increments of spread between the 1-year maturity AAA EUR Financial Sector and the 1-year maturity German Government yield (FG Spread). The Figure shows the response to shocks in FG Spread over eight weeks after the impulse. The shadow areas depicts the standard error bands.

A similar analysis is repeated for the model price deviations. In this case, we include the ECB liquidity money indicator in the VAR system. This analysis could provide additional insights not only into the fitting ability of the Nelson-Siegel curve under alternative scenarios of liquidity but also into the relationships between errors across maturities. Table 2.9 reports the Granger causality concerning the five-variable VAR for the first differences of price deviations and liquidity. Three patterns should be highlighted: Firstly, as expected, the ECB liquidity indicator has significant explanatory power with respect to errors for all maturities. However, regardless of tenor, noise cannot explain liquidity, corroborating the exogenous nature of this variable in the system. Concerning the cross interactions between noises, the 3- and 12-month series of residuals could not be explained by the remaining regressors in the corresponding equation at conventional significance levels. Lastly, the 12-month errors have significant explanatory ability for the short-run errors (1 and 6 months).

In accordance with the causality patterns detected, we only pay attention to the impulse-response functions for a liquidity shock. Figure 2.8 depicts the responses of the noise measure to a shock in the ECB liquidity indicator. The immediate effect of an increase in liquidity is a reduction of errors for all maturities. In other words, the observed term structure and estimated term structure tend to diverge under market liquidity shortages. According to the confidence intervals, the effect of liquidity tends to be more persistent over medium- and long-term horizons. For the 6- and 12-month levels, the effect vanishes after five weeks, while the remaining maturities become statistically negligible after two weeks. In sum, a positive liquidity shock tends to increase the goodness of fit of the Nelson-Siegel model, and the effect could remain significant for over five weeks.

2.6 Concluding remarks

Credit derivative markets have experienced structural change since August 2007. Concerns about the increasing risk of counterparty defaults and the impossibility of financing future positions have prompted to a preference for receiving payments earlier. Consequently, the replication of interest rate derivatives using deposit interest is no longer consistent. This novel situation has led to a new pricing framework based on multiple discount curves, which is currently employed by interbank market agents. Evidence of this new paradigm in the financial markets is provided by the departure of deposit and OIS rates, the differences between implicit forward rates and deposit and FRA rates, and the dramatic increase in BS spreads, a floating-to-floating version of interest rate swaps.

This article studies the economic drivers behind the multi-curve framework that arose in the interbank market. The information embedded in BS spreads is employed to analyze the multiple curve differentials. The main features of these spreads are captured by three independent factors associated with the level, slope and curvature using the Nelson and Siegel (1987) model. Then, we develop a time series analysis of the factors inspired by the methodology of Diebold and Li (2006).

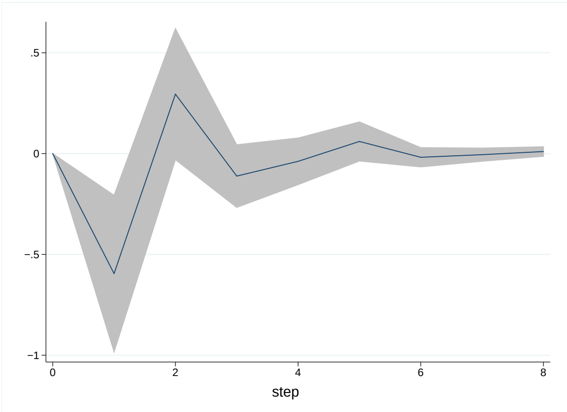
The empirical results presented in this article show that the multi-curve framework mirrors the

Table 2.9: Granger causality tests for noise components VAR models

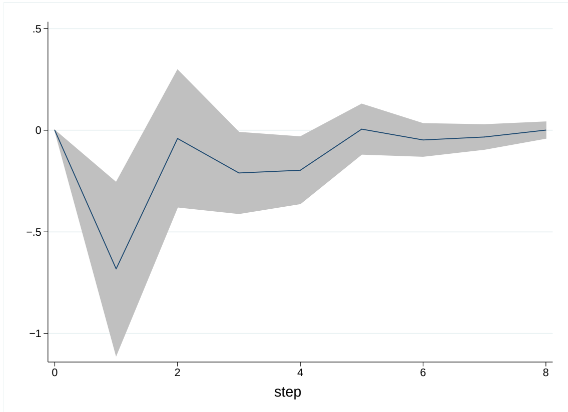
Equation	Excluded	χ^2 statistic
$\Delta Noise_{1M}$	$\Delta Noise_{3M}$	0.3475
	$\Delta Noise_{6M}$	2.0316
	$\Delta Noise_{12M}$	5.3911*
	Δ ECB Liq	9.1338***
	All	18.6320**
$\Delta Noise_{3M}$	$\Delta Noise_{1M}$	2.8075
	$\Delta Noise_{6M}$	1.3384
	$\Delta Noise_{12M}$	1.0947
	Δ ECB Liq	11.1450***
	All	38.9240***
$\Delta Noise_{6M}$	$\Delta Noise_{1M}$	4.6181*
	$\Delta Noise_{3M}$	1.1670
	$\Delta Noise_{12M}$	5.3279*
	Δ ECB Liq	18.0570***
	All	66.1950***
$\Delta Noise_{12M}$	$\Delta Noise_{1M}$	2.2536
	$\Delta Noise_{3M}$	0.1573
	$\Delta Noise_{6M}$	0.2937
	Δ ECB Liq	28.8590***
	All	43.7030***
Δ ECB Liq	$\Delta Noise_{1M}$	0.1851
	$\Delta Noise_{3M}$	2.4660
	$\Delta Noise_{6M}$	4.4353
	$\Delta Noise_{12M}$	1.0249
	All	8.7269

Granger causality Wald tests on the significance of all the lags from the excluded variable. Variables $Noise_{1M}$, $Noise_{3M}$, $Noise_{6M}$ and $Noise_{12M}$ are the residuals of Nelson and Siegel (1987) model. The variable ECB Liq stands for the ECB liquidity indicator of the money market for the Euro Area published by the ECB. The model lags have been selected according to the Bayesian Information Criterion. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

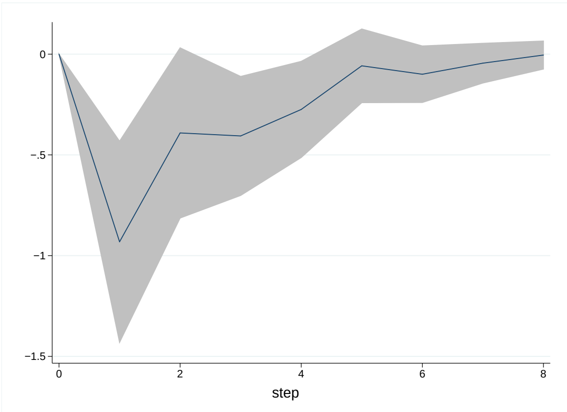
Figure 2.8: Impulse-response figures for increments of noise components in 5-variable VAR



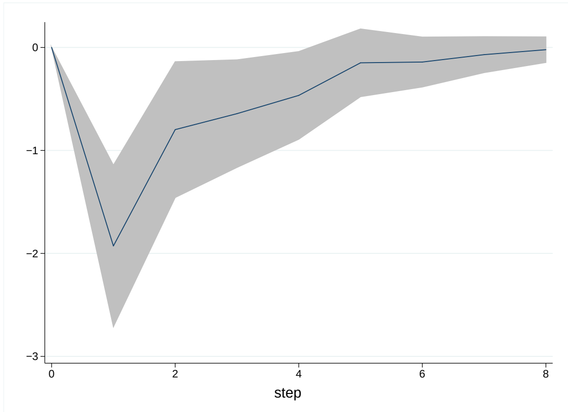
Response of 1-month noise to shock in liquidity



Response of 3-month noise to shock in liquidity



Response of 6-month noise to shock in liquidity



Response of 12-month noise to shock in liquidity

A five-variable VAR is estimated with the increments of the noise variable at four tenors (1, 3, 6 and 12 months) and the increments of the ECB liquidity indicator of the money market for the Euro Area (ECB Liq) published by ECB. The Figure shows the response to shocks in the ECB liq over eight weeks after the impulse. The shadow areas depicts the standard error bands.

standard single-curve setting in terms of level, slope and curvature factors. A projection of the time series coefficients onto a set economic variables highlights the role of credit and liquidity risk as determinants of the multi-curve framework. In particular, the factor level covaries significantly with a proxy for systemic risk, the spread between AAA Financial and German sovereign yield. In a posterior commonality analysis, we found that this level factor captures a 90% of the total variation in the curves. Additionally, our approach considers the informational content embedded in the deviations from the BS pricing curve, similarly to Hu et al. (2013) for the US Treasuries. These curve residuals are significantly correlated with interbank liquidity, as proxied by the ECB liquidity indicator. Finally, a dynamic analysis using a VAR model shows that systemic risk seems to be a significant economic driver of the BS level factors, and price deviations are mainly explained by the liquidity in the euro area money market.

Chapter 3

The term structure of interbank counterparty risk

Counterparty risk affects any kind of financial contract. The compensation for the risk that an interbank market counterparty does not honor her obligations has increased since August 2007. This article explores the term structure of counterparty risk and risk premia components embedded in interbank spreads quotes. We employ the interest rate Basis Swaps as a vehicle used by investors to express their views about the risk that a counterparty in the interbank market fails. Our results confirm that the interbank counterparty risk exploited after August 2007. Moreover, this risk relates to credit variables. The risk compensation to investors in the short run ranges from 20 to 60 basis points depending on the tenor during distressed times. Finally, important sources of commonality among counterparty risk and risk premiums at different tenors are found. Risk-premiums determinants reveal that investors compensation relates to financial sector credit and liquidity uncertainty and risk aversion.

3.1 Introduction

Counterparty risk could affect any kind of financial contract. Since August 2007, the impact of the counterparty risk in the pricing of interbank instruments is simply huge. Investors perception of higher aggregate levels of credit and liquidity risk has been reflected in the underlying reference interest rates associated to those interbank instruments such as the Euribor or the Eonia. In parallel to the impact on the quotes, the perception of higher counterparty risk has resulted in the establishment of clauses and collateralized agreements in contracts related to OTC derivatives in the interbank market with the purpose of mitigating those risks. For example, Whittall (2010) points out the existence of a liquidation mechanism similar to that employed in the future contracts of exchange markets. In particular, the borrower deposits the net present value of the contract in the collateral bank account, available to the lender, and she receives interest with respect to the collateral deposited according to a fixed tax. These collateralization agreements extended in the interbank market are nominated Credit Support Annex (CSA), the liquidation is daily and the fixed interest paid to the lender is the Eonia.

These abrupt changes in market quotes and the presence of collateral agreements are incompatibles with the existence of a unique interest rate curve benchmark, see Chibane and Sheldon (2009). A single term-structure of interest rates implies a non-arbitrage relationship among instruments of different maturities. In order to avoid arbitrage opportunities, prices must be consistent across the term curve. Surprisingly, this market consensus has broken since August 2007. Market quotes of interbank interest rate derivatives prior to the start of the crisis seemed to support this price consistency across the curve and, as a consequence, the existence of a unique interbank term structure curve. In the post-crisis period, instead, market agents started to attribute differential risks to instruments linked to different tenor interbank reference rates. As a consequence the single-curve framework replication strategies were not supported by market quotes any longer and the common market practice has tended to consider multiple curves differentiated by tenor.

Why does this multiplicity of curves exist? What is their informational content? What are the commonalities between the different curves driving forces? These questions are of crucial importance to understand the post-crisis important changes in the interbank market.

This paper empirically analyzes the term structure of counterparty risk in the interbank market. In particular, we focus on the determinants of the risk premium embedded in Basis Swap (BS) spreads. A BS is a contract between two parties to interchange, at different frequencies, payments linked to different interest rates reference indexes. BS are quoted at different maturities and may be interpreted as the spread differences between swap curves linked to different tenor indexes. Therefore, the distinct tenor BS spreads reflect interbank counterparty risk differentials of borrowing/lending at different periodicity. Before the start of the crisis, the interbank BS spread quotes were small, almost negligible, evidence that the market was not attributing significant risk differences to the different tenor rates. Nevertheless the BS explosion since August 2007 indicated that these market perceptions changed completely. Given that a term structure of BS spreads exists, counterparty risk term structure information can be inferred from these instruments.

The estimation methodology is developed in two steps. Firstly, an estimation of an affine continuous time process is performed for the arrival rate of interbank market counterparty events. The maximum likelihood (ML) estimates reflect that the credit environment worsens under the risk-neutral compared to the actual distribution. These differences between the actual and risk neutral results reflect the existence of a systematic risk premium priced in the BS quotes. From the model estimation results we derive the consequent model implicit BS spreads risk premiums and counterparty components. We also capture the noise measure associated to the model pricing errors. The performance of the pricing model is good in terms of the magnitude of size and volatility of mispricing errors.

Secondly, we employ these risk premium, counterparty and noise estimated time series to analyze their relationship with a set of macro-financial variables and explore the existence of common factors.

The economic importance of our results lay on the characterization of the counterparty intensities and risk premiums embedded in the different tenor Euro interbank market BS quotes and the study or their determinants. This article analyzes the relationship of counterparty risk and risk premium estimates to other financial and macroeconomic variables and it compares these results across the different tenor BS curves. We also analyze the behavior of model implicit noise residuals and its economic content. Our contribution to the financial literature is threefold.

First, this article explores the main covariates of BS spreads. A preliminary analysis reveals strong comovements in each tenor BS data. In particular, a principal component analysis on the BS series reveals that around 92% of total variation of a given tenor BS spreads are explained by the first principal component. This means that a single factor captures the first order changes in BS spreads. Regression analysis reveals that the first principal component relates to credit risk variables while second order changes are more related to variables summarizing the level of distress in economic and financial conditions as well as the uncertainty perceived by agents reflected in their degree of risk aversion.

Second, motivated by this former evidence, this paper digs into the components of BS spreads. We set up a one-factor affine continuous time model to estimate risk premium for the different tenor sets of BS data. Our modeling proposal also permits to sketch the time series of implicit counterparty risk intensities from BS prices. The empirical findings report counterparty risk intensities on the order of 100 to 250 bps -depending on tenor- during distressed times. The strong commonalities between the distinct tenor curves counterparty risk intensities imply that the same factor underlies the risk level evolution implicit in the different BS spreads curves. Among the different tenors, the medium term ones are better represented by this common factor, which captures the BS curves level of risk.

Concerning the risks premiums associated to BS of different maturity, we note that they represent up to 20 to 60 basis points (bps) compensation for the changes in the risk environment.

These premiums are characterized by a strong first principal component that may be interpreted as an aggregate level of distress risk compensation. This component is more related to medium term BS tenors. The 1-month and 12-month BS spread display important idiosyncrasies with respect to the rest of the tenors.

Using a wide set of financial and macro variables, we find that counterparty risk relates to credit variables, particularly to German CDS spreads, which can be interpreted as a state variable summarizing the level of risk agents are willing to bear in their interbank deposit borrowing and lending transactions. Risk premium estimates significantly covariate with financial sector specific variables -credit and liquidity- and also risk aversion. The model explanatory power is higher for shorter maturities and it is particularly remarkable in the case of longer tenors with Adjusted R^2 values up to 54%.

The third contribution of this paper accounts for the informational content of pricing model residuals. Inspired by the emerging strand of the literature on the analysis of price deviations from benchmark, we implement an error based measure to capture the unexplained component of the pricing model; see, for instance, Hu et al. (2013) and Rubia et al. (2014). More in detail, we employ an estimate of the volatility of the model mispricing errors also called noise measure in (Hu et al., 2013). The OLS projections of the noise measure onto a set of macroeconomic variables show that these noise series strongly covariate with liquidity measures.

The literature about the multiple term structures is yet scarce. We structure this literature in three major strands. On the one hand, papers setting the theoretical grounds of the multiplicity framework, such as Bianchetti (2009), Mercurio (2009), Morini (2009) and Henrard (2009). On the other hand, practitioners papers focused on the consistent construction of multiple curves from interest rate instruments, such as West (2011), Fujii and Takahashi (2010*b*) and Chibane and Sheldon (2009) among others. Finally, papers working on the accommodation of pre-crisis no-arbitrage models to the multiple curve situation such as Fujii and Takahashi (2010*a*), Kenyon (2010) and Mercurio (2010). Relative to these latter papers, an alternative to the multi-curve setting in order to account for the current market situation that has not so often been considered consists of modeling the counterparty and liquidity risk probabilities. The framework adopted in this paper closely follows this alternative considering an equilibrium model instead of no-arbitrage models.

In particular, our paper relates to the literature considering the estimation of risk premiums using the intensity framework. The methodology employed here uses the intensity modeling of Lando (1998), Longstaff et al. (2011) and Pan and Singleton (2008).

Our interest in interbank spreads closely relates to previous theoretical work by Liu et al. (2006), Duffie and Singleton (1997), Duffie and Singleton (1999), Collin-Dufresne et al. (2001) and Collin-Dufresne and Solnik (2001) who are more focused on the analysis of market premia implicit in interest rate swap spreads, understood as the differences between swap and treasury bond rates. Our approach differs from theirs in the nature of the data. Our interest lays in the study of the risks implicit in interbank BS spread quotes instead of sovereign spreads. Also, Duffie and Singleton

(1997), Duffie and Singleton (1999) and Liu et al. (2006) follow strongly a single curve framework. However in line with multiple curves current market practices, we regard as important to take into account the differential risks embedded in discount and forward curves. Collin-Dufresne and Solnik (2001) take into account this precise assumption and differentiate between the risks of the swap instruments per-se and those implicit in the derivative underlying rates. Nevertheless these authors do not consider stochastic intensities of default in their model as we do.

This paper is most closely related to Filipovic and Trolle (2013). As these authors, we are concerned about the separate identification of risk components in interbank spreads. We also concentrate on a single factor model which may capture both default and liquidity terms. Relative to Filipovic and Trolle (2013) we do not model the dynamics of the different curves interest rates. Our choice is to focus instead on BS pricing formulas and market quotes disregarding the interaction of the spreads with interest rates. To the best of our knowledge this is the first study quantifying the size of the BS quotes risk premium, and one of the few articles shedding light on the reasons for the post-crisis interest rates curves multiplicity.

Thus, this paper analyzes the term structure of counterparty risk in the interbank market using the informational content of Basis Swap spreads. The reminder of the paper is structured as follows. Section 3.2 introduces the topic. The BS market structure and the dataset are presented in section 3.3. Section 3.4 studies the sources of counterparty risk in BS quotes. Section 3.5 describes the model and disentangles the components of BS spreads. Section 3.6 analyzes the counterparty risk and risk premiums commonalities and their determinants. Some conclusions are provided in Section 3.7.

3.2 Counterparty risk, multiple curves and Basis Swap spreads.

3.2.1 Counterparty risk and multiple interest rate curves

Under the classical single-curve framework, there exists a correspondence between implicit rates from deposits, and rates from forward rate agreements (FRAs). This relationship is based on the strategy for pricing this derivative, where we implicitly assume that the derivative payoffs are replicated by selling and buying zero-coupon bonds without risk. A detailed discussion about this strategy is provided in Chapter 2.

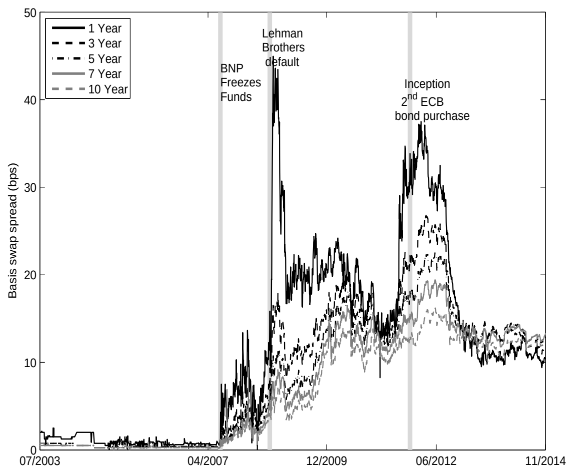
As a consequence of the lack of confidence and illiquidity crises that marked the start of the crisis, market makers began attributing differential credit and liquidity risks to different tenor (deposit) financing operations that take place at the interbank market level.[1] Deposit rates started to

[1] In parallel to the recognition of these risks, the perception of higher counterparty risks resulted in the establishment of clauses and collateral agreements (such as CSA) in interbank markets contracts in order to mitigate the consequences associated to counterparty defaults. Although these clauses helped to mitigate the counterparty risk concerning the derivative contracts themselves, the credit and liquidity risks embedded in the instrument reference rates still had impact

reflect credit and liquidity risks as a part from market risks and this meant that borrowing at floating rates of different tenor started not to be equivalent, contrary to what happened before the crisis when only market risks were accounted. These differential risks also started to be reflected in the quotes of derivative operations that were linked to these deposit rates and implied flows/payments of different tenor/frequency. These changes in market quotes were significant in the case of market instruments such as Basis Swaps capturing the spread between the different tenor IRS curves and therefore the differential costs of different tenor funding. Basis Swaps quotes were negligible before the start of the crisis and became highly significant afterwards.

Figure 3.1 shows this explosion for the particular case of Basis Swap spreads, an IRS derivative with two floating legs (e.g. Euribor 6M versus Euribor 3M). Figure 3.1 depicts a significant increment of the spreads, clearly associated to a higher risk of lending at longer frequencies, which it was not the case before the crisis. This spread was stable during 2009, even when the worst part of the financial crisis had already took place. An interesting question is whether those spread levels will ever come back to the pre-crisis levels. Tuckman and Porfirio (2003) point out that these risks were already recognized before the crisis. Nevertheless the market did not significantly price them until the outbreak of the financial crisis. These risks were evident with the explosion of Basis Swap spread quotes and the divergences between the traded implicit forwards of different instruments such as deposits, FRAs and IRS.

Figure 3.1: 3M vs 6M Basis Swap spread time series.



3M vs 6M BS spread daily time series for different maturities. The sample period ranges from July 28th 2003 to November 12th 2014.

As a consequence of these changes the pre-crisis single term structure curve framework could

on these derivatives quotes.

not account for the new situation given that interbank derivative instruments market quotes started not to be consistent with the assumption of a single curve. In the pre-crisis context, replication strategies for IRS based on assuming a single curve framework were consistent with market quotes. These replication strategies assumed that financing at any tenor was equivalent and disregarded credit and liquidity issues that may matter in getting funding at different frequency. Therefore they implied that the IRS floating payments did not depend on the floating rate periodicity and thus that Basis Swaps were zero. These replication strategies were not satisfactory in order to set IRS valuations and to account for significantly different from zero Basis Swaps after the crisis.

Given that the pre-crisis single curve valuation framework became not satisfactory, market makers mainly adopted a practical solution to adapt the previous setting to the current context. In particular, they adopted a multi-curve setting, a new framework where they discriminate between underlying interbank market reference rates according to their tenor. Under this setting, agents estimate different curves associated to different tenor underlying rates, use them in estimating future implicit values for these rates and consider a unique discounting curve in the computation of the present value of these flows. To estimate the different curves, distinct sets of instruments linked to different tenor rates are used. For instance, to construct the curve associated to Euribor 6M frequency we employ FRAs and IRS associated to 6-month payment frequency. As a discounting curve, the term structure of the Eonia rate is usually employed. For more details about these practices see for instance West (2011), Fujii and Takahashi (2010*b*) and Bianchetti (2009) [2].

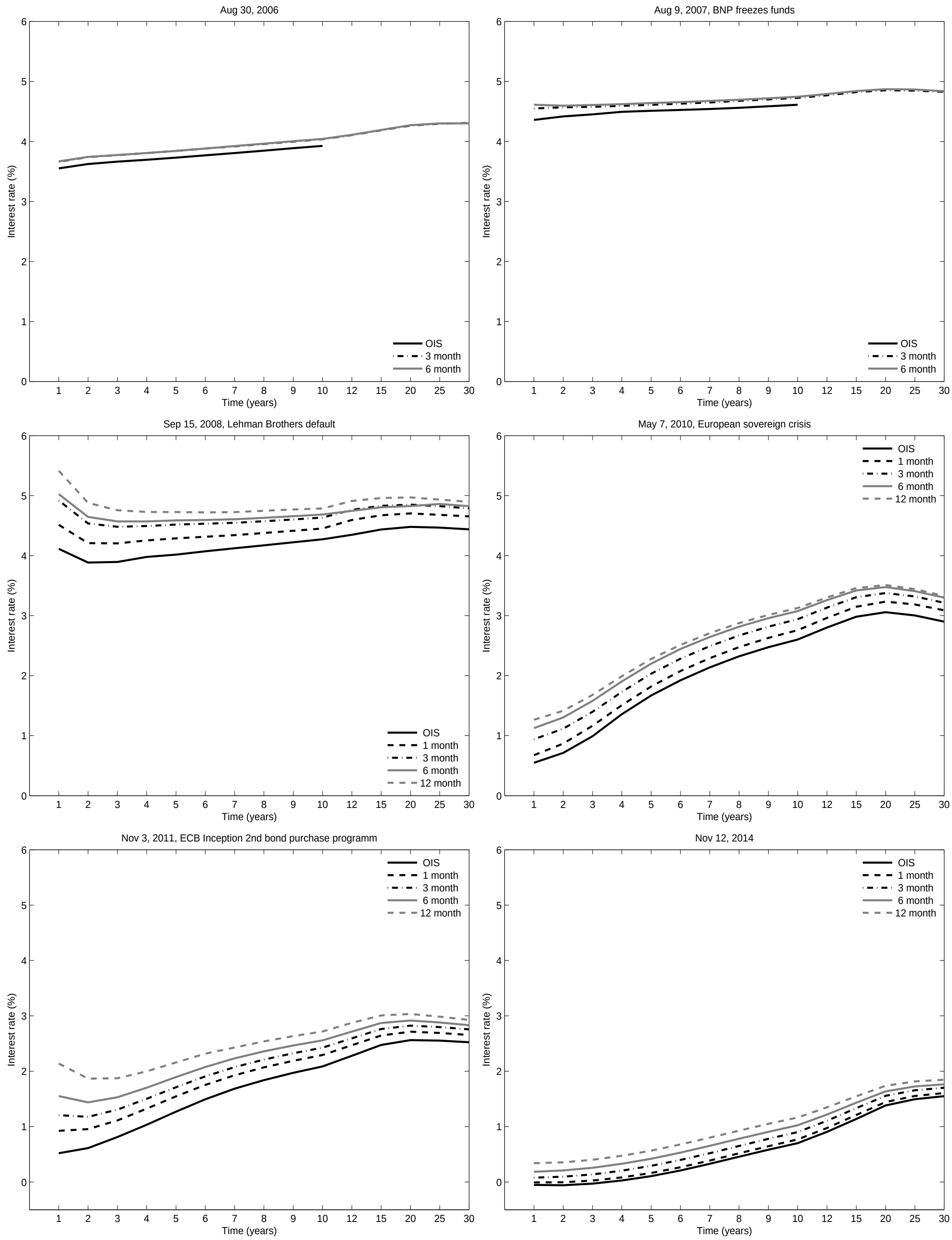
Figure 3.2 illustrates the stratification of the IRS term structure at different dates. Prior to the financial crisis, the existence of a single-curve setting was clear as the gaps between the different tenor curves were negligible. This can be observed from the term structures corresponding to August 30th 2006. However, since the start of the crisis the discrepancies between different tenor curves are evident, particularly during the Lehman Brothers and sovereign debt crisis episodes, as the curves on September 15th 2008 and May 7th 2010, respectively, show. Although the gaps between different tenor curves are clearly more important on periods of strong financial stress such as before the start of the second ECB bond repurchase program on November 3rd 2011, this stratification is still reflected on more recent dates such as November 12th 2014 even though financial distress has clearly declined.

3.2.2 About the risks embedded in interbank derivative contracts

It is important to distinguish between the risks inherent in the BS reference rates and the risks of the BS contract. The former arise because Euribor and Eonia rates capture the cost of unsecured short-term loans between interbank financial institutions and, therefore, they may be influenced by credit and liquidity factors as well as market wide conditions. In particular, interbank rates reflect

[2] Most interbank derivative contracts are collateralized through CSA, which implies that the collateral is capitalized at Eonia rate and in order to avoid no-arbitrage opportunities this rate curve must also be considered in the discounting process. This is the reason why Eonia curve is employed for discounting.

Figure 3.2: IRS curves on different dates.



IRS curves on different dates. The sample period ranges from August 2006 to November 2014.

a compensation for the counterparty risk involved in unsecured interbank borrowing and also risk premiums related the funding liquidity of the borrowing bank. Market wide conditions include the uncertainty about the future path of short-term interest rates, translated into a term premium, the ease of trading (market liquidity) and factors associated to the fixing process and microstructure of the interbank market. All these factors may drive a wedge between the rates paid on deposits of different tenor and thus may be reflected in Basis Swap quotes.

Completely separate from the risk of the Euribor and Eonia indexes, is the counterparty risk of the BS contract, i.e. the risk that one of the swap counterparties will fail on its obligations to make the contracted floating payments. This risk may be argued to be small, given that the swap arrangement requires exchanging interest rate payments and that each counterparty is at risk only for the net present value of the swap (i.e. the difference between the value of receiving and the value of paying contracted cash flows). Still, this risk is largely eliminated by means of collateral requirements, very extended between financial institutions in OTC markets in recent years. The most commonly used contracts in OTC market interest rate derivative transactions under collateralization clauses consider the ISDA Master Agreement Credit Support Annex (CSA), which establishes collateral and margination rules between the counterparties. In case of OTC transactions that are executed through Central Counterparties, the clearing house assumes the legal counterparty risk of the trade. For more details about these issues see for example Ametrano (2011), Johannes and Sundaresan (2007) and Piterbarg (2010).

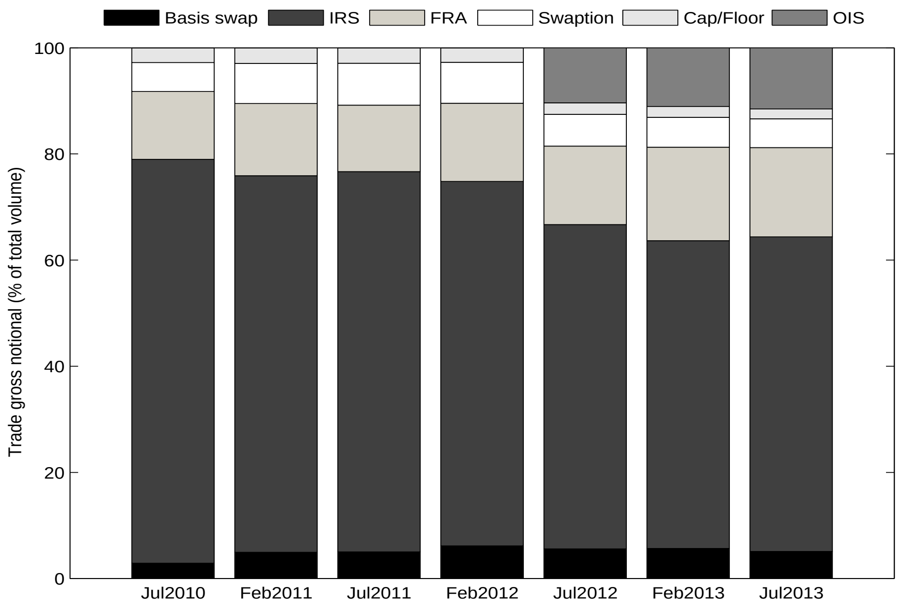
3.3 The structure of the Basis Swap market

3.3.1 The product

BS are contracts between two parties to interchange, at different frequencies, payments linked to different interest rates reference indexes. BS quotes may be interpreted as the spread differences between the swap curves linked to different tenor Euribor indexes in the interbank market. To illustrate the mechanism of a BS, see, for example, the 3-months Euribor vs 6-months Euribor Basis Swap. In this product, one of the counterparties makes payments linked to the 3-months Euribor and, in exchange, receives 6-months Euribor. If the 6-months Euribor rate is expected to be greater than the 3-months Euribor compounded quarterly, then a basis spread has to be added to the shorter tenor leg of the swap for the contract to be in equilibrium at inception.

The traded volume of BS contracts has increased during recent years. Figure 3.3 shows the gross notional evolution of Basis Swap trades with respect to other interest rate linked products such as Interest Rate Swaps (IRS), Forward Rate Agreements (FRA), Swaptions, Caps/Floors or the Overnight Indexed Swap (OIS) from July 2010 until July 2013. Previous records are not available before those dates. Data from OIS starts in April 2012. As observed, the most traded products are the IRS, although their importance has decreased in recent years. Contrarily, FRAs and BSs trading volume has increased.

Figure 3.3: Gross notional in percentage of the traded total volume for different Interbank Market instruments

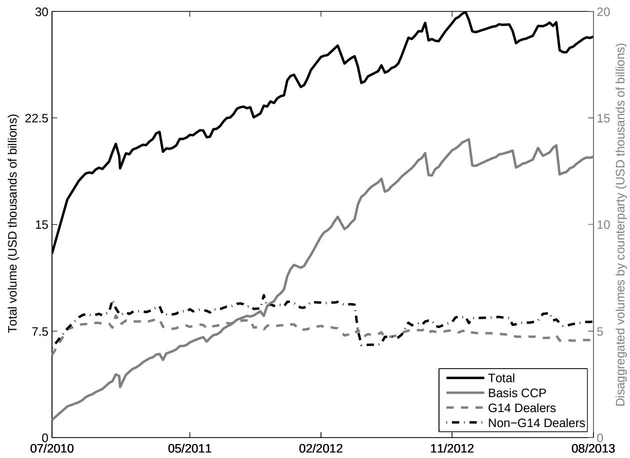


Each bar contains the BS, IRS, FRA, Swaption, OIS and Cap/Floor Trades Gross Notional. Data ranges from July 2010 until July 2013, with the exception of OIS series, which starts in April 2012. Data are extracted from DTCC and Trioptima.

Figure 3.4 depicts the evolution of the total outstanding volume of BS contracts (left axis). Figure also includes the amounts disaggregated by type of counterparty (right axis). These counterparties can be clearing counterparty houses (CCP), major dealers (G14 dealers) and remainder counterparties. As observed in Figure 3.4, the total outstanding amount of BS was approximately USD 13,000 billions in July 2007. This quantity has increased up to USD 28,217 billions in August 2013. With regard to the type of counterparty, Figure 3.4 shows a clear change in the tendency of BS contracts settlement. At the beginning, dealers and non-dealers captured the major market quote with approximately USD 5,000 billions, respectively. These quantities have kept constant during the whole sample period. However, an increasing trend is observed in the trading of clearing houses (CCP); its position has become dominant in the Basis Swap market since February 2012. For example, CCP trades in BS contracts account for 13,182 billions in August 2013, which represents approximately 46.7% of the trading in August 2013 [3].

[3]This pattern is corroborated by our conversations with traders, who highlight that BS contracts exchanged in the interbank market are commonly cleared through central clearing houses of which one of the most important is the London Clearing House (LCH).

Figure 3.4: Basis Swap trades gross notional disaggregated by the type of counterparty.



Basis Swap trades gross notional disaggregated by the type of counterparty. Basis Swap outstanding trades gross notional data correspond to left axis. Basis Swap disaggregated by type of counterparty are in right axis. Outstanding trades gross notional data are in billions of USD and it is based on 14 financial entities interest rate derivatives transaction weekly reports. Data are disaggregated by the type of counterparty: G14 dealers, non-G14 dealers and central clearing counterparties (Basis CCP). The sample period ranges from July 30th, 2007 to August 30th, 2013. Data have been extracted from DTCC and TriOptima.

3.3.2 Data analysis

The dataset consists of weekly quotes of BS spreads corresponding to 1-, 3-, 6- and 12-months Euribor tenors against Eonia (from now onwards we denote these BS spreads as BS1M, BS3M, BS6M and BS12M, respectively). The sample period comprises from December 19th 2007 through November 12th 2014 covering the main episodes of the European sovereign crisis. Unfortunately, direct market quotes of these spreads are only available for certain given maturities. Nevertheless, we construct the Euribor vs Eonia BS spreads that are not directly available in the market by non-arbitrage arguments. For instance, Euribor 6M vs Eonia spread series are obtained by adding Euribor 3M vs Eonia to Euribor 6M vs Euribor 3M BS quotes. For each tenor, we consider BS spreads corresponding to maturities 1-, 3-, 5-, 7- and 10-year. A detailed description of the procedure is included in Appendix B.

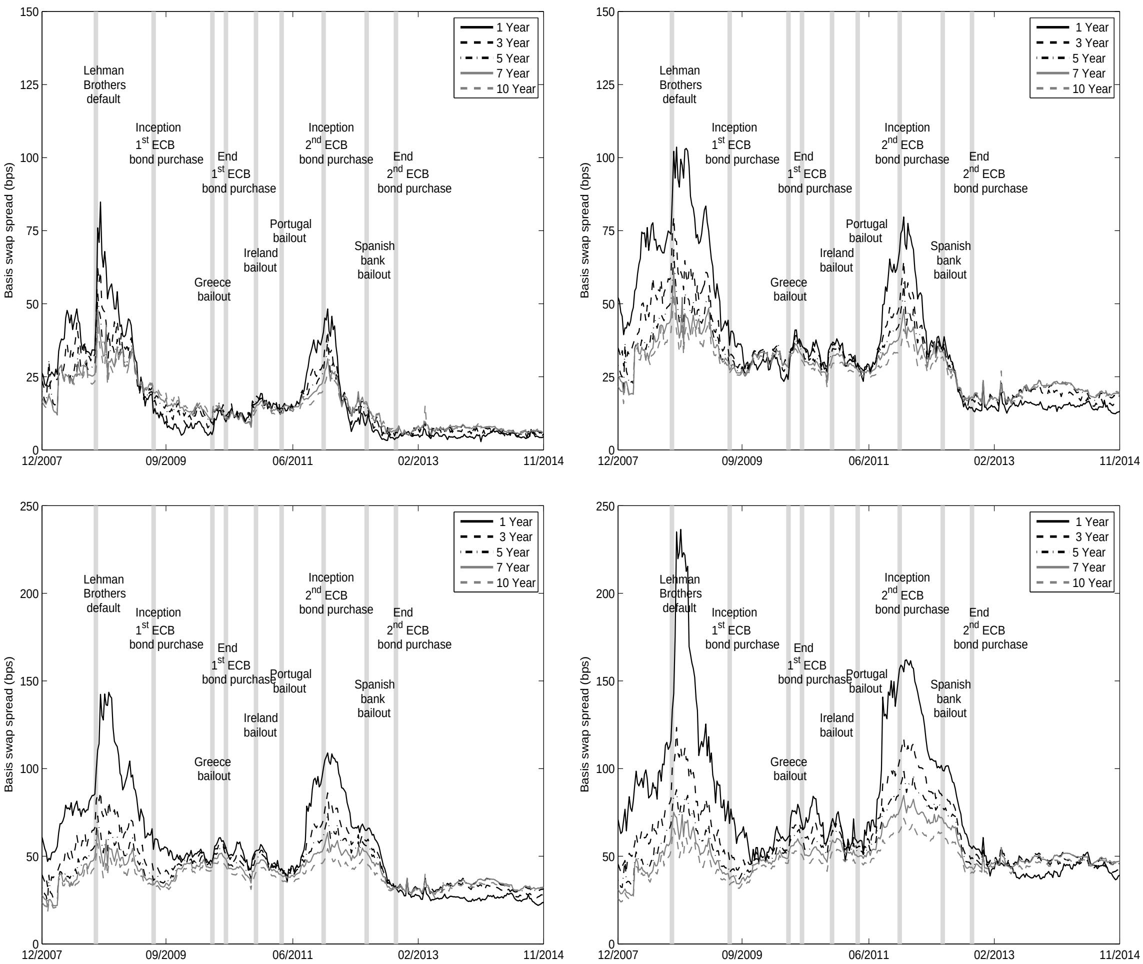
Figure 3.5 exhibits the time series of the BS spreads under study.[4] This Figure also includes several important events of the financial crisis such as the Lehman Brothers' default or the inception of the ECB bond purchasing programs. Some interesting conclusions emerge from this figure. First, the level of the spreads increases with the Euribor tenor. Second, the term structure of spreads peaks in credit shocks such as the collapse of Lehman Brothers in September 15th, 2008, and the worsening of the European sovereign debt crisis during November 2011. Third, the term structure seems to exhibit a downward slope shape in general. This monotonicity is stressed for long-term Euribor tenors (6- and 12-month), and during distress periods. The shape of the Euribor 1-month term structure is time-varying. Finally, Figure 3.5 also reveals the possibility of a high co-movement between the series.

To provide a different perspective of our dataset, Table 3.1 summarizes the main descriptive statistics of BS spreads. Some previous observations are confirmed. For example, the term structure of the BS is, on average, downward sloping. This result seems to be also robust on median; a special case is the BS 1M vs. Eonia, which reports an upward-sloping term structure in median. This result appears to confirm that BS act as an interest hedging instrument for the short run. In general, the highest volatility values correspond to the shortest maturities. Autocorrelation coefficients reveal that shorter maturities exhibit more persistence, and this persistence is declining in the long-run.

Figure 3.5 suggests the existence of commonalities between the different maturities of BS spreads within each set of distinct tenors BS quotes. To explore this issue, we perform a principal component analysis (PCA) on the BS spread quotes in levels and increments. Table 3.2 reports the resulting loading coefficients and explained variances for the first three factors. Some interesting results arise from this Table. First, there exists a strong first principal component that accounts for a high percentage of the BS variance both in levels and differences. The explanatory power is on average 92.48% and 72.12% for levels and differences, respectively. This first PC consists of an

[4] A full spectrum of maturities from 1- to 10-years is available to us. For the ease of explanation, we just employ five maturities throughout the text. Nevertheless, all different results remain qualitatively similar to the number of maturities used. These results are available upon request.

Figure 3.5: Euribor versus Eonia Basis Swap spreads for different maturities.



Weekly time series of the Euribor versus Eonia Basis Swap spreads. The distinct figures correspond to the different Euribor tenors basis spreads: 1-month (top,left), 3-months (top, right), 6-months (bottom, left) and 12-months (bottom, right). Data period comprises from December 19th 2007 to November 12th 2014.

Table 3.1: Basis Swaps summary statistics

		Mean	Std.	Median	Min	Max	Skew.	Kurtosis	ρ_N 4	12	24	N
BS1M	1y	17.02	15.62	10.90	2.80	84.80	1.47	4.67	0.91	0.73	0.51	361
	3y	16.15	11.49	12.80	3.50	62.35	1.27	4.20	0.91	0.79	0.57	361
	5y	15.50	9.21	13.90	4.60	53.85	1.05	3.67	0.90	0.80	0.60	361
	7y	15.12	8.24	13.80	5.20	47.80	0.96	3.50	0.90	0.81	0.63	361
	10y	14.85	7.48	13.90	5.42	41.95	0.86	3.11	0.89	0.81	0.66	361
BS3M	1y	37.29	23.04	31.20	12.35	103.60	0.97	3.04	0.95	0.81	0.57	361
	3y	32.59	13.77	31.45	14.20	79.65	0.74	2.94	0.93	0.80	0.55	361
	5y	30.40	10.06	30.00	14.80	68.45	0.59	2.91	0.89	0.75	0.49	361
	7y	28.85	8.37	28.80	14.90	60.90	0.50	2.89	0.88	0.71	0.47	361
	10y	27.20	7.00	27.20	14.83	53.65	0.44	2.82	0.85	0.69	0.48	361
BS6M	1y	55.21	27.49	51.40	22.00	143.50	0.97	3.57	0.94	0.76	0.49	361
	3y	47.01	14.45	45.85	26.30	86.75	0.57	2.54	0.92	0.74	0.42	361
	5y	43.27	10.28	41.80	23.50	74.95	0.46	2.42	0.88	0.66	0.30	361
	7y	40.51	8.31	39.50	21.10	64.90	0.25	2.46	0.85	0.59	0.24	361
	10y	37.32	6.61	36.50	17.60	57.25	0.02	2.73	0.80	0.51	0.21	361
BS12M	1y	78.71	40.76	66.80	36.60	236.45	1.54	5.39	0.92	0.67	0.34	361
	3y	63.07	19.65	56.05	40.80	123.45	1.13	3.23	0.92	0.71	0.32	361
	5y	56.72	13.93	51.80	32.20	99.85	0.98	3.14	0.90	0.67	0.26	361
	7y	52.34	11.24	49.90	27.60	84.65	0.62	3.18	0.88	0.63	0.24	361
	10y	47.50	8.74	46.40	24.00	71.60	0.15	3.48	0.84	0.57	0.21	361

Descriptive statistics for different Euribor tenor versus Eonia Basis Swap spreads term structures. The table presents the mean, standard deviation, median, minimum, maximum, skewness, kurtosis and 4, 12 and 24 lags autocorrelations of the term structures selected maturities are 1, 3, 5, 7 and 10 years. The distinct Euribor tenors are 1, 3, 6 and 12 months. The historical series are expressed in basis points and correspond to weekly data from December 19th 2007 to November 12th 2014.

equally weighted contribution for all maturities, and admits an interpretation as a level component of the BS term structure.

Table 3.2: Principal component analysis of BS spreads

	Levels				Differences			
	BS1M	BS3M	BS6M	BS12M	BS1M	BS3M	BS6M	BS12M
	Panel A.- 1^{st} Principal component							
1y	0.44	0.43	0.41	0.40	0.43	0.41	0.37	0.36
3y	0.45	0.45	0.46	0.46	0.41	0.42	0.43	0.45
5y	0.45	0.45	0.47	0.47	0.47	0.47	0.48	0.49
7y	0.45	0.45	0.46	0.46	0.48	0.47	0.48	0.47
10y	0.44	0.44	0.44	0.44	0.45	0.46	0.47	0.45
Variance (%)	95.96	95.41	90.33	88.21	71.21	73.77	71.11	72.36
	Panel B.- 2^{nd} Principal component							
1y	0.62	0.71	0.71	0.71	0.48	0.58	0.70	0.72
3y	0.37	0.31	0.31	0.31	0.61	0.52	0.42	0.36
5y	-0.05	-0.13	-0.12	-0.10	-0.11	-0.15	-0.14	-0.08
7y	-0.35	-0.36	-0.35	-0.34	-0.40	-0.39	-0.38	-0.37
10y	-0.59	-0.51	-0.50	-0.52	-0.48	-0.46	-0.42	-0.46
Variance (%)	3.26	3.85	8.78	11.03	15.56	14.27	16.35	17.84
	Panel C.- 3^{rd} Principal component							
1y	-0.51	-0.44	0.47	0.53	0.26	-0.57	-0.59	-0.59
3y	0.24	0.36	-0.39	-0.49	-0.49	0.72	0.79	0.75
5y	0.67	0.58	-0.53	-0.46	0.71	-0.36	-0.11	0.09
7y	0.05	0.04	-0.05	0.01	-0.13	0.06	-0.08	-0.18
10y	-0.48	-0.58	0.58	0.51	-0.41	0.16	-0.08	-0.21
Variance (%)	0.41	0.43	0.55	0.56	6.02	5.32	5.98	4.21

Loading coefficients and explained variance for the BS principal components. BS spread tenors are 1-, 3-, 6- and 12-months against Eonia. Each BS spread consists of maturities 1-, 3-, 5-, 7- and 10-year. Data sample is weekly and comprises from December 19th 2007 to November 12th 2014.

The second PC exhibits a significantly less explanatory power than first PC. The explained variance accounts for 6.73% and 16.01% in levels and differences on average. Looking at the BS loadings, they disentangle short and long maturities; this is consistent with a slope interpretation of this component. Finally, the explained variance of the third PC is almost negligible, and the third PC as a curvature component. Nevertheless, the degree of convexity in the BS term structure curves is small, meaning that the curvature component is not important and that the BS spread curves are fairly monotonous. All these results are parallel to those of traditional interest rates term structure traditional PC analysis.

3.4 The sources of counterparty credit risk

These previous results suggest the existence of factors behind the movement of the BS spreads. To analyze the possible economic sources of this co-movement, we project the first and second PCs onto a set of financial and economic variables, which represent the information in the market.

3.4.1 State variables

To proceed with our analysis we have selected the variables according to four different groups: money and interest rates, stock market, credit market and risk aversion variables respectively.

Money and interest rate market The multi-curve setting is clearly linked to the risk of lending in the interbank market, or interbank risk (Filipovic and Trolle, 2013). Therefore, the money and interest rate variables are the first group that draws our attention. This group includes the i) interest rate level in the Euro Area, denoted by *IR Level*. The interest rate is the risk-free lending rate in the Euro Area, and it is proxied by the Eonia Index, which is computed as a weighted average of all overnight lending actual transactions executed by the Eonia panel banks in the Euro money market [5]. It is calculated by the ECB and it has been taken from ECB.

The ii) interest rate slope (*IR Slope*) is usually taken as an indicator of overall economic health; see Collin-Dufresne et al. (2001) and Groba, Diaz and Serrano (2013). The risk-free interest rates slope in the Euro Area is proxied by the spread between the 10-year and 2-year Eonia swap quotes. Eonia Swaps or, alternatively, OIS are similar to plain vanilla IRS transactions – they both are exchanges of a fixed and variable interest rates –, with the variable rate being linked to Eonia Index. The data is taken from Bloomberg. Lastly, we use iii) the ECB Liquidity Indicator of the Euro Area money market (*ECB Liq*) published by ECB. The composite indicator includes arithmetic averages of individual liquidity measures. The data sources for these measures are the ECB, Bank of England, Bloomberg, JPMorgan Chase & Co., Moody's KMV and ECB calculations.

Stock market variables. This group includes the iv) Euro Stoxx Banks Price Index, a capitalization-weighted index which reflects the stock performance of companies in the European Monetary Union (EMU) that are involved in the banking sector. The data source is Bloomberg. The time series of this variable is considered in *logs*. Additionally, we also work with the v) Euro Stoxx VIX Index, a market estimate of future volatility based on a weighted average of implied volatilities of options written on Euro Stoxx 50 stocks. It captures implied volatility on Eurex traded options with a rolling 30 day expiry. The source is Bloomberg.

Credit market variables. The list includes the vi) Itraxx Senior Financials, an index that comprises 25 equally-weighted 5-years maturity Credit Default Swaps (CDS) on investment grade European entities involved in the financial sector. The index is from Markit. Then, we have the vii) the German CDS, the Federal Republic of Germany Senior CDS quotes in USD and maturity

[5] Euribor and Eonia rates were contributed by the same panel of banks until June 1st 2013 but since then the Eonia and Euribor panels are allowed to be different.

5-years and is taken from Bloomberg. This variable is named as *German CDS*. Finally, the viii) AAA Fin - German Government yield (*FG Spread*), that it is the spread between 1-year maturity AAA EUR Financial Sector and the 1-year maturity German Government yields. Each of the yields is calculated as a composite yield of representative securities around the 1-year maturity. The source is Bloomberg.

Risk aversion variables. Finally, we include a risk aversion variable as the ix) ECB Risk Aversion Indicator, an Euro Area global risk aversion indicator published by ECB, and denoted as *ECB RA*. The indicator is constructed as the first principal component of five risk aversion indicators, namely Commerzbank Global Risk Perception, UBS FX Risk Index, Westpac's Risk Appetite Index, BoA ML Risk Aversion Indicator and Credit Suisse Risk Appetite Index. A rise in the indicator denotes an increase in risk aversion. This indicator comes from Bloomberg, Bank of America Merrill Lynch (BoA ML), UBS, Commerzbank and ECB calculations.

To avoid the risk of using variables with similar information content, we compute the correlation matrix for all the candidate variables to be included in our regression analysis, which is reported in Table 3.3. We observe that either the Euro Stoxx Banks or the Euro Stoxx VIX is highly correlated with the Itraxx Financial and ECB risk aversion indexes. Also, the Itraxx Financial index exhibits a strong correlation with the German CDS. To avoid collinearity problems, we remove from our study the stock market variables and the Itraxx Senior Financial index. Standard stationarity tests systematically lead to reject the existence of a unit-root for the increments.

Table 3.3: Pairwise correlations of increments of explanatory variables

	IR Level	*IR Slope*	*ECB Liq*	*EuroStoxxBanks*	*EuroStoxxVix*	*Itraxx Fin.*	*German CDS*	*FG Spread*	*ECB RA*
IR Level	1.00								
IR Slope	0.03	1.00							
ECB Liq	0.12	-0.18	1.00						
EuroStoxxBanks	-0.00	-0.06	0.10	1.00					
EuroStoxxVix	0.12	0.18	-0.19	-0.67	1.00				
Itraxx Fin.	0.05	-0.16	-0.03	-0.71	0.46	1.00			
German CDS	0.04	-0.06	-0.16	-0.51	0.37	0.60	1.00		
FG Spread	0.13	0.22	-0.37	-0.19	0.26	0.23	0.23	1.00	
ECB RA	0.11	0.17	-0.17	-0.66	0.82	0.54	0.43	0.26	1.00

3.4.2 OLS results

As a first approach to study the determinants of the multi-curve framework, we project the different tenor BS first and second principal components onto the previously presented explanatory variables. Let ΔPC_{it} denote the increments of the principal component i -of a particular tenor BS- at time t; we model the conditional mean of this process. In particular, we consider the following OLS regression specification:

$$\Delta PC_{it} = \alpha_i + \gamma_{1i}\Delta IRLevel_t + \gamma_{2i}\Delta IRSlope_t + \gamma_{3i}\Delta ECBLiq_t + \gamma_{4i}\Delta GermanCDS_t + \gamma_{5i}\Delta FGSpread_t + \gamma_{6i}\Delta ECBRA_t + \varepsilon_{it}, \quad (3.1)$$

where $\theta_i = (\alpha_i, \gamma_i')'$ denotes the main parameters of interest and ε_i denotes random disturbances.

Tables 3.4 report the estimated parameters, White (1980) robust standard errors for individual significance, and adjusted R^2 coefficients of these regressions. Some interesting results appear.

The results in Table 3.4 show that the first principal component significantly relates to credit risk variables, in particular the bond spread between the AAA Financial and German government plays a leading role in explaining the fluctuations in the BS spread curves level factor. German CDS spreads are also significant, particularly at shorter tenors. Notably, this pattern remains qualitatively unchanged across maturities. This means that economic and financial credit conditions are reflected on the level of BS spread quotes.

The first principal component also accounts for the risk perceived by investors in the Euro Area when they lend to financial institutions compared to more secure investment alternatives. Not surprisingly, the ECB risk aversion index is also statistically significant for longer tenors. Indeed, the adjusted R^2 shows that the explanatory ability of the model is clearly higher for the 6- and 12-month tenors.

Regarding the main drivers of fluctuations in the second principal component, we highlight the role of economic agents' perception of future uncertainty, as proxied by the ECB Risk Aversion indicator. This variable is statistically significant at conventional confidence levels for all tenors. The explanatory ability of, on one hand, interest rate level and slope and, on the other hand, liquidity signal that the second principal component responds to the level of distress in economic and financial conditions, respectively. The explanatory power of the linear model increases with the tenor. Indeed, the adjusted R^2 reaches 37% for the 12-month maturity.

3.5 The components of Basis Swap spreads

3.5.1 Model setup

We assume that there is a single factor counterparty risk spread embedded on the Euribor short rate reflecting the risk of borrowing/lending transactions between contributor banks. This is also the underlying variable of the BS spreads of a given tenor. The counterparty risk spread is modeled dynamically following an intensity approach. The formulation is similar to Pan and Singleton (2008). In particular, we consider the risk intensity $\lambda_t^{\mathbb{Q}}$ as the BS derivative contract underlying factor for a particular tenor. The counterparty risk intensity is a latent variable which is derived implicitly from the BS quotes as part of the model estimation process. Information about $\lambda_t^{\mathbb{Q}}$ is

Table 3.4: OLS regressions for BS spreads principal components

	1^{st} PC				2^{nd} PC			
Variables	BS1M	BS3M	BS6M	BS12M	BS1M	BS3M	BS6M	BS12M
Constant	0.0159	0.0039	0.0150	0.0312	0.0088	0.0090	0.0216	0.0251
	(0.0940)	(0.0951)	(0.0906)	(0.0841)	(0.0444)	(0.0409)	(0.0385)	(0.0395)
IR Level	0.7409	0.1857	0.8083	1.7568**	0.4506	0.2533	0.8861**	1.1386***
	(0.8274)	(0.8119)	(0.7883)	(0.8430)	(0.4665)	(0.3736)	(0.4087)	(0.4139)
IR Slope	-3.7140**	-3.1233*	-0.9101	2.4645	2.0607**	2.1289**	3.5578***	4.4347***
	(1.8613)	(1.7774)	(1.7659)	(1.6764)	(1.0090)	(0.9198)	(0.8668)	(0.8373)
ECB Liq	0.4444	1.1919	0.5142	-0.4277	-0.5123	-0.8863*	-1.6881***	-2.0014***
	(1.3007)	(1.3284)	(1.1568)	(0.9137)	(0.6610)	(0.5139)	(0.5451)	(0.5174)
German CDS	0.0545**	0.0644**	0.0564**	0.0417	0.0025	0.0151	0.0103	-0.0047
	(0.0239)	(0.0265)	(0.0273)	(0.0287)	(0.0130)	(0.0108)	(0.0089)	(0.0101)
FG Spread	6.9712**	5.5999**	5.6053**	5.6222**	0.5326	0.3488	0.5344	-0.4550
	(2.7504)	(2.7166)	(2.5593)	(2.2229)	(1.2743)	(1.0604)	(0.9029)	(0.9022)
ECB RA	0.0072	0.3163*	0.4752***	0.7087***	0.2026*	0.2034**	0.2850***	0.2907***
	(0.1789)	(0.1846)	(0.1730)	(0.1554)	(0.1045)	(0.0840)	(0.0839)	(0.0831)
Adj-R^2	12.16	11.66	14.96	26.04	9.45	14.54	34.84	36.96
N	360	360	360	360	360	360	360	360

Heteroskedasticity consistent standard errors and Adj-R^2 (in percentages) from regressing the different tenor BS first and second PC on a set of explanatory variables. All estimated coefficients are insignificant at the 10% level unless signaled as: (***) significant at 1% level, (**) significant at 5% level and (*) significant at 10% level. Data considered: BS spreads weekly data from December 19th 2007 to November 12th 2014 and corresponding to maturities 1Y, 3Y, 5Y, 7Y and 10Y.

very interesting, as it summarizes the level of risk implicit in the BS quotes for a particular tenor curve. The comparison of the $\lambda_t^{\mathbb{Q}}$ estimations between the different BS curves allows us to analyze the existence of common factors impacting the different curves simultaneously.

Under this framework we may consider that the interbank counterparty risk events are triggered by the first jump of a Poisson process with stochastic risk neutral intensity following a log-OU process under the risk neutral measure $\mathbb{Q}$,

$$d\ln\lambda_t^{\mathbb{Q}} = \kappa^{\mathbb{Q}}(\theta^{\mathbb{Q}} - \ln\lambda_t^{\mathbb{Q}})dt + \sigma dW_t^{\mathbb{Q}} \tag{3.2}$$

where parameters $\kappa^{\mathbb{Q}}$, $\theta^{\mathbb{Q}}$ and σ capture the long-run mean, mean-reversion rate and the volatility of the process, respectively. The Ornstein-Uhlenbeck process followed by the log-intensities in 3.2 ensures the positiveness of the counterparty risk intensity. The risk-neutral intensity process $\lambda_t^{\mathbb{Q}}$ admits equivalent formulation in terms of the actual data generating process $\mathbb{P}$,

$$d\ln\lambda_t^{\mathbb{Q}} = \kappa^{\mathbb{P}}(\theta^{\mathbb{P}} - \ln\lambda_t^{\mathbb{Q}})dt + \sigma dW_t^{\mathbb{P}}, \tag{3.3}$$

The processes under $\mathbb{P}$ and $\mathbb{Q}$ measures are connected by the market price of risk,

$$\Lambda_t = \delta_0 + \delta_1 \ln\lambda_t^{\mathbb{Q}}, \tag{3.4}$$

with $\kappa^{\mathbb{P}} = \kappa^{\mathbb{Q}} - \delta_1\sigma$ and $\kappa^{\mathbb{P}}\theta^{\mathbb{P}} = \kappa^{\mathbb{Q}}\theta^{\mathbb{Q}} + \delta_0\sigma$.

3.5.2 Pricing the Basis Swap

The BS is a contract between two parties to interchange, at different frequencies, payments linked to different interest rates reference indexes. In the interbank market the BS quotes may be interpreted as the spread differences between the swap curves linked to different tenor Euribor indexes. In the following we assume that there is a credit-related spread embedded on the Euribor short rate reflecting the underlying credit quality of the contributor banks. Under this assumption, the contract price for maturity T Euribor vs. Eonia. BS would be computed according to the following expression,

$$\Delta_{x,y} = \frac{\begin{pmatrix} E_t\left\{\sum_{j=1}^{n_x} e^{-\int_t^{T_{x,j}} r(s)ds}\left(\frac{1}{B(T_{x,j-1},T_{x,j})} - 1\right)\right\} \\ -\left(P_d\left(t,T_{y,0}\right) - P_d\left(t,T_{n_y}\right)\right)\end{pmatrix}}{\sum_{j=1}^{n_y} P_d\left(t,T_{y,j}\right)\tau_y\left(T_{y,j-1},T_{y,j}\right)}, \tag{3.5}$$

with the date schedules corresponding to the swap floating legs linked to OIS and Euribor rates are $T_y = \left\{T_{y,0},...,T_{y,n_y}\right\}$ and $T_x = \left\{T_{x,0},...,T_{x,n_x}\right\}$, respectively. $P_d(t,T)$ is the value at time t of the risk free zero coupon bond with maturity T, i.e. $P_d(t,T) = E_t\left[e^{-\int_t^T r(u)du}\right]$, where r_t is the risk-free instantaneous interest rate at time t. B(t,T) is the value at time t of the interbank market risky zero coupon bond with maturity T, $B(t,T) = E_t\left[e^{-\int_t^T (r(u)+\lambda^{\mathbb{Q}}(u))du}\right]$, where $\lambda_t^{\mathbb{Q}}$ is the credit spread. There exists a relationship between the value of the risky zero coupon bond $B(t,T)$ and the Euribor rates set at time t, i.e. $L(t,T) = \frac{1}{\tau_x(t,T)}\left(\frac{1}{B(t,T)} - 1\right)$. $E_t[.]$ is the expectation at time t and $\tau_x()$ and $\tau_z()$ denote the day count fractions between two particular payment dates according to the established calculation basis.

An interesting case is that the Basis Swap spread would be zero in case of the values of the risk free zero coupon bonds and the interbank market risky zero coupon bonds were the same at any maturity, $\Delta_{(x,y)}$ is equal to zero. This situation would hold if it existed a unique interest rate term structure curve in the interbank market.

3.5.3 Econometric procedure and results

The parameters that characterize the model can be estimated by maximum likelihood given a number of additional assumptions. The reader is referred to the original Pan and Singleton (2008) paper for details, but we briefly sketch the main steps involved in the estimation of this model in the sequel. In particular, the estimation procedure assumes that BS contracts for a certain maturity are priced with no error, whereas prices for the remaining maturities can be determined under non-arbitrage conditions. We consider that 5-year maturity BS contracts are perfectly priced to recover a time series of the counterparty intensity process using a non-linear optimization technique. This maturity choice is arbitrary, but based on the sensible appreciation that the 5-year contract is the most heavily traded maturity in practice. The remaining BS contract maturities (1, 3, 7 and 10 year maturities) are assumed to be priced with random errors (ε_{1Y}, ε_{3Y}, ε_{7Y} and ε_{10Y}) that obey a normal multivariate distribution with zero mean vector and variance σ_{BS}. For parsimony and computational tractability, we assume that the pricing errors are constant across maturities, noting however that results do not qualitatively differ from more general specifications (results under heteroskedasticity are available upon request). The estimation of this model also requires the discretization of $\lambda_t^{\mathbb{Q}}$ in expression 3.2 and 3.3, for which we adopt the Euler's approach and set $\Delta t = 1/52$.

Expectations in equation 3.5 under $\mathbb{Q}$ and under $\mathbb{P}$ when $\lambda_t^{\mathbb{Q}}$ follows a log-OU process are not in closed form, so they are computed using a Crank-Nicholson discretization scheme for the corresponding partial differential equation. In these expressions, we consider a bootstrapped Overnight Indexed Swap (OIS) curve to infer the risk free rates to discount future payoffs. Finally, the joint density function is,

$$f^{\mathbb{P}}(\Theta,\lambda) = f^{\mathbb{P}}(\varepsilon_{1Y}|\sigma_{BS}) \cdot f^{\mathbb{P}}(\varepsilon_{3Y}|\sigma_{BS}) \cdot f^{\mathbb{P}}(\varepsilon_{7Y}|\sigma_{BS}) \cdot f^{\mathbb{P}}(\varepsilon_{10Y}|\sigma_{BS}) \cdot f^{\mathbb{P}}(\ln\lambda^{\mathbb{Q}}|\kappa^{\mathbb{P}}, \kappa^{\mathbb{P}}\theta^{\mathbb{P}}, \sigma) \cdot \left|\frac{\partial BS^{\mathbb{Q}}(\lambda^{\mathbb{Q}}|\kappa^{\mathbb{Q}}, \kappa^{\mathbb{Q}}\theta^{\mathbb{Q}}, \sigma)}{\partial\lambda^{\mathbb{Q}}}\right|^{-1} \quad (3.6)$$

with parameter vector $\Theta = \left(\kappa^{\mathbb{Q}}, \kappa^{\mathbb{Q}}\theta^{\mathbb{Q}}, \sigma, \kappa^{\mathbb{P}}, \kappa^{\mathbb{P}}\theta^{\mathbb{P}}, \sigma_{BS}\right)$ and $f^{\mathbb{P}}(\cdot)$ the density function of the Normal distribution.

Table 3.5 reports the results of the maximum likelihood estimation.

Table 3.5: Model Estimation Results

	BS1M	BS3M	BS6M	BS12M
$\kappa^{\mathbb{Q}}$	0.3135	0.4183	0.4413	0.4636
	(0.0475)	(0.0855)	(0.0830)	(0.0990)
$\kappa^{\mathbb{Q}}\theta^{\mathbb{Q}}$	-2.3534	-2.8525	-2.8428	-2.7889
	(0.3741)	(0.5569)	(0.5716)	(0.8574)
σ	1.0795	1.0794	1.0552	0.9008
	(0.0588)	(0.1659)	(0.2901)	(0.3025)
$\kappa^{\mathbb{P}}$	0.5836	1.1477	1.7242	1.9890
	(0.3526)	(0.5307)	(0.7931)	(0.6324)
$\kappa^{\mathbb{P}}\theta^{\mathbb{P}}$	-4.1154	-6.8067	-9.3096	-9.9635
	(2.3917)	(3.2507)	(4.8552)	(4.7582)
σ_{BS}	0.0003	0.0005	0.0008	0.0013
	(0.0027)	(0.0041)	(0.0252)	(0.0341)

Model estimation results. The table reports the maximum likelihood estimation results corresponding to the model parameters with standard errors in parenthesis. These estimations have been calculated for the distinct 1, 3, 6 and 12 months BS tenors. The sample period considered in these estimations corresponds to Basis Swap spreads weekly data from December 19th 2007 to November 12th 2014.

Concerning the mean reversion and long-run mean parameters estimates under the risk neutral and actual probability measures, we observe that $\kappa^{\mathbb{P}}\theta^{\mathbb{P}} < \kappa^{\mathbb{Q}}\theta^{\mathbb{Q}}$, which implies that the average counterparty intensity level is higher under the $\mathbb{Q}$ distribution than under the $\mathbb{P}$ distribution and that $\lambda_t^{\mathbb{Q}}$ will tend to be larger under $\mathbb{Q}$ than under $\mathbb{P}$ meaning that the credit conditions are worse under the risk-neutral environment. Additionally, $\kappa^{\mathbb{P}} > \kappa^{\mathbb{Q}}$, signaling that there is generally much more persistence under $\mathbb{Q}$ than under $\mathbb{P}$ meaning that the convergence of the counterparty intensity process to a certain long-run mean is faster under the actual than under the risk-neutral measure. From Table 3.5 we also observe that the volatility of mispricing errors, σ_{BS} , is small compared to BS spreads magnitudes, meaning that the model has good performance.

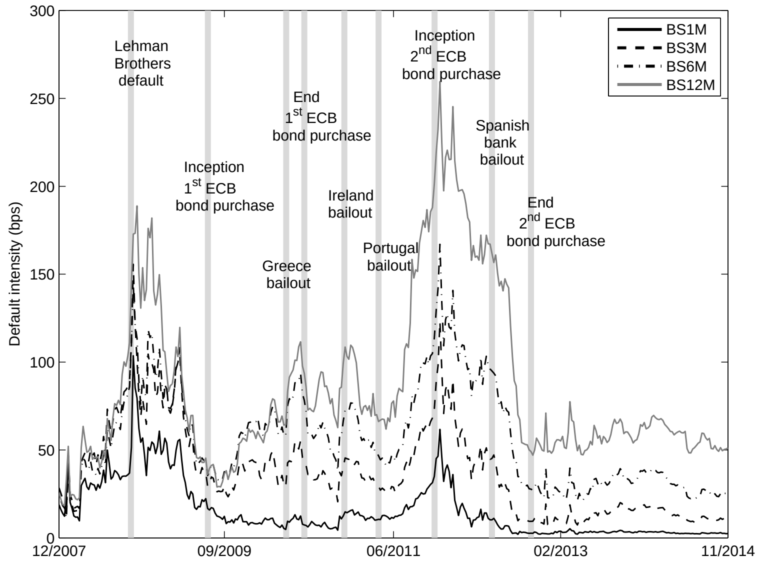
3.6 Risk premium and counterparty risk determinants

This section analyzes the information extracted from the model -namely counterparty risk, risk premium and model residuals- for each tenor BS spread curve, examining the degree of comovement among the different tenor series. The information content of these components and their determinants are also studied.

3.6.1 Counterparty risk intensities, risk premium and model residuals

The lambda parameter is the BS underlying variable. From the model estimation results we may derive time series for the model's implicit lambda corresponding to the sample observation period. Given that we estimated the model for different sets of BS spread curves, we consequently derive different lambda time series, each corresponding to a distinct tenor BS spread curve. In the following figure we depict these estimated lambda time series.

Figure 3.6: Time series of the counterparty risk intensities



Time series of the different tenor BS counterparty risk intensities. Data period ranges from December 19th 2007 to November 12th 2014.

From the previous figure we first note that the lambdas follow a similar pattern to the original data BS spread levels, meaning that lambdas are capturing the BS curves level of risk. The magnitude of the lambdas is important, ranging from 100 to 250 bps depending on the tenor in turbulent times. Particularly remarkable are the values of longer tenor lambdas during the sovereign debt crisis which are even higher than their corresponding values during the Lehman Brothers default period.

Second, from Figure 3.6, we observe that there exist strong commonalities among the different lambda time series given that their evolution is very similar. To assess this hypothesis we perform a principal component analysis on these series, obtaining the following results.

Table 3.6: PCA results of the BS counterparty risk intensities

	Levels			Differences		
	PC1	PC2	PC3	PC1	PC2	PC3
BS1M	0.47	0.64	0.50	0.48	-0.65	0.58
BS3M	0.53	0.31	-0.43	0.52	-0.23	-0.56
BS6M	0.53	-0.32	-0.51	0.53	0.19	-0.38
BS12M	0.47	-0.63	0.56	0.47	0.70	0.46
Variance (%)	81.51	15.91	2.38	86.34	10.15	3.27

PCA results of the different tenors BS counterparty risk intensities expressed in levels and in differences. The table presents the factor loadings of the first three principal components and the percentage variance explained by each component. These figures are computed by performing a principal component analysis of the counterparty risk intensities corresponding to the distinct Euribor tenor vs Eonia Basis Swap spread term structures. The distinct Euribor tenors are 1, 3, 6 and 12 months. The historical series of the factors correspond to weekly data from December 19th 2007 to November 12th 2014.

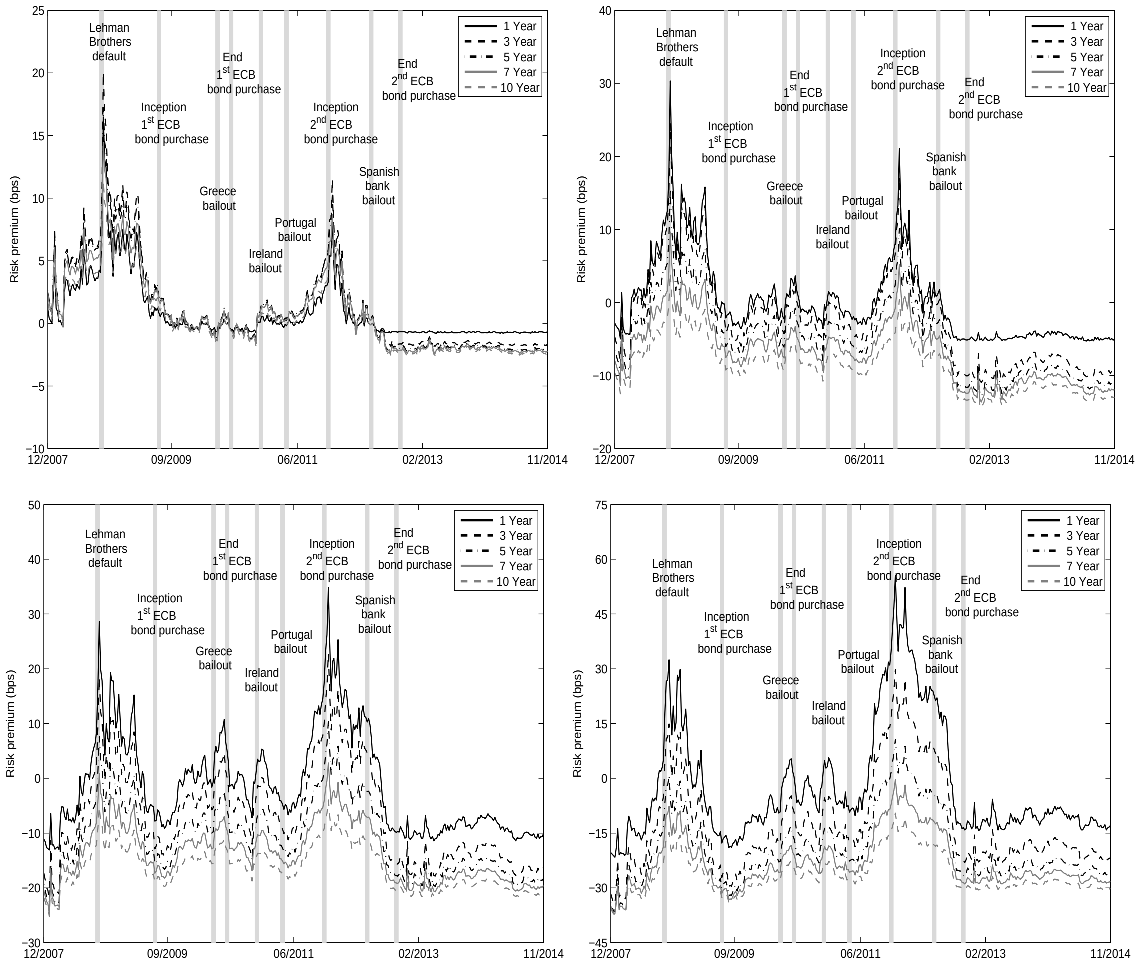
Table 3.6 evidences the existence of a strong first principal component capturing up to 82% and 86% of the lambdas time series variance in levels and differences, respectively. This means that the same factor is valid across all the different set of curves and underlies the evolution of the different lambdas, accounting for the BS curves risk level joint evolution. This first principal component behaves as a level factor, as the PC loadings in Table 3.6 reveal. It is important to note that among the different tenor lambdas, the ones associated to 1-month and 12-month tenors display more idiosyncratic patterns.

Concerning the distress risk premium component embedded in BS spread quotes, we estimate it taking into consideration the evolution of the risk-neutral intensity under the $\mathbb{P}$ and $\mathbb{Q}$ measures. Differences between actual and risk neutral probabilities reflect a compensation demanded by risk averse investors to bear the risk of unpredictable variation in the arrival rate of a counterparty risk event due to changes in the borrowing and lending environment (changes in economic fundamentals, etc). In particular, the BS risk premium will be computed as the difference between the BS spreads under risk-neutral and actual measures, calculated in absolute terms.

$$BSRP = \Delta^{\mathbb{Q}}_{x,y} - \Delta^{\mathbb{P}}_{x,y} \tag{3.7}$$

Depicting the BS risk-premiums corresponding to different tenor BS in Figure 3.7, we observe that they increased substantially since August 2007 and particularly during the Lehman collapse and European debt crisis episodes in September 2008 and late 2009, respectively. These risk-premiums display a clear inverted term structure and they increase with tenor. Their magnitude at short maturities goes from 20 to 60 basis points depending on the tenor during distressed market episodes.

Figure 3.7: Time series of Basis Swap spreads risk premiums.



Weekly time series of the Euribor versus Eonia Basis Swap spreads risk-premiums. The distinct figures correspond to the different Euribor tenors basis spreads risk-premiums: 1-month (top,left), 3-month (top, right), 6-month (bottom, left) and 12-month (bottom, right). Data period comprises from December 19th 2007 to November 12th 2014.

To further examine the commonalities in the BS risk-premiums across tenors and maturities we perform separate principal component analyses (PCA). Firstly, we perform PCA for each maturity and secondly for each tenor. Respectively, Tables 3.7 and 3.8 display these results.

From the results reported in Table 3.7 we observe that commonalities are quite important since the first three principal components accounts for 81% of the variability in the level of the different maturities risk premium series across tenors. Analyzing the PCA loadings, we notice that heterogeneities across tenors correspond to 1-month and 12-month tenors. Medium term -3-months and 6-months- tenors may be interpreted as a benchmarks given that their behavior is closest to the first principal component for all maturities.

Table 3.7: Principal component analysis of BS Risk Premiums for different maturities

	Levels					Differences				
	1Y	3Y	5Y	7Y	10Y	1Y	3Y	5Y	7Y	10Y
	Panel A.- 1^{st} Principal component									
BS1M	0.46	0.47	0.47	0.47	0.47	0.48	0.47	0.47	0.47	0.47
BS3M	0.53	0.53	0.53	0.53	0.53	0.52	0.52	0.52	0.52	0.52
BS6M	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
BS12M	0.47	0.47	0.47	0.46	0.46	0.47	0.48	0.48	0.48	0.48
Variance (%)	80.50	81.09	81.17	81.05	80.61	83.09	85.98	86.23	86.18	85.94
	Panel B.- 2^{nd} Principal component									
BS1M	0.65	0.65	-0.64	-0.63	-0.63	-0.65	0.68	0.70	0.71	0.72
BS3M	0.31	0.30	-0.30	-0.31	-0.31	-0.24	0.19	0.16	0.15	0.13
BS6M	-0.33	-0.31	0.30	0.30	0.30	0.19	-0.19	-0.18	-0.18	-0.18
BS12M	-0.61	-0.63	0.64	0.65	0.65	0.70	-0.68	-0.67	-0.66	-0.66
Variance (%)	16.83	16.13	16.10	16.26	16.67	11.78	9.72	9.08	8.84	8.75
	Panel C.- 3^{rd} Principal component									
BS1M	0.49	0.50	0.51	0.51	0.52	0.59	-0.54	-0.52	-0.51	-0.50
BS3M	-0.45	-0.43	-0.42	-0.42	-0.42	-0.58	0.56	0.57	0.57	0.58
BS6M	-0.48	-0.50	-0.51	-0.51	-0.51	-0.35	0.38	0.38	0.37	0.37
BS12M	0.57	0.56	0.55	0.55	0.54	0.44	-0.49	-0.51	-0.52	-0.53
Variance (%)	2.35	2.60	2.56	2.53	2.55	3.81	3.84	4.29	4.58	4.88

Loading coefficients and explained variance for the BS Risk-Premiums corresponding to different maturities principal components. BS maturities are 1-, 3-, 5-, 7- and 10-years. For each of these maturities we analyze the principal components across tenors. BS spread tenors are 1-, 3-, 6- and 12-month against Eonia. Data sample is weekly and comprises from December 19th 2007 to November 12th 2014.

From the results reported in Table 3.8 we observe that, once we analyze each tenor separately, the first principal component accounts for practically the entire variation of the risk-premium variations across maturities, meaning that commonalities are more evident. This result is a direct consequence of the consideration of a single-factor model and its estimation separately for each tenor.

Concerning the model residuals, we follow existing literature Hu et al. (2013) considering that these deviations, or noise, contain valuable information, especially about liquidity issues (see, for example, Berenguer et al. (2013) and Rubia et al., 2014), given that, during times of distress, liquidity shortages can lead to price deviations from fundamental values. Interested in this issue, we implement the noise measure of Hu et al. (2013), the RMSE between the market observed BS

Table 3.8: Principal component analysis of BS Risk Premiums for different tenors

	Levels				Differences			
	BS1M	BS3M	BS6M	BS12M	BS1M	BS3M	BS6M	BS12M
	Panel A.- 1^{st} Principal component							
1y	0.44	0.44	0.44	0.45	0.43	0.43	0.44	0.44
3y	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
5y	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
7y	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
10y	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Variance (%)	98.54	98.91	99.58	99.64	97.57	97.16	98.03	98.46
	Panel B.- 2^{nd} Principal component							
1y	0.81	0.84	0.85	0.84	0.81	0.84	0.86	0.87
3y	0.14	0.07	0.03	0.06	0.14	0.09	0.03	0.00
5y	-0.17	-0.19	-0.19	-0.18	-0.16	-0.18	-0.20	-0.21
7y	-0.33	-0.30	-0.29	-0.29	-0.32	-0.31	-0.30	-0.29
10y	-0.43	-0.40	-0.39	-0.42	-0.44	-0.41	-0.36	-0.34
Variance (%)	1.45	1.09	0.41	0.35	2.37	2.81	1.95	1.51
	Panel C.- 3^{rd} Principal component							
1y	-0.38	-0.29	0.25	0.28	-0.39	-0.33	0.24	0.20
3y	0.71	0.64	-0.53	-0.51	0.72	0.70	-0.61	-0.54
5y	0.29	0.33	-0.40	-0.42	0.27	0.28	-0.34	-0.37
7y	-0.13	-0.05	-0.03	-0.05	-0.13	-0.11	0.04	-0.01
10y	-0.50	-0.63	0.71	0.70	-0.49	-0.56	0.68	0.73
Variance (%)	0.01	0.01	0.01	0.01	0.06	0.04	0.02	0.02

Loading coefficients and explained variance for the BS Risk-Premiums corresponding to different tenors principal components. BS spread tenors are 1-, 3-, 6- and 12-month against Eonia. For each of these tenors we analyze the principal components across maturities. BS maturities are 1-, 3-, 5-, 7- and 10-years. Data sample is weekly and comprises from December 19th 2007 to November 12th 2014.

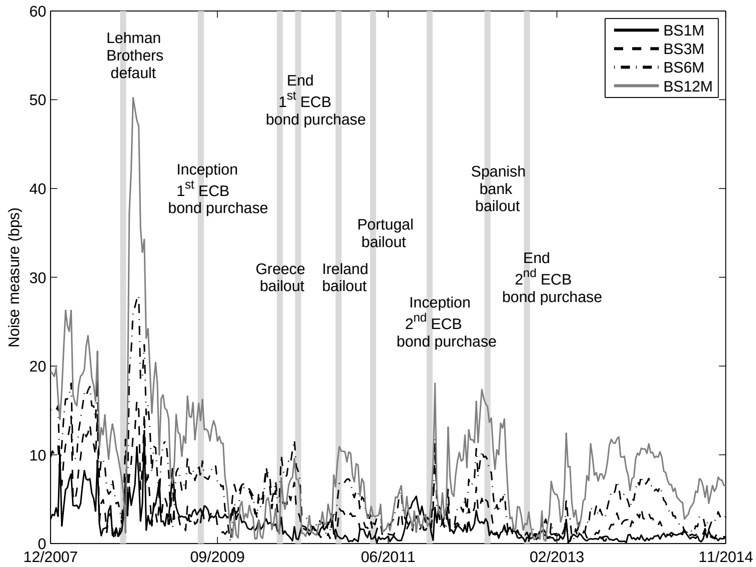
quotes and the Pan and Singleton (2008) model-implied spreads,

$$Noise_t = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[BS_t^{market} - BS_t^{model}\right]^2}, \tag{3.8}$$

where N is the number of maturities in the BS spread curve, BS_t^{market} is the BS quote, and BS_t^{model} is the model-implied BS spread corresponding to maturity i and time t.

Figure 3.8 displays the time series of the noise measure for different tenors. Noise is time-varying, exhibiting remarkable increases during periods of financial distress and liquidity/credit crises, such as the Lehman Brothers collapse and European sovereign debt crisis. Notably, changes in noise are relatively more intense for longer BS tenors. This is consistent with the idea that longer maturities are more sensitive to changes in monetary policy, financial distress and market conditions, such as the exit of arbitrage capital from the marketplace (see Hu et al. (2013) and Rubia et al., 2014).

Figure 3.8: Time series of Hu et al. (2013) noise measure



Time series of the Hu et al. (2013) noise measure applied to the residuals of the model for different BS tenors. Data period ranges from December 19th 2007 to November 12th 2014.

To examine the degree of comovement between the different tenor noise series, we perform a principal component analysis whose results are shown in Table 3.9.

From Table 3.9 we conclude that the degree of commonality between the different tenor noise measure series is quite important given that 80% and 66% of their variation in levels and differences, respectively, is accounted by the first principal component. Similarly to previous PCA results, we observe that, among the different tenor series, the 1-month and 12-month tenors display more

Table 3.9: Noise measure PCA results

	Levels			Differences		
	PC1	PC2	PC3	PC1	PC2	PC3
BS1M	0.45	0.74	-0.48	0.38	0.73	-0.55
BS3M	0.51	0.21	0.72	0.54	0.30	0.64
BS6M	0.54	-0.33	0.16	0.57	-0.32	0.19
BS12M	0.50	-0.54	-0.48	0.49	-0.53	-0.51
Variance (%)	79.86	12.96	6.41	66.26	24.67	7.36

PCA results of the Hu et al. (2013) measure (expressed in levels and in differences) corresponding to distinct tenors BS spreads model residuals. The table presents the factor loadings of the first three principal components and the percentage variance explained by each component. These figures are computed by performing a principal component analysis of the Hu et al. (2013) measure applied to the distinct Euribor tenor vs Eonia Basis Swap spread model residuals. The distinct Euribor tenors are 1, 3, 6 and 12 months. The historical series of the factors correspond to weekly data from December 19th 2007 to November 12th 2014.

heterogeneous behaviour.

3.6.2 OLS regressions

In the following, we regress weekly changes of the different BS spreads components -counterparty risk intensities, risk-premiums and noise measures- on the set of macroeconomic and financial variables presented in section 3.4 and following a similar specification to 3.1. Tables 3.10, 3.11, 3.12 and 3.13 report the resulting estimated parameters, White (1980) robust standard errors for individual significance, and adjusted R^2 coefficients.

The determinants of the lambda series are summarized in Table 3.10 where we observe that credit variables play a crucial role explaining fluctuations in counterparty risk intensities, particularly *German CDS*. *German CDS* can be interpreted as a state variable summarizing the level of risk that interbank market agents are willing to bear in their deposit operations across tenors. At longer tenors, additional variables are significant, in particular risk aversion -*ECB RA*- and financial sector credit risk -*FG Spread*-. The significance of the *ECB RA* variable reveals that the risk perceived by investors in the Euro Area when they lend to financial institutions compared to more secure investment alternatives is relevant to price counterparty risk at longer tenors. The significance of *FG Spread* signals that agents also regard financial sector specific credit conditions when they price interbank counterparty risk at longer tenors. Not surprisingly, the adjusted R^2 shows that the explanatory ability of the model is higher for the 6- and 12-month tenors.

We perform a similar exercise concerning weekly changes in the different tenors and maturities risk-premium series, showing the results of these regressions in Tables 3.11 and 3.12.

Table 3.10: OLS robust regressions of the counterparty risk intensities

	$\lambda_t^{\mathbb{Q}}$			
Variables	1M	3M	6M	12M
Constant	-0.0649	-0.1336	-0.0408	0.1299
	(0.2605)	(0.3681)	(0.3675)	(0.4320)
IR Level	-0.7841	-3.3590	-1.3412	4.0845
	(1.9916)	(3.0744)	(3.1584)	(4.7099)
IR Slope	-6.3632	-7.3587	-1.9573	10.5124
	(4.6521)	(6.8429)	(6.4329)	(7.2606)
ECB Liq	3.8549	9.7017*	7.2880	2.9939
	(3.6845)	(5.6111)	(5.0604)	(5.3739)
German CDS	0.1549**	0.3065***	0.3369***	0.3735**
	(0.0649)	(0.1113)	(0.1223)	(0.1586)
FG Spread	12.6988	17.9505	19.1318*	28.0543**
	(7.7876)	(10.9154)	(10.7562)	(12.2682)
ECB RA	0.1812	0.9774	1.5819***	3.3786***
	(0.4329)	(0.6085)	(0.5887)	(0.7129)
Adj-R^2	6.03	10.46	13.02	23.49
N	360	360	360	360

OLS robust regressions of the model counterparty risk intensities. The table reports the OLS results from regressing changes in the different tenor counterparty risk intensities against changes in the macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 values (in percentages). The sample period corresponds to weekly data from December 19th 2007 to November 12th 2014. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

Table 3.11: OLS robust regressions of BS1M and BS3M risk premia

	BS1M					BS3M				
Variables	1Y	3Y	5Y	7Y	10Y	1Y	3Y	5Y	7Y	10Y
Constant	0.0012	-0.0365	-0.0445	-0.0191	-0.0531	-0.0539	-0.0555	-0.0479	-0.0137	-0.0394
	(0.1486)	(0.1200)	(0.1155)	(0.1072)	(0.1317)	(0.1552)	(0.1310)	(0.1264)	(0.1168)	(0.1417)
IR Level	2.7841*	0.7981	-0.1589	0.6648	-1.7993	1.9199	-0.1873	-0.8067	0.3449	-1.9735
	(1.5016)	(1.1588)	(0.8538)	(1.0879)	(2.2646)	(1.3388)	(1.1248)	(1.0106)	(1.1675)	(2.2227)
IR Slope	-3.0399	-0.3424	-2.7559	-6.2527**	-4.1956*	-0.9334	-0.3745	-2.8701	-6.4265**	-3.9644
	(2.3954)	(1.8264)	(2.2152)	(2.6387)	(2.5082)	(2.0950)	(1.8918)	(2.5180)	(2.7446)	(2.5688)
ECB Liq	-1.8215	0.5766	1.5483	0.5179	1.8928	-2.2965	1.7366	2.7302	1.6886	2.8847*
	(2.5573)	(1.6283)	(1.4431)	(1.4201)	(1.4762)	(2.2952)	(1.6667)	(1.7165)	(1.6426)	(1.5582)
German CDS	0.0765**	0.0472	0.0736***	0.0615**	0.0383	0.1187***	0.0821**	0.0884***	0.0688**	0.0379
	(0.0363)	(0.0371)	(0.0283)	(0.0264)	(0.0543)	(0.0409)	(0.0406)	(0.0338)	(0.0310)	(0.0565)
FG Spread	10.6838**	7.3129**	6.2809**	6.0880**	7.4688***	8.7221*	6.5586*	5.7194*	5.5883*	6.7553**
	(4.7638)	(3.3400)	(3.1877)	(2.8431)	(2.4235)	(4.6848)	(3.4156)	(3.4186)	(3.1412)	(2.7607)
ECB RA	0.2742	0.2610	0.1113	-0.1992	-0.4952*	0.7742***	0.6075**	0.4742**	0.0975	-0.1870
	(0.2780)	(0.2894)	(0.1861)	(0.2453)	(0.2595)	(0.2519)	(0.2863)	(0.2172)	(0.2800)	(0.2828)
Adj-R^2	17.68	8.29	7.26	9.62	4.75	20.33	10.39	9.55	8.99	3.44
N	360	360	360	360	360	360	360	360	360	360

OLS robust regressions of the 1M and 3M tenor Basis Swap spreads risk premia. The table reports the OLS results from regressing changes in the risk premium of the 1-month Euribor tenor Basis Swap spreads and the 3-month Euribor tenor Basis Swap spreads at different maturities against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 values (in percentages). The sample period corresponds to weekly data from December 19th 2007 to November 12th 2014. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

Table 3.12: OLS robust regressions of BS6M and BS12M risk premia

	BS6M					BS12M				
Variables	1Y	3Y	5Y	7Y	10Y	1Y	3Y	5Y	7Y	10Y
Constant	0.0151	-0.0173	-0.0103	0.0233	-0.0072	0.1734	0.0527	0.0415	0.0728	0.0364
	(0.1528)	(0.1292)	(0.1264)	(0.1179)	(0.1431)	(0.2475)	(0.1404)	(0.1322)	(0.1223)	(0.1432)
IR Level	5.1744***	0.7662	-0.2443	0.7143	-1.7461	12.6880***	3.2918**	1.1027	1.7197	-1.0601
	(1.7792)	(1.0938)	(1.0255)	(1.1510)	(2.1351)	(3.6424)	(1.4564)	(1.2407)	(1.2031)	(1.8948)
IR Slope	7.8856***	2.7917	-0.9726	-5.0738*	-2.9812	28.5024***	9.5512***	3.2530	-2.0582	-0.6708
	(2.5347)	(1.9018)	(2.5309)	(2.7367)	(2.5914)	(4.1715)	(2.1221)	(2.5668)	(2.7737)	(2.6210)
ECB Liq	-6.2544***	0.6531	2.1308	1.3379	2.7801*	-14.5152***	-1.7834	0.9591	0.5255	2.3379*
	(2.2447)	(1.5880)	(1.6104)	(1.5528)	(1.4917)	(3.1146)	(1.6561)	(1.4806)	(1.4164)	(1.3204)
German CDS	0.0958**	0.0806**	0.0870**	0.0641*	0.0344	0.0331	0.0731*	0.0860**	0.0598	0.0305
	(0.0436)	(0.0399)	(0.0362)	(0.0331)	(0.0569)	(0.0890)	(0.0441)	(0.0426)	(0.0382)	(0.0567)
FG Spread	9.9017**	7.1049**	5.9116*	5.6528*	6.8131**	12.1484**	8.7487**	7.1847**	6.6957**	7.6020***
	(4.2674)	(3.3753)	(3.4276)	(3.1509)	(2.7860)	(5.0605)	(3.6104)	(3.4858)	(3.1813)	(2.8511)
ECB RA	1.4246***	0.8436***	0.6335***	0.2411	-0.0687	3.2143***	1.4951***	1.0121***	0.5500**	0.1542
	(0.2732)	(0.2750)	(0.2143)	(0.2772)	(0.2811)	(0.4884)	(0.2772)	(0.2133)	(0.2733)	(0.2685)
Adj-R^2	42.52	17.07	10.96	8.23	2.71	53.56	35.62	19.63	11.89	2.97
N	360	360	360	360	360	360	360	360	360	360

OLS robust regressions of the 6M and 12M tenor Basis Swap spreads risk premia. The table reports the OLS results from regressing changes in the risk premium of the 6-month Euribor tenor Basis Swap spreads and the 12-month Euribor tenor Basis Swap spreads at different maturities against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 values (in percentages). The sample period corresponds to weekly data from December 19th 2007 to November 12th 2014. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

First, from Table 3.11, we observe that the risk-premium component for short tenor BS spreads mainly relates to credit variables. In particular, both *German CDS* and *FG Spread* credit risk variables are significant. In addition, the three-months tenor BS spread also relates to risk aversion. This result reveals that agents' perceptions concerning uncertainties in credit conditions determine the risk-premiums of their short tenor interbank transactions.

Second, from Table 3.12 and regarding long tenor risk premium regressions, similar to shorter tenor risk premium regressions, we highlight the role of economic agents' perception of future uncertainty and financial sector credit conditions, as proxied, respectively, by the ECB Risk Aversion indicator and the spread between the AAA financial sector and German government bond yields. These variables are statistically significant at conventional confidence levels for almost all maturities. At short maturities, liquidity and the level of instability in economic conditions -as captured by the interest rates level and slope- have also a very significant impact on longer tenor risk premiums. These latter results reveal that at longer tenors and in the short-run investors ask for counterparty risk compensation due liquidity restrictions and uncertainty related to distressed economic conditions.

It is important to highlight the explanatory power of the model risk-premium regressions is clearly more important for short maturities, it increases with tenor and can reach up to 54%, meaning that the explanatory sources explain a very important fraction of the risk-premium series weekly variations for short maturities and longer tenors.

Finally, to complete our study, we develop an analysis to identify the explanatory variables of the noise measures underlying our model estimations. Table 3.13 summarizes our empirical results. The key role in explaining departures from the model is clearly played by liquidity. Liquidity is statistically significant at standard confidence levels for 6-months and 12-months tenors. Consistently, the adjusted R^2 increases with tenor, reaching its highest value for the 12-month case. ECB liquidity coefficients are negative, indicating that increments in price deviations are related to decreases in market liquidity. This result is remarkable, and it is fully consistent with previous literature regarding the information content embedded in this model's residuals (see Hu et al. (2013) and Rubia et al., 2014). Noticeably, 12-months tenor regressions display other significant explanatory variables as well capturing the level of distress in economic conditions (i.e. summarized byt interest rates slope) and agents' risk aversion.

3.7 Conclusions

Interbank market quotes have experienced very important changes in the last years. Market makers have attributed new risks to different tenor interbank lending and borrowing transactions that have been reflected in the quotes of interest rate derivatives linked to interbank deposit rates.

This article studies the counterparty risk information embedded in different tenor BS spread

Table 3.13: OLS robust regressions of the Hu et al. (2013) noise measure

	Noise			
Variables	1M	3M	6M	12M
Constant	0.0089	-0.0079	0.0130	0.0380
	(0.0701)	(0.0867)	(0.1012)	(0.1379)
IR Level	0.7050	0.7710	2.3269**	3.1853**
	(1.0072)	(0.8439)	(1.0237)	(1.3526)
IR Slope	-0.5325	-0.4262	2.6175	5.6182**
	(1.3621)	(1.7024)	(2.2352)	(2.7164)
ECB Liq	-0.6633	-1.3087	-3.4442**	-5.9511***
	(0.9483)	(1.1756)	(1.5684)	(1.9070)
German CDS	0.0080	0.0313	0.0493	0.0679
	(0.0255)	(0.0293)	(0.0318)	(0.0464)
FG Spread	0.3859	-1.0340	-3.5894	-4.3931
	(1.5525)	(2.6034)	(2.5576)	(3.3656)
ECB RA	0.0604	-0.0198	0.2923*	0.6478***
	(0.1442)	(0.1257)	(0.1768)	(0.2366)
Adj-R^2	-0.10	0.65	11.77	19.52
N	360	360	360	360

OLS robust regressions of the model residuals Hu et al. (2013) measure. The table reports the OLS results from regressing changes in the distinct tenors BS noise measures against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 values (in percentages). The sample period corresponds to weekly data from December 19th 2007 to November 12th 2014. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

curves distinguishing this information from risk-premiums, i.e. compensations due to changes in counterparty risk conditions (changes in economic fundamentals, etc.). The multi curve framework is modeled considering the underlying variables of different tenor deposits vs Eonia spreads which correspond to different tenor counterparty risk intensities. Methodologically, we follow a similar approach to Pan and Singleton (2008). This allows us to analyze the importance of implicit counterparty risk and study its commonalities across tenors. The results confirm that the level of risk in the BS spread series is well captured by the different tenor counterparty risk intensities, whose degree of commonality is relevant and magnitude has significantly increased during the crisis -their values range from 100 to 250 bps depending on the tenor in turbulent times- .

Risk premiums commonalities are very important and their magnitude is particularly remarkable in the short run ranging from 20 to 60 bps depending on the tenor during financial distress episodes.

The empirical results presented in the article also show that counterparty risk is clearly determined by credit variables and in particular German CDS, capturing the state of credit conditions of the more secure investments in the Euro Area. Risk premium determinants reveal that the uncertainty that agents perceive on counterparty risk conditions are due to financial sector credit risk and liquidity restrictions. Risk compensation also relates to agents' risk aversion.

Therefore, despite counterparty risk and risk variables represent first-order effect variables explaining curves multiplicity, liquidity and risk aversion are not negligible second order explanatory sources and their impact is on interbank spreads risk premiums.

Finally, the relationship between model residuals -interpreted as price deviations from fundamental values- and liquidity is also noticeable and fully consistent with Chapter 2 results. This result suggests that the impact of liquidity may be of different nature compared to credit shocks [6].

[6] This issue is further explored in Chapter 4.

Chapter 4

Interbank spreads permanent and transitory components and their relationship to credit and liquidity risks

In this chapter we estimate and analyze the transitory and permanent components of the Euro interbank market Basis Swap spreads variations during the crisis period. This analysis provides a deeper understanding of the nature and relative importance of financial shocks impacting on the dynamics of BS spreads. This analysis is of particular interest given that these quotes reflect a clear change of paradigm since the start of the crisis. We study their information content, in particular their relationship to liquidity and credit risk proxy variables, as a way of understanding the role of credit and liquidity shocks. Our results show that liquidity shocks are permanent. Their impact lays on the short run for short tenors but on the entire term structure for long tenors. Credit shocks are permanent at short tenors but they turn transitory at longer tenors, meaning that their duration at long tenors is shorter. Its impact is on the entire term structure. The permanent component is relatively more important than the transitory one at short tenors and the opposite happens at long tenors, suggesting that the explanatory power of credit shocks is more important compared to liquidity shocks. These findings bring new and very interesting insights concerning the impact of credit and liquidity shocks to the interbank market.

4.1 Introduction

An increasing interest in studying interbank market spreads has emerged since the beginning of the crisis, as an explosion in these spreads has been observed in market quotes. This explosion has been particularly evident in financial distressed periods, for instance during the Lehman Brothers default and the Euro-area sovereign debt crisis episodes, despite these spreads levels indicate a clear change of paradigm since August 2007.

Interbank market spreads (such as Euribor 6M deposit versus Eonia rates) reflect differing costs of lending at different periodicity. These differential lending costs may be attributable to higher liquidity and credit risks being involved in lending at longer frequencies. Therefore, the burst in interbank market spread quotes may be a reflection of the change of perception by market makers in recent years concerning these risks. Recent literature has recognized and found evidence on the role of these risks in determining spreads, see for instance Beirne (2012), Michaud and Upper (2008), Schwartz (2010), Eisenschmidt and Tapking (2009) or McAndrews et al. (2008).

As a result of these quotes changes and in order to preserve consistency between the different interbank market instruments valuations, a new Multiple Curve (MC) valuation framework has been adopted by market practitioners [1]. This framework considers various curves differentiated by tenor (1-month, 3-month, 6-month, 12-month or overnight) which are constructed using separate sets of interbank market instruments linked to different tenor rates (Euribor 1-month, 3-month, 6-month, 12-month or Eonia). In recent years an increasing literature devoted to studying the MC curve phenomena has also emerged, see for example the recent papers by Mercurio (2009) and Henrard (2014) and Filipovic and Trolle (2013).

While the previously mentioned studies have recognized that the drivers of interbank market spreads and Multiple Curve differentials are both credit and liquidity risks, little has been said about the nature and relative importance of these risks. Providing a better understanding about the impact of these risks is relevant to explain the causes of the spreads evolution in recent times, the emergence of the MC setting and the functioning of the interbank and money markets. These are questions of interest to regulators, policy makers, market makers and practitioners alike. In this paper we aim at shedding light on these issues.

In Chapter 2 we apply Nelson-Siegel model to interbank spreads and found that model residuals are very much related to liquidity risks. This result confirms that during distressed times liquidity shortages generate market prices deviations from fundamental values. These price deviations are expected to be transitory in nature and suggests that accounting for the nature of financial shocks may be very relevant to have a clearer characterization of the different risks influence.

Therefore, motivated by our previous research results, in this chapter we separate interbank spread shocks into transitory and permanent components.

[1] The pre-crisis unique curve setting does not work given that implicit forward rates computed from market instruments linked to distinct tenor rates may differ. This means that it is not possible to replicate all interbank market quotes using a single-curve.

The isolation of the interbank spreads transitory and permanent factors is achieved by modelling them as two latent variables and solving the associated state-space equation problem. We follow a state-space equation specification that is similar to Adolfatto et al. (2008). This formulation has been previously applied in several papers interested in studying monetary policy shocks unobservable components, see for instance Lafuente et al. (2014) and Lafuente et al. (2011). As estimation method we use the particle filter approach employed by Fernandez-Villaverde and Rubio-Ramirez (2007), which is a sequential Montecarlo filter method, useful to optimally estimate the state-space equation. This approach is an alternative solution to the Kalman-Filter, which cannot be optimally applied to the Adolfatto et al. (2008) formulation. To our knowledge, this paper is the first time that this methodology is applied in the analysis of interbank spreads.

Once these components are estimated, we study their information content, in particular their relationship to a set of economic variables. The objective of the paper is studying the explanatory power of liquidity and credit risk proxy variables, separating their impact from the effect of other potential explanatory variables. It is worth to mention that our approach has the advantage of isolating true liquidity and credit risks influences on market spreads. In the literature, see for instance Buhler and Trapp (2009*a*) and Buhler and Trapp (2009*b*) it is well recognized the problem of identification of the credit and liquidity factors embedded in spreads due to the potential correlation effects between these variables. The methodology applied in this paper avoids these potential correlation issues and allows to provide clearer conclusions about the separate impact of these risks.

In our analysis we work with Euro interbank market BS spreads quotes. Basis Swaps are convenient instruments for our purposes as they capture the differences between interbank curves linked to different tenor rates [2]. Our focus is, in particular, on the spreads between the different tenor rates curves with respect to the overnight rate curve and we use market quotes to artificially construct them if not available in the market. The spreads so constructed contain a very rich set of information as they reflect the market expected costs of lending at different tenor rates compared to lending at the overnight rate. Since the overnight rate is considered a riskless rate proxy for the interbank market, the differential costs embedded in Euribor versus Eonia BS spreads are likely to reflect other risks apart from market risk factors. Using these spreads in our analysis permit us studying these risks and compare the different role of their permanent and transitory components across maturities and tenors.

The main contribution of this article is twofold. First we show that it is possible to isolate the BS information data into permanent and transitory factors and we study the commonalities in

[2] A Basis Swap (BS) is an interest rate derivative that involves the exchange of two floating rates at different tenors. BSs in the interbank market are over-the-counter (OTC) instruments, and they are mainly used by counterparties to swap interest rate payments linked to short-term reference rates of different tenor for a given time period – the maturity of the contract. BS spreads reflect the difference between lending at compound shorter tenor rates compared to longer tenor rates for a given time period. Therefore, the term structure of BS captures the spread between the tenor IRS curves, and the differential costs of funding at distinct tenors.

these factors across maturities and tenors. Secondly, we analyze the factors information content, understanding their relationship to interbank market credit and liquidity shocks.

Our findings are that, in the interbank market, liquidity shocks display a permanent behaviour while credit risk variables may be understood as permanent factors at short-medium tenors but as transitory factors at long tenors. These results can be interpreted as if liquidity shocks were more infrequent and had a higher duration while the opposite happens for credit shocks at longer tenors. The effect of liquidity shocks depending on maturity changes as the BS tenor increases, their impact is only at short maturities in the case of short to medium tenors but on the entire term structure at long tenors while credit shocks always impact on the entire term structure. The explanatory power of permanent factors is more important at shorter tenors but transitory factors are prevalent at longer tenors, meaning that credit shocks are relatively more important compared to liquidity shocks. For certain maturities and tenors other variables capturing the level of instability in the economy and the agents risk aversion are also significant.

The current paper relates to previous literature interested in the nature of the shocks in financial markets, in particular the nature of liquidity shocks. Our motivation relates to Bao et al. (2011) and references therein, although our focus is on interbank market spreads instead of corporate yield spreads. Our methodology also differs from theirs.

This paper also relates to literature isolating and studying the differential role of transitory and permanent components on money market variables. Our approach is close to Adolfatto et al. (2008), Fernandez-Villaverde and Rubio-Ramirez (2007) and Lafuente et al. (2014) among others. This methodology has been proved successful in the context of studying monetary policy shocks but instead we apply it to another setting which are interbank market shocks. The best of our knowledge this paper is the first attempt to apply this methodology to financial spread series.

The rest of the chapter is organized as follows. Section 4.2 presents the model considered in the estimation of the BS spreads components. Section 4.3 introduces the data. In Section 4.4 we describe the estimation results and in section 4.5 we study their determinants. Section 4.6 concludes.

4.2 The model and the Particle-Filter estimation methodology

We are interested in decomposing Basis Swap (BS) spreads changes into two latent, transitory and permanent, components. In this decomposition, we closely follow the methodology and specification of Adolfatto et al. (2008).

The observation equation is $b_t = z_t + u_t$ where b_t is a Basis Swap spread series corresponding to a particular tenor and maturity, z_t is the permanent component and u_t the transitory component of this series. The permanent factor is modeled so that its changes will exhibit significant duration. The time evolution of this shock can be represented as follows,

$$z_{t+1} = \begin{cases} z_t, & \text{with probability} \quad p \\ g_{t+1}, & \text{with probability} \quad 1-p \end{cases} \tag{4.1}$$

where $g_{t+1} \overset{iid}{\sim} N(0, \sigma_g^2)$.

The persistence of this factor is achieved since, with a high probability, the value of this component does not change over time. Changes in its value eventually occur, but we do not restrict the moment nor the level of those changes.

The transitory factors are expected not to be very persistent and they are modelled according to an AR(1) autoregressive process with a positive and small coefficient,

$$u_{t+1} = \phi u_t + e_{t+1}, \quad \text{with} \quad 0 < \phi << 1 \tag{4.2}$$

where $e_{t+1} \overset{iid}{\sim} N(0, \sigma_e^2)$.

The previous expressions can be compacted into a state-space equation of the form,

$$\begin{bmatrix} z_{t+1} \\ u_{t+1} \end{bmatrix} = \begin{bmatrix} p & 0 \\ 0 & \phi \end{bmatrix} \begin{bmatrix} z_t \\ u_t \end{bmatrix} + \begin{bmatrix} N_{t+1} \\ e_{t+1} \end{bmatrix} \tag{4.3}$$

where

$$N_{t+1} = \begin{cases} (1-p)z_t, & \text{with probability} \quad p \\ g_{t+1} - pz_t, & \text{with probability} \quad 1-p \end{cases} \tag{4.4}$$

The former equations are expressed as a function of the model parameters which are the probability of no regime change (p), the estimated volatility of the permanent and transitory components (namely, σ_g and σ_e, respectively) and the AR(1) parameter associated with the time evolution of the transitory shock (ϕ).

Our objective is not only estimating the parameters $\{p, \phi, \sigma_e, \sigma_g\}$ but also identifying the unobservable components $\hat{z}_{t|t-1}$ and $\hat{u}_{t|t-1}$ from the observable time series of the BS spreads. This could be achieved applying a Kalman Filter. Nevertheless, as pointed out by Adolfatto et al. (2008), the use of the Kalman Filter is not fully optimal because the vector of perturbations in the state equation is a mixture of a Bernoulli and a Gaussian noise and therefore it does not follow a multivariate normal distribution. To overcome the non-optimality of the Kalman-Filter, these authors follow Fernandez-Villaverde and Rubio-Ramirez (2007) approach and use the particle filter to proceed with the maximum likelihood estimation.

Here, we also apply the particle filter which is a sequential Montecarlo filter. In its implementation we follow three main steps. First, we compute $\hat{u}_{t|t-1}$ taking as given initial values for the parameters $\{p, \phi, \sigma_e, \sigma_g\}$. The second step consists of computing the likelihood function corresponding to the observable data series b_t. Lastly, we maximize the likelihood function with respect to the model parameters. Here we provide a more detailed explanation of these steps.

1. In the first step we compute $\hat{z}_{t|t-1}$ and then evaluate the density function of $\hat{u}_{t|t-1}$ given $\{p, \phi, \sigma_e, \sigma_g\}$ and assuming, without loss of generality, that $z_0 = 0$.

   (a) For the first period, we draw a random sample of size $I = 1000$ from a unifrom distribution in (0,1) and from a normal distribution with zero mean and σ_g^2 variance. We call each observation of these two initial samples as $U_1^i \sim U(0,1)$ and $x_1^i \sim N(0, \sigma_g^2)$, respectively, where $i = 1, 2, ..., I$. We use these two values to generate a new sample that we denote $N_{1|0}^i$ as follows,

$$N_{1|0}^i = \begin{cases} (1-p)z_0 = 0 & \text{if} \quad U_1^i \leq p \\ x_1^i - pz_0 = x_1^i & \text{if} \quad U_1^i > p \end{cases} \tag{4.5}$$

   where $(1-p)$ is the probability of regime change and we have assumed that $z_0 = 0$. We use the $N_{1|0}^i$ values in order to generate I samples of $z_{1|0}^i$ as follows,

$$z_{1|0}^i = pz_0 + N_{1|0}^i = N_{1|0}^i \tag{4.6}$$

   (b) Next, we use the first period observation value of the Basis Swap spread b_1 and the previously estimated values of $z_{1|0}^i$ in order to generate a random sample of the transitory component of the series $u_{1|0}^i$,

$$u_{1|0}^i = b_1 - z_{1|0}^i \tag{4.7}$$

   for $i = 1, 2, ..., I$.

   (c) We evaluate the relative weight of each observation $u_{1|0}^i$:

$$q_{u_{1|0}^i} = \frac{p(u_{1|0}^i)}{\sum_{j=1}^{I} p(u_{1|0}^j)} \tag{4.8}$$

   where the probability $p(u_{1|0}^i)$ corresponds to the marginal distribution of the first observation of an AR(1) process, namely a Gaussian distribution with zero mean and variance $\frac{\sigma_e^2}{1-\phi}$: $u_{1|0}^i \sim N\left(0, \frac{\sigma_e^2}{1-\phi}\right)$.

(d) We update the initial sample $z^i_{1|0}$ by performing a weighted resampling with replacement in accordance with the above mentioned weights. We name these resampled values as z^i_1.

(e) We repeat the process described above for each time period taking into account that, from the second period onwards, the relative weight of each observation of the transitory component will be computed according to the conditional distribution of an AR(1) process. This means that, for a generic t period, the conditional distribution of $u^i_{t|t-1}$ on $u^i_{t-1|t-2}$ would be,

$$u^i_{t|t-1}|u^i_{t-1|t-2} \sim N\left(\phi u^i_{t-1|t-2}, \sigma_e^2\right) \tag{4.9}$$

2. The second step consists of computing the likelihood function of the vector of Basis Swap spreads values $\mathbf{b} \equiv (b_1, b_2, \ldots, b_T)'$ where T denotes its sample size. Using the Law of Large Numbers, we compute the conditional probabilities of $b_t|b_{t-1}$,

$$p(b_t|b_{t-1}) = \frac{1}{I}\sum_{i=1}^{I} p(u^i_{t|t-1}) \tag{4.10}$$

where $i = 1,2,...,I$ and $p(u^i_{t|t-1})$ is calculated according to equation 4.9.

Once these conditional probabilities are computed, we can evaluate the likelihood function as,

$$p(b_1, b_2, \ldots, b_T) = \prod_{t=1}^{T}\left[\frac{1}{I}\sum_{i=1}^{I} p(u^i_{t|t-1})\right] \tag{4.11}$$

3. In the third and last step the likelihood function is maximized with respect to $\{p, \phi, \sigma_e, \sigma_g\}$, namely,

$$\underset{\{p,\phi,\sigma_g,\sigma_e\}}{\text{Max}} \; p(b_1, b_2, \ldots, b_T) \tag{4.12}$$

For more detailed explanations concerning this filter see for instance Durbin and Koopman (2012), chapter 12.

4.3 The data

The dataset comprises BS spread market quotes from December 19th, 2007 to November 12th, 2014. The data frequency is weekly, and they have been taken from Bloomberg. We are interested in the BS spreads of different Euribor tenors with respect to Eonia, which is the underlying rate of Overnight Indexed Swaps (OIS). We focus on the BS contracts whose payments are associated to Euro interbank deposit rates for tenors 1, 3, 6 and 12-months (from now onwards we denote these BS spreads as BS1M, BS3M, BS6M and BS12M, respectively). In addition, each BS contract correspond to 1, 3, 5 and 10 years maturities. Given that market does not provide these BS spreads quotes for all tenors, we build synthetically those BS spreads by non-arbitrage when they are not available. This procedure requires the use of BS pricing formulas stated in Section B. Information and details about the BS contract are reported in Table 4.1, which summarizes the available BS market quotes (Panel I), and the synthetically obtained BS spreads (Panel II). As an example of our procedure see, for instance, the series of Euribor 6M vs Eonia spreads, which is not directly available in the market. We add Euribor 3M vs Eonia to Euribor 6M vs Euribor 3M BS quotes, previously transforming the latter from type 1 to type 2 swap contract. As a robustness check, we confirm that this methodology matches the quotes for existing data.

Table 4.1: Contract details concerning Basis Swap Spread market quotes.

Interest rates	Tenors	Type of contract	Payment Frequency	Calculation basis
Panel I.- Contract details concerning Basis Swap spread market quotes				
Euribor vs. Eonia	3M vs overnight	2 swaps	Annually	Act/360
Euribor vs. Eonia	3M vs 1M	2 swaps	Annually	30/360
Euribor vs. Eonia	6M vs 3M	1 swap	Quarterly	Act/360
Euribor vs. Eonia	6M vs 1M	2 swaps	Annually	30/360
Euribor vs. Eonia	12M vs 3M	2 swaps	Annually	30/360
Euribor vs. Eonia	12M vs 6M	2 swaps	Annually	30/360
Panel II.- Derivation details concerning Euribor vs Eonia Basis Swap spreads				
Euribor vs. Eonia	1M vs overnight	(1) Euribor 3M vs Eonia - Euribor 3M vs Euribor 1M		
		(2) Euribor 6M vs Eonia - Euribor 6M vs Euribor 1M		
Euribor vs. Eonia	3M vs overnight	Direct Market Quote		
Euribor vs. Eonia	6M vs overnight	Euribor 3M vs Eonia + Euribor 6M vs Euribor 3M		
Euribor vs. Eonia	12M vs overnight	(1) Euribor 3M vs Eonia + Euribor 12M vs Euribor 3M		
		(2) Euribor 6M vs Eonia + Euribor 12M vs Euribor 6M		

Figure 4.1 shows the time evolution of the BS time series used. Some interesting aspects arise from this Figure. First, BS premiums tend to increase in the presence of risk uncertainty. For example, Figure 4.1 shows that Lehman Brothers bankruptcy in September 2008 resulted in a sharp rise of BS spreads that lasted for several months. Analogously, BS spreads significantly rose during the European sovereign debt crisis as, for instance, during the Greek government bailout in May 2010, or the financial aid asked for Ireland in November 2010, or Spain in June 2012. Second, the term structure of BS spreads is consistently downward-sloping, specially at longer maturities (3-, 6- and 12-months). This effect is observable at 1-month BS spreads during distress times. Finally, BS spreads seem to react to the special measures undertook by the ECB during the European sovereign

crisis.[3] The implementation of these actions appear to be correlated to a gradual decrease of BS spreads. In sum, BS spreads seem to capture the liquidity shortage within the financial sector, and the perception of default risk associated to lending in the interbank market, as pointed out by Filipovic and Trolle (2013).

Table 4.2 provides some descriptive statistics. We observe that BS curves are, on average, downward-sloping and convex. Moreover, the volatility of BS spreads tends to be higher for short term maturities. A cross-sectional inspection to the results reveals that i) long-tenors BS spreads are higher than short-tenors, and ii) long-tenors are more volatile than the shorter ones. In addition, the median is in general lower than the mean, signaling that the distribution is skewed to the right, particularly for shorter maturities. Finally, autocorrelation coefficients reveal that shorter maturities exhibit more persistence, and this persistence is declining with the time-horizon in the long-run.

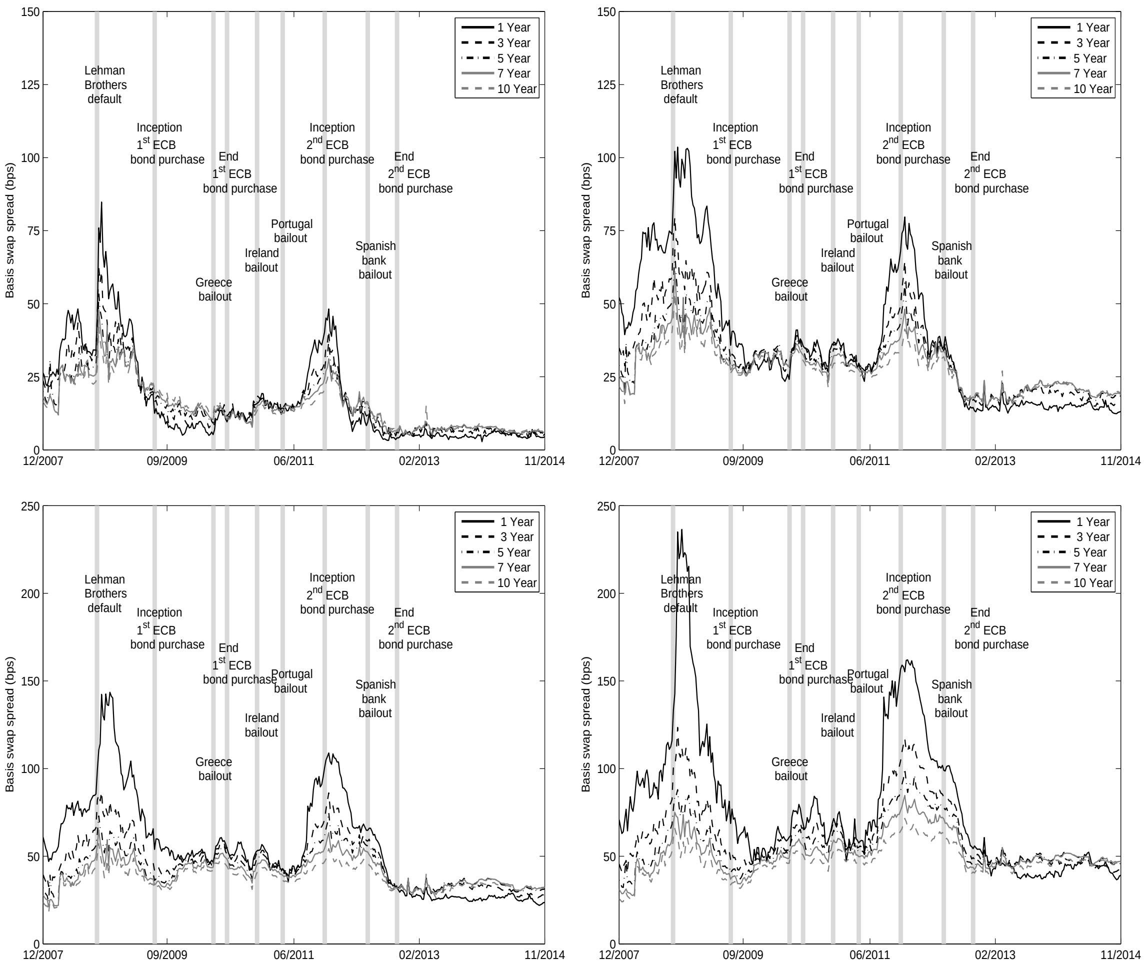
4.3.1 Commonality analysis

As an initial exercise to deal with the nature of comovements in the BS time series, we perform a principal components (PC) analysis on the entire sample of (standardized) Euribor tenor BS spreads. The results show a strong commonality in the data, where a first PC accounts for a 78.22% of the total BS explained variance. This percentage increases to 94.69% and 97.72% when incorporating the information content in the second and third component, respectively. An inspection to the loading coefficients (not reported here, but available upon request) shows that the first PC can be understood as an equally-weighted portfolio of the BS series. The second PC loadings clearly disentangle the short-term tenors (1M and 3M) from long term ones (6M to 1-year); while the first component represents a level factor, the second component reflects a slope factor. Finally, the third PC could be interpreted as a curvature factor embedded in the cross-section of BS spreads. A further inspection of the first PC loading coefficients reveals that the medium-term tenors are representative of the joint behaviour of the level factor, while the 1-month and 12-month tenors, particularly the latter, may display slight heterogeneities with respect to the medium tenor spreads.

To further ensure about the interpretation of the term structure components, we run a PC analysis for each tenor; then, we execute four different PC analysis. The results are consistent across tenors, and they are consistent with the standard interest rate term structure assessment. The first PC clearly captures most of the variation in the BS spreads; for example, the lowest (highest) explained variance for this first PC is 90.15% (96.40%). Moreover, the loading coefficients of first PCs are

[3] In order to enable banks to access funding just after the Lehman's collapse, the ECB conducted massive injections of liquidity in October 8th 2008, and special term refinancing operations in September 29th 2008. Additionally, the ECB also intervened in the debt markets for preventing government borrowing costs to rise to prohibitively high levels, and ensuring depth and liquidity in certain dysfunctional market segments. The first goal was achieved by the Securities Market Program introduced in May 2010 and its successor, the Outright Monetary Transactions, launched in August 2012. The second objective was pursued by the purchase of Euro-denominated covered bonds under two programmes, introduced in June 30th 2010 and October 31st 2012. Through the Long Term Refinancing Operations conducted in fall 2011 the ECB also intended to enable banks to access to long-term funding.

Figure 4.1: Euribor versus Eonia Basis Swap spreads at different maturities.



Weekly time series of the Euribor versus Eonia Basis Swap spreads. The distinct figures correspond to the different Euribor tenors basis spreads: 1-month (top,left), 3-month (top, right), 6-month (bottom, left) and 12-month (bottom, right). Data period comprises from December 19th, 2007, to November 12th, 2014.

Table 4.2: Basis Swap spreads summary statistics

		Mean	Std.	Median	Min	Max	Skew.	Kurtosis	ρ_N 4	12	24	N
BS1M	1y	17.02	15.62	10.90	2.80	84.80	1.47	4.67	0.91	0.73	0.51	361
	3y	16.15	11.49	12.80	3.50	62.35	1.27	4.20	0.91	0.79	0.57	361
	5y	15.50	9.21	13.90	4.60	53.85	1.05	3.67	0.90	0.80	0.60	361
	7y	15.12	8.24	13.80	5.20	47.80	0.96	3.50	0.90	0.81	0.63	361
	10y	14.85	7.48	13.90	5.42	41.95	0.86	3.11	0.89	0.81	0.66	361
BS3M	1y	37.29	23.04	31.20	12.35	103.60	0.97	3.04	0.95	0.81	0.57	361
	3y	32.59	13.77	31.45	14.20	79.65	0.74	2.94	0.93	0.80	0.55	361
	5y	30.40	10.06	30.00	14.80	68.45	0.59	2.91	0.89	0.75	0.49	361
	7y	28.85	8.37	28.80	14.90	60.90	0.50	2.89	0.88	0.71	0.47	361
	10y	27.20	7.00	27.20	14.83	53.65	0.44	2.82	0.85	0.69	0.48	361
BS6M	1y	55.21	27.49	51.40	22.00	143.50	0.97	3.57	0.94	0.76	0.49	361
	3y	47.01	14.45	45.85	26.30	86.75	0.57	2.54	0.92	0.74	0.42	361
	5y	43.27	10.28	41.80	23.50	74.95	0.46	2.42	0.88	0.66	0.30	361
	7y	40.51	8.31	39.50	21.10	64.90	0.25	2.46	0.85	0.59	0.24	361
	10y	37.32	6.61	36.50	17.60	57.25	0.02	2.73	0.80	0.51	0.21	361
BS12M	1y	78.71	40.76	66.80	36.60	236.45	1.54	5.39	0.92	0.67	0.34	361
	3y	63.07	19.65	56.05	40.80	123.45	1.13	3.23	0.92	0.71	0.32	361
	5y	56.72	13.93	51.80	32.20	99.85	0.98	3.14	0.90	0.67	0.26	361
	7y	52.34	11.24	49.90	27.60	84.65	0.62	3.18	0.88	0.63	0.24	361
	10y	47.50	8.74	46.40	24.00	71.60	0.15	3.48	0.84	0.57	0.21	361

Descriptive statistics for different Euribor tenor versus Eonia Basis Swap spreads term structures. The table presents the mean, standard deviation, median, minimum, maximum, skewness, kurtosis and 4, 12 and 24 lags autocorrelations of the term structures selected maturities are 1, 3, 5, 7 and 10 years. The distinct Euribor tenors are 1, 3, 6 and 12 months. The historical series are expressed in basis points and correspond to weekly data from December 19th 2007 to November 12th 2014.

approximately equal, reinforcing the view that first PCs behave as level factors. We also observe that medium term maturities (from 5- to 7- year) present slightly higher loading coefficients. This may indicate that medium terms are acting as level benchmarks. The second PC could be interpreted as a slope factor: the loading coefficients are statistically significant for shorter and very long term maturities, differing in their sign. The explained variance is 5.59%, on average. Lastly, third PCs clearly represent curvature factors, and their explained variance is residual – on average, 0.33%.

From the previous results we conclude that the different BS spread curves have strong commonalities and that their term structure follow similar level, slope and curvature patterns. Heterogeneities in the joint BS behaviour may arise, across maturities, in the short and very long run and, across tenors, at shorter and longer tenors.

4.4 Empirical results

4.4.1 Parameter estimates

The maximization of the likelihood function presented in Section 4.2 yields the point estimates and the standard deviations collected in Table 4.3 and the time series of transitory and permanent factors depicted in Figures 4.2 and 4.3. These estimations have been performed separately for each tenor BS and maturity.

Analyzing the estimation results, we observe that the probability of regime change increases with tenor for short-medium run maturities. In particular, the 1 to 5 years maturity average is 10%, 28%, 37% and 54%, respectively, for 1-month, 3-month, 6-month and 12-month tenors, meaning that the mean duration of permanent shocks increases with tenor. In the long-run, the probability has similar value across tenors and it is around 10%. The shocks volatilities in the two regimes differ significantly. The volatility of the transitory factor is clearly lower than the one corresponding to permanent shocks. Comparing these volatilities across tenors and maturities, we may conclude that, concerning the transitory component, volatilities slightly decrease with maturity and are also slightly higher as tenors increase. Regarding the permanent component, the volatility tends to decrease with maturity, it increases with tenor for short maturities and the opposite happens in the medium to long run. Finally, the estimated AR(1) coefficient is positive, in general it is statistically significant and clearly lower than one, consistently with the assumptions made.

4.4.2 Principal component analysis of transitory and permanent factors

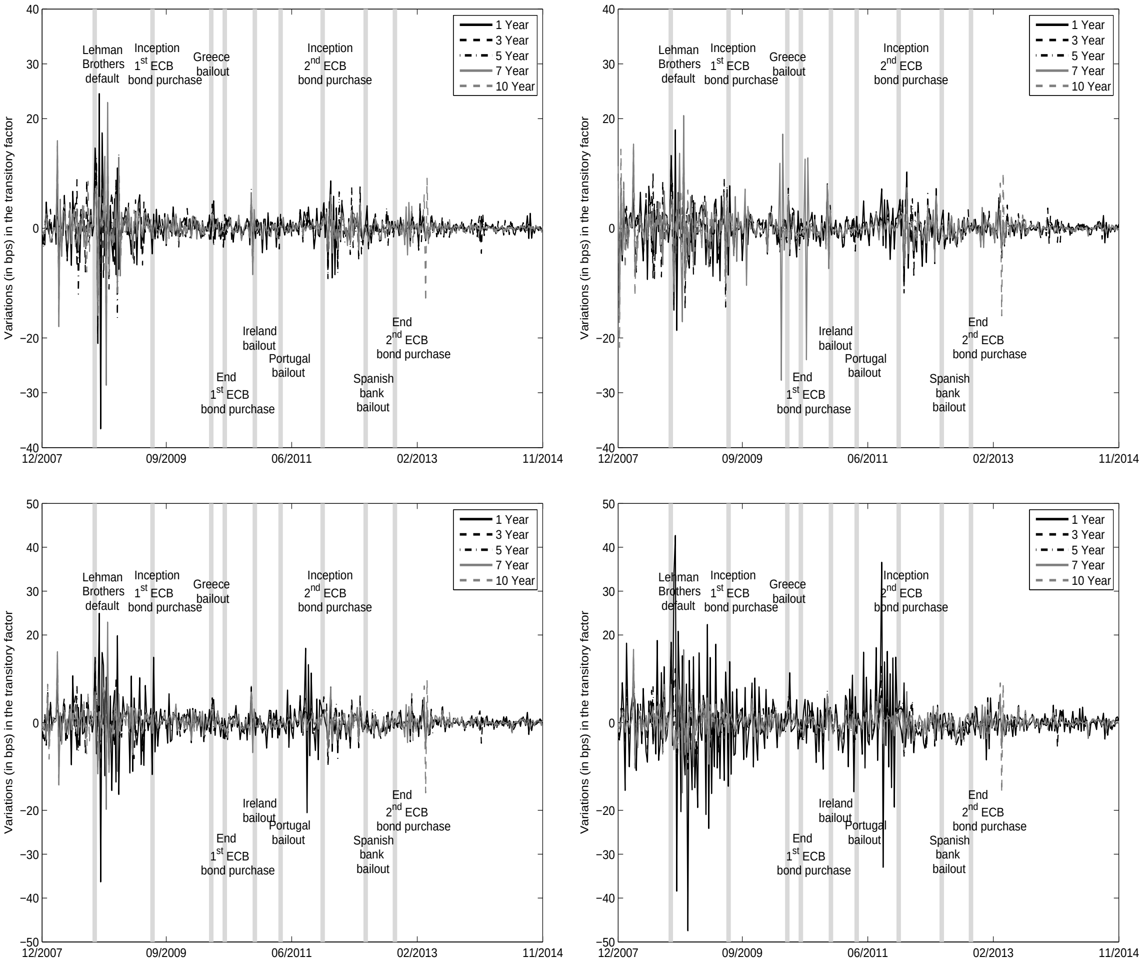
Previously reported empirical findings in Section 4.3.1 showed the existence of strong commonalities in BS spreads across maturities and tenors. It is interesting to study whether these conclusions change when we focus on the Basis Swaps permanent and transitory components.

Table 4.3: Particle-Filter estimation results

		p	σ_g	σ_e	ϕ
BS1M	1y	0.8935	0.1025	0.0193	0.2042
		(0.0549)	(0.0392)	(0.0020)	(0.0854)
	3y	0.9033	0.0592	0.0185	0.0740
		(0.0859)	(0.0893)	(0.0026)	(0.0963)
	5y	0.8928	0.0743	0.0138	0.2322
		(0.0292)	(0.0126)	(0.0011)	(0.0989)
	7y	0.9087	0.0923	0.0133	0.2647
		(0.0208)	(0.0282)	(0.0007)	(0.0753)
	10y	0.9125	0.0768	0.0122	0.2351
		(0.0209)	(0.0132)	(0.0008)	(0.1008)
BS3M	1y	0.6791	0.0439	0.0202	0.0878
		(0.2781)	(0.0190)	(0.0065)	(0.0802)
	3y	0.7991	0.1154	0.0225	0.1288
		(0.3120)	(0.2547)	(0.0026)	(0.1270)
	5y	0.6941	0.0541	0.0145	0.1630
		(0.2344)	(0.0268)	(0.0039)	(0.1211)
	7y	0.7933	0.0811	0.0143	0.1474
		(0.1178)	(0.0302)	(0.0036)	(0.1123)
	10y	0.8813	0.0743	0.0131	0.2156
		(0.0508)	(0.0152)	(0.0013)	(0.1066)
BS6M	1y	0.7837	0.1085	0.0211	0.2166
		(0.0929)	(0.0279)	(0.0039)	(0.1106)
	3y	0.5208	0.0841	0.0245	0.0233
		(0.4629)	(0.3111)	(0.0027)	(0.0637)
	5y	0.6000	0.0344	0.0136	0.0904
		(0.2365)	(0.0177)	(0.0037)	(0.0823)
	7y	0.9044	0.0769	0.0158	0.2082
		(0.0355)	(0.0206)	(0.0012)	(0.1075)
	10y	0.8921	0.0699	0.0136	0.1862
		(0.0383)	(0.0176)	(0.0011)	(0.1163)
BS12M	1y	0.4646	0.1533	0.0244	0.2310
		(0.1676)	(0.0258)	(0.0073)	(0.0704)
	3y	0.4772	0.0239	0.0288	0.0557
		(0.4083)	(0.0262)	(0.0059)	(0.0669)
	5y	0.4417	0.0123	0.0231	0.0620
		(0.3568)	(0.0147)	(0.0054)	(0.0485)
	7y	0.9067	0.0586	0.0188	0.1851
		(0.0565)	(0.0162)	(0.0015)	(0.0951)
	10y	0.9162	0.0572	0.0167	0.1787
		(0.0372)	(0.0138)	(0.0013)	(0.0976)

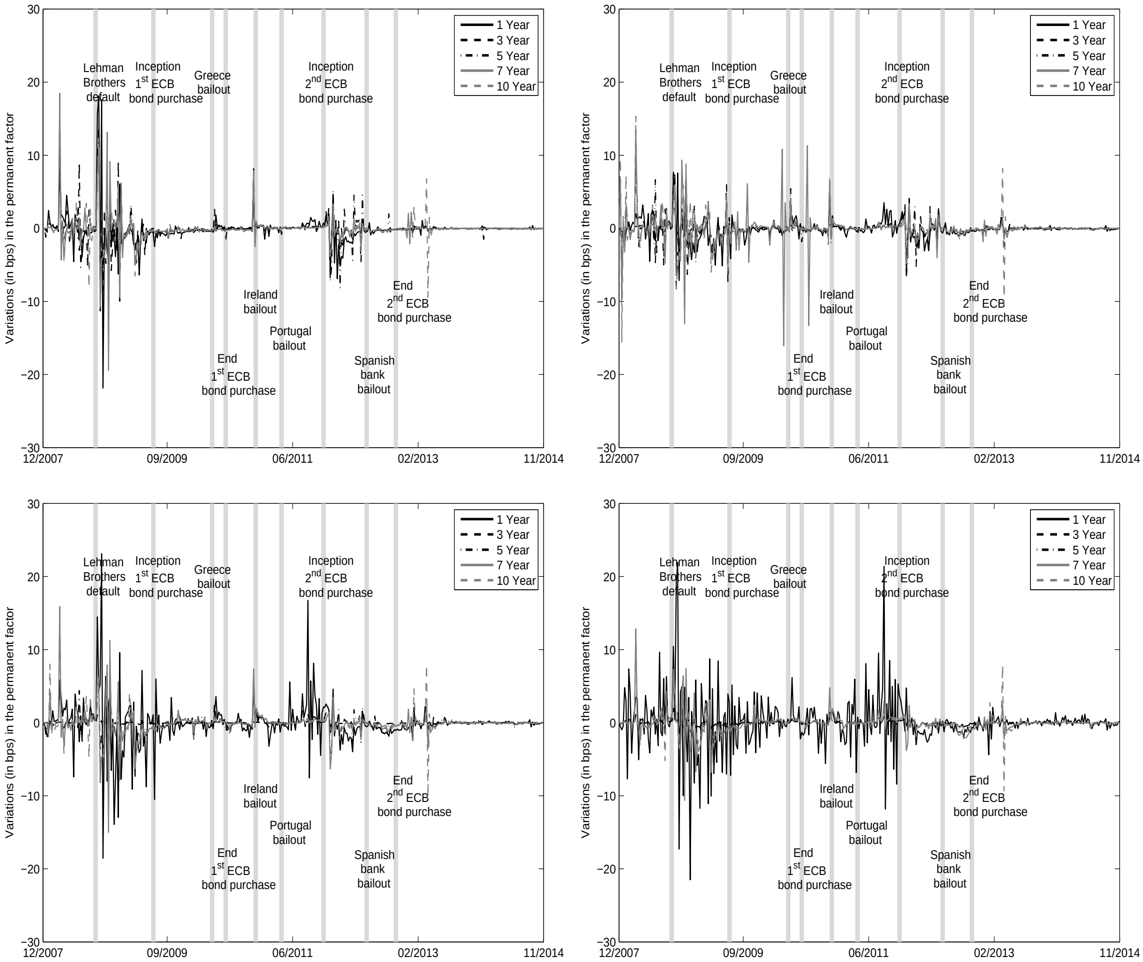
Maximum likelihood estimation results using the particle filter. The table reports the maximum likelihood estimation results corresponding to the model parameters with standard errors in parenthesis. These estimations have been calculated for the distinct 1, 3, 6 and 12 months BS tenors and the 1,3,5 7 and 10-years maturities. The sample period considered in these estimations corresponds to Basis Swap spreads weekly data from December 19th 2007 to November 12th 2014.

Figure 4.2: Euribor versus Eonia Basis Swap spreads transitory component variations.



Weekly time series of the changes in the Euribor versus Eonia Basis Swap spreads transitory component. The distinct figures correspond to the different Euribor tenors basis spreads: 1-month (top,left), 3-month (top, right), 6-month (bottom, left) and 12-month (bottom, right). Data period comprises from December 19th, 2007, to November 12th, 2014.

Figure 4.3: Euribor versus Eonia Basis Swap spreads permanent component variations.



Weekly time series of the changes in the Euribor versus Eonia Basis Swap spreads permanent component. The distinct figures correspond to the different Euribor tenors basis spreads: 1-month (top,left), 3-month (top, right), 6-month (bottom, left) and 12-month (bottom, right). Data period comprises from December 19th, 2007, to November 12th, 2014.

To make this comparison, we firstly perform a principal component analysis (PCA) of the estimated transitory and permanent shocks considering all the tenors and maturities altogether. The results reveal that the first three principal components explain 80% of the factors variation. This means that there exist important commonalities in the factors, although heterogeneities may not be negligible. The principal components loadings (not reported here but available upon request) show that these principal components may be interpreted as level, slope and curvature factors. Although the first principal component is the most important -representing 42% of the changes-, it is very remarkable the role of the second principal component which captures around 30% of the variation. This means that changes in the slope of the permanent and transitory time series are not infrequent.

To further examine the heterogeneities in the BS permanent and transitory shocks across tenors and maturities we perform separate principal component analyses. Firstly, we perform a PCA for each tenor and secondly for each maturity. From the results reported in Table 4.4 we observe that, once we analyze each tenor separately, the first three principal components represent between 89% and 99% of the variations, meaning that the commonalities are more evident. Remarkably, the second principal component remains quite important, representing between 15% and 36% of the changes and meaning that changes in slope are important. Analyzing the PCA loadings we may conclude that the most important heterogeneities across maturities correspond to short term maturities in the case of shorter tenors and to long term maturities in the case of longer tenors. The results are similar if we compare transitory and permanent shocks.

Table 4.4: PCA results of the distinct BS tenors transitory and permanent factors

	Transitory				Permanent			
	PC1	PC2	PC3	All	PC1	PC2	PC3	All
BS1M	58.14	22.00	9.91	90.05	63.72	21.09	8.68	93.49
BS3M	58.38	21.11	8.37	87.87	65.15	15.11	10.61	90.87
BS6M	55.41	29.58	7.99	92.98	58.05	35.65	3.67	97.36
BS12M	76.10	16.08	4.67	96.85	77.63	19.87	2.15	99.65

PCA results for the BS tenors transitory and permanent factors grouped according to the tenor of the BS underlying rate. The table presents the percentage variance of the different BS tenors transitory and permanent factors explained by their first principal components. These figures are computed by performing a principal component analysis separately to the transitory and permanent factor associated to the distinct tenors Basis Swap spread term structures. The distinct Euribor tenors are 1, 3, 6 and 12 months. The historical series of the factors correspond to weekly data from December 19th 2007 to November 12th 2014.

Secondly, we perform a PCA for each maturity. The results are reported in Table 4.5. In this case, we observe that commonalities are stronger since the first three principal components account for practically the entire variation in the series. The first principal component accounts for most of the variations, meaning that level changes across tenors are the most frequent. Analyzing the PCA loadings, we notice that heterogeneities across tenors in the transitory case correspond to the 1-

month tenor in the short run and to the 12-month tenor in the medium to long run. In the permanent case, they correspond to 1-month and 3-month tenors in the short run and to 1-month and 12-months tenors in the medium to long run. In the permanent case the 6-month tenor may be interpreted as a benchmark since its behavior is closest to the first principal component for all maturities.

Table 4.5: PCA results of the distinct BS maturities transitory and permanent factors

	Transitory				Permanent			
	PC1	PC2	PC3	All	PC1	PC2	PC3	All
1Y	77.61	18.18	2.75	98.53	76.54	18.64	3.67	98.85
3Y	77.77	15.50	5.30	98.58	88.28	9.21	2.48	99.96
5Y	78.94	12.96	6.57	98.47	87.71	9.09	3.03	99.83
7Y	75.92	18.08	5.11	99.10	78.92	15.83	4.23	98.98
10Y	83.78	10.08	4.86	98.72	86.30	8.69	3.54	98.53

PCA results for the BS tenors transitory and permanent factors grouped according to the maturity of the BS spreads. The table presents the percentage variance of the different BS maturities transitory and permanent factors explained by their first principal components. These figures are computed by performing a principal component analysis separately to the transitory and permanent factor associated to the maturities of the different tenors Basis Swap spreads. The distinct Euribor tenors are 1, 3, 6 and 12 months. The historical series of the factors correspond to weekly data from December 19th 2007 to November 12th 2014.

Finally, summarizing the previous findings we may conclude that, for both permanent and transitory components, despite commonalities are important, heterogeneities may also be very relevant across tenors and maturities. Their behavior cannot be represented by only one component and a second principal component usually matters. The most important heterogeneities across maturities arise in the short run for shorter tenors and in the long run for longer tenors. Regarding heterogeneities across tenors, in the case of transitory shocks, shorter tenors in the short-run and longer tenors in the long-run tend to behave differently. In the case of permanent shocks, shorter tenors in the short-run and shorter and longer tenors in the long-run display a heterogeneous performance.

4.5 The determinants of transitory and permanent components

In this section, we analyze the determinants of the interbank spreads transitory and permanent components corresponding to different maturities and BS Euribor tenors. As determinants, we take into account a broad set of economic and financial explanatory variables capturing distinct economic and financial aspects that may covary with the evolution Basis Swap rates.

4.5.1 Variables description

The number of variables that could be potentially linked to the term structure is initially unbounded. Following the researh design in Longstaff et al. (2011) and Groba, Lafuente and Serrano (2013), we focus on a panel of economic variables that are grouped in four categories: money and interest rates, stock market, credit market and risk aversion variables. Here is the description of the variables employed.

Money and interest rate market The multi-curve setting is clearly linked to the risk of lending in the interbank market, or interbank risk (Filipovic and Trolle, 2013). Therefore, the money and interest rate variables are the first group that draws our attention. This group includes the i) interest rate level in the Euro Area, denoted by *IR Level*. The interest rate is the risk-free lending rate in the Euro area, and it is proxied by the Eonia Index, which is computed as a weighted average of all overnight lending actual transactions executed by the Eonia panel banks in the Euro money market [4]. It is calculated by the ECB and it has been taken from ECB. The ii) interest rate slope (*IR Slope*) is usually taken as an indicator of overall economic health; see Collin-Dufresne et al. (2001) and Groba, Diaz and Serrano (2013). The risk-free interest rates slope in the Euro Area is proxied by the spread between the 10-year and 2-year Eonia swap quotes. Eonia Swaps or, alternatively, OIS are similar to plain vanilla IRS transactions – they both are exchanges of a fixed and variable interest rates –, with the variable rate being linked to Eonia Index. The data is taken from Bloomberg. Lastly, we use iii) the ECB Liquidity Indicator of the Euro Area money market (*ECB Liq*) published by ECB. The composite indicator includes arithmetic averages of individual liquidity measures. The data sources for these measures are the ECB, Bank of England, Bloomberg, JPMorgan Chase & Co., Moody's KMV and ECB calculations.

Stock market variables. This group includes the iv) Euro Stoxx Banks Price Index, a capitalization-weighted index which reflects the stock performance of companies in the European Monetary Union (EMU) that are involved in the banking sector. The data source is Bloomberg. The time series of this variable is considered in *logs*. Additionally, we also work with the v) Euro Stoxx VIX Index, a market estimate of future volatility based on a weighted average of implied volatilities of options written on Euro Stoxx 50 stocks. It captures implied volatility on Eurex traded options with a rolling 30 day expiry. The source is Bloomberg.

Credit market variables. The list includes the vi) Itraxx Senior Financials, an index that comprises 25 equally-weighted 5-years maturity credit default swaps (CDS) on investment grade European entities involved in the financial sector. The index is from Markit. Then, we have the vii) the German CDS, the Federal Republic of Germany Senior CDS quotes in USD and maturity 5-years and is taken from Bloomberg. This variable is named as *German CDS*. Finally, the viii) AAA Fin - German Government yield (*FG Spread*), that it is the spread between 1-year maturity AAA EUR Financial Sector and the 1-year maturity German Government yields. Each of the yields

[4]Euribor and Eonia rates were contributed by the same panel of banks until June 1st 2013 but since then the Eonia and Euribor panels are allowed to be different.

is calculated as a composite yield of representative securities around the 1-year maturity. The source is Bloomberg.

Risk aversion variables. Finally, we include a risk aversion variable as the ix) ECB Risk Aversion Indicator, an Euro Area global risk aversion indicator published by ECB, and denoted as *ECB RA*. The indicator is constructed as the first principal component of five risk aversion indicators, namely Commerzbank Global Risk Perception, UBS FX Risk Index, Westpac's Risk Appetite Index, BoA ML Risk Aversion Indicator and Credit Suisse Risk Appetite Index. A rise in the indicator denotes an increase in risk aversion. This indicator comes from Bloomberg, Bank of America Merrill Lynch (BoA ML), UBS, Commerzbank and ECB calculations.

To avoid the risk of using variables with similar information content, we compute the correlation matrix for all the candidate variables to be included in our regression analysis, which is reported in Table 4.6. We observe that either the Euro Stoxx Banks or the Euro Stoxx VIX is highly correlated with the Itraxx Financial and ECB risk aversion indexes. Also, the Itraxx Financial index exhibits a strong correlation with the German CDS. To avoid collinearity problems, we remove from our study the stock market variables and the Itraxx Senior Financial index. Standard stationarity tests systematically lead to reject the existence of a unit-root for the increments.

Table 4.6: Pairwise correlations of increments of explanatory variables

	IR Level	*IR Slope*	*ECB Liq*	*EuroStoxx50*	*EuroStoxxVix*	*Itraxx Fin.*	*German CDS*	*FG Spread*	*ECB RA*
IR Level	1.00								
IR Slope	0.03	1.00							
ECB Liq	0.19	-0.11	1.00						
EuroStoxx50	0.01	-0.05	0.07	1.00					
EuroStoxxVix	0.05	0.17	-0.14	-0.68	1.00				
Itraxx Fin.	0.02	-0.13	-0.00	-0.69	0.46	1.00			
German CDS	0.10	-0.01	-0.14	-0.52	0.38	0.56	1.00		
FG Spread	0.12	0.14	-0.36	-0.17	0.24	0.21	0.25	1.00	
ECB RA	0.11	0.12	-0.12	-0.64	0.81	0.53	0.42	0.22	1.00

4.5.2 Regression Results

To study the determinants of the Basis Swaps components, we develop a regression analysis on the permanent and transitory factors that correspond to each BS tenor and maturity as previously estimated in Section 4.4. Let ΔF_{it} denote the increments of the permanent or transitory factor corresponding to a the i-th maturity BS spread of a particular tenor at time t: we model the conditional mean of this process. In particular, we consider the following OLS regression specification,

$$\Delta F_{it} = \alpha_i + \gamma_{1i}\Delta IRLevel_t + \gamma_{2i}\Delta IRSlope_t + \gamma_{3i}\Delta ECBLiq_t + \gamma_{4i}\Delta GermanCDS_t + \gamma_{5i}\Delta FGSpread_t + \gamma_{6i}\Delta ECBRA_t + \varepsilon_{it}, \quad (4.13)$$

with $\theta_i = (\alpha_i, \gamma_i')'$ denoting the main parameters of interest, and ε_t being random disturbances.

Tables 4.7, 4.8, 4.9 and 4.10 reports the OLS estimates from projecting the permanent and transitory components of the different maturity and tenor BS spreads onto the set of regressors. We report the estimated parameters, White (1980) robust standard errors and the adjusted R^2 coefficients.

The results in Tables 4.7, 4.8, 4.9 and 4.10 show that the significance of the different explanatory variables depends on the BS spread tenor. Analyzing separately each of the tenors we make the following inferences.

For 1-month BS spreads, both transitory and permanent components are associated to credit risk variables. The transitory factor relates to German CDS spread and the permanent one to the spread between the AAA EUR financial sector and the German government yields (from now onwards denoted as FG spread). Changes in the interest rate slope, proxing the degree of economic health, are relevant for permanent fluctuations in the very short run. Permanent changes explanatory power are more important compared to transitory changes.

At 3-months BS tenor, as it happened in the case of 1-month tenor, both transitory and permanent components are linked to credit variables. Liquidity starts to play a role and it is related to the permanent component in the very short run. Regarding economic variables, interest rates slope and risk aversion are significant in the permanent case indicating that the agents' perception concerning risks and economic health also matter. Transitory shocks relate to economic agents' degree of risk aversion. Permanent changes are relatively more relevant than transitory ones.

At the 6-months tenor, we start noticing a variation in the significance of some of the variables, signaling that the nature of some of these variables is changing. The FG spread, although it is still relevant for permanent fluctuations, starts to become significant in explaining transitory factor changes in the short run. Something similar is observable regarding the interest-rates slope. The qualitative behavior of the rest of the explanatory variables remains practically the same as in the 3-month tenor case. Remarkably, the transitory factor significant power becomes more important than the permanent one.

At the 12-months tenor, we observe a complete change in the nature of transitory and permanent factors. The permanent component almost exclusively relates to liquidity shocks. While the transitory component is related to FG spreads. Other economic variables matter for the transitory component, as interest rates level and slope and risk aversion. In this case the transitory component has also the highest explanatory power. Comparing the R^2 coefficients across maturities and tenors, we conclude that the model explanatory power increases with tenor and is higher at shorter-medium

Table 4.7: OLS robust regressions of BS1M transitory and permanent components

	Transitory					Permanent				
Variables	1Y	3Y	5Y	7Y	10Y	1Y	3Y	5Y	7Y	10Y
Constant	0.1305	0.1062	0.0882	0.1207	0.0565	-0.1359	-0.1464**	-0.1175	-0.1343	-0.0693
	(0.2091)	(0.1452)	(0.1584)	(0.1600)	(0.1437)	(0.1262)	(0.0680)	(0.1091)	(0.1135)	(0.1011)
IR Level	3.2042	0.3953	1.9956	1.2912	0.6096	-0.8880	-0.0068	-1.1068	-0.2825	0.0641
	(2.7846)	(1.3212)	(1.4181)	(2.2336)	(1.5467)	(1.4860)	(0.5106)	(1.1307)	(1.6462)	(1.2047)
IR Slope	4.0272	0.4454	-2.3943	-5.6014	-3.4751	-4.8254**	-1.2474	-1.3541	-1.3865	-2.1778
	(3.9793)	(2.2585)	(3.2192)	(4.0806)	(3.1512)	(2.3984)	(1.0975)	(2.2085)	(2.6147)	(2.0179)
ECB Liq	2.5266	1.3689	1.4988	0.4893	1.0322	-4.2449	-1.1557	-0.3992	-0.1423	-0.4551
	(4.9380)	(2.2548)	(2.6078)	(2.9858)	(2.2415)	(2.8547)	(1.1235)	(1.9576)	(2.3463)	(1.8480)
German CDS	0.0927*	0.0612	0.0906**	0.0690	0.0480	-0.0327	-0.0245	-0.0268	-0.0280	-0.0257
	(0.0482)	(0.0451)	(0.0420)	(0.0428)	(0.0316)	(0.0283)	(0.0176)	(0.0259)	(0.0293)	(0.0184)
FG Spread	5.4144	-0.1587	-2.0325	0.4744	3.0208	7.1339	6.9249***	8.0978***	4.8998	3.2475
	(8.6482)	(4.7311)	(5.4382)	(4.8345)	(3.8222)	(5.7212)	(2.1381)	(3.0192)	(3.0097)	(2.4416)
ECB RA	0.4672	0.4466	0.3230	-0.0078	-0.2604	-0.2308	-0.1319	-0.2619	-0.1881	0.0205
	(0.3829)	(0.3146)	(0.2266)	(0.3756)	(0.2772)	(0.1813)	(0.1277)	(0.1674)	(0.2225)	(0.1573)
Adj-R^2	7.27	2.14	4.09	1.63	1.06	17.62	18.55	9.08	1.60	1.04
N	360	360	360	360	360	360	360	360	360	360

OLS robust regressions of the 1M tenor Basis Swap spreads transitory and permanent components. The table reports the OLS results from regressing changes in the transitory and permanent factors of the 1-month Euribor tenor Basis Swap spreads at different maturities against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 percentage values. The sample period corresponds to weekly data from December 19th 2007 to November 12th 2014. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

Table 4.8: OLS robust regressions of BS3M transitory and permanent components

	Transitory					Permanent				
Variables	1Y	3Y	5Y	7Y	10Y	1Y	3Y	5Y	7Y	10Y
Constant	0.0328	0.0548	0.0292	0.0259	0.0399	-0.0917	-0.1164**	-0.0668	-0.0320	-0.0399
	(0.1735)	(0.1408)	(0.1522)	(0.2067)	(0.1624)	(0.0714)	(0.0514)	(0.0857)	(0.1243)	(0.1091)
IR Level	2.1728	-1.1895	1.1804	0.3726	0.0033	-0.5315	0.2157	-1.0582	0.1961	0.3558
	(1.7718)	(1.0334)	(1.2411)	(1.7890)	(1.5794)	(0.7623)	(0.2688)	(0.8734)	(1.1775)	(1.2394)
IR Slope	3.6232	1.7226	-2.7436	-3.2797	-1.7479	-3.4036**	-1.9343***	-2.0078	-2.9130*	-3.2513*
	(2.7390)	(2.0898)	(2.6655)	(3.6817)	(3.1433)	(1.3833)	(0.7308)	(1.4397)	(1.7466)	(1.9240)
ECB Liq	0.6159	1.9089	1.5087	1.5233	1.1595	-2.7458**	-0.5361	0.3798	-0.3788	-0.1819
	(3.0457)	(1.6577)	(1.7180)	(2.3724)	(2.2169)	(1.2767)	(0.5070)	(1.1463)	(1.5969)	(1.7327)
German CDS	0.1133**	0.0539	0.1036**	0.0609	0.0704	0.0006	-0.0010	-0.0131	-0.0114	-0.0368*
	(0.0481)	(0.0482)	(0.0440)	(0.0511)	(0.0432)	(0.0203)	(0.0165)	(0.0205)	(0.0268)	(0.0221)
FG Spread	6.6568	4.4853	-1.7302	-0.3360	1.3392	3.9552*	3.4722***	6.6478***	5.5616***	4.1941**
	(5.5487)	(3.3858)	(4.1233)	(4.0423)	(3.5455)	(2.1180)	(1.0242)	(1.7635)	(2.1073)	(1.9372)
ECB RA	0.9332***	0.6521**	0.5008**	0.5522*	-0.1667	-0.2849**	-0.1602	-0.3099**	-0.4427**	-0.0950
	(0.2807)	(0.3184)	(0.2255)	(0.3312)	(0.3025)	(0.1420)	(0.1102)	(0.1387)	(0.2192)	(0.1780)
Adj-R^2	15.10	6.04	5.42	0.92	-0.30	20.03	9.11	9.46	3.70	2.24
N	360	360	360	360	360	360	360	360	360	360

OLS robust regressions of the 3M tenor Basis Swap spreads transitory and permanent components. The table reports the OLS results from regressing changes in the transitory and permanent factors of the 3-month Euribor tenor Basis Swap spreads at different maturities against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 percentage values. The sample period corresponds to weekly data from December 19th 2007 to November 12th 2014. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

Table 4.9: OLS robust regressions of BS6M transitory and permanent components

	Transitory					Permanent				
Variables	1Y	3Y	5Y	7Y	10Y	1Y	3Y	5Y	7Y	10Y
Constant	0.0417	-0.0124	0.0167	0.1322	0.0415	-0.0374	-0.0115*	-0.0164	-0.1074	-0.0120
	(0.2168)	(0.1241)	(0.1268)	(0.1442)	(0.1400)	(0.1445)	(0.0064)	(0.0572)	(0.0981)	(0.0930)
IR Level	3.9707	0.2844	0.8770	0.1254	-0.1022	0.6057	0.0197	-0.2222	0.7812	0.7184
	(2.7630)	(1.0438)	(0.9651)	(1.8081)	(1.2743)	(1.6174)	(0.0428)	(0.4571)	(1.1835)	(0.9160)
IR Slope	17.0672***	2.4992	-0.8134	-3.1648	-1.5525	-6.6864***	-0.1112	-0.9832	-2.3054	-2.6699
	(3.5194)	(1.8811)	(2.6059)	(3.6777)	(2.9291)	(2.3274)	(0.0920)	(1.0295)	(2.0700)	(1.6800)
ECB Liq	2.5982	0.7153	2.3426	1.6984	1.8865	-8.3969***	-0.1081	-0.3313	-0.2548	-0.1249
	(3.9004)	(1.5131)	(1.6479)	(2.4758)	(1.7919)	(2.6830)	(0.0772)	(0.7421)	(1.7411)	(1.3252)
German CDS	0.1095	0.0770*	0.0984**	0.0746*	0.0480	-0.0226	-0.0007	-0.0118	-0.0250	-0.0233
	(0.0709)	(0.0398)	(0.0391)	(0.0436)	(0.0355)	(0.0492)	(0.0021)	(0.0153)	(0.0280)	(0.0194)
FG Spread	14.1173*	7.5911**	2.5504	1.9175	3.8477	-0.6967	0.4934***	4.4010***	4.3474*	3.2539*
	(7.6636)	(3.1612)	(4.0666)	(4.4020)	(3.4047)	(5.7739)	(0.1829)	(1.3898)	(2.3640)	(1.8572)
ECB RA	1.5886***	0.7723***	0.6721***	0.4635	0.2002	-0.3575	-0.0190	-0.2453**	-0.3368	-0.1499
	(0.3430)	(0.2506)	(0.1864)	(0.3133)	(0.2358)	(0.2237)	(0.0124)	(0.0962)	(0.2115)	(0.1500)
Adj-R^2	28.62	16.88	10.63	3.31	1.64	19.25	11.44	9.65	3.83	2.36
N	360	360	360	360	360	360	360	360	360	360

OLS robust regressions of the 6M tenor Basis Swap spreads transitory and permanent components. The table reports the OLS results from regressing changes in the transitory and permanent factors of the 6-month Euribor tenor Basis Swap spreads at different maturities against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 percentage values. The sample period corresponds to weekly data from December 19th 2007 to November 12th 2014. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

Table 4.10: OLS robust regressions of BS12M transitory and permanent components

	Transitory					Permanent				
Variables	1Y	3Y	5Y	7Y	10Y	1Y	3Y	5Y	7Y	10Y
Constant	0.0505	0.0698	0.0579	0.1455	0.0868	0.1123	-0.0238	-0.0044	-0.0713	-0.0137
	(0.3268)	(0.1384)	(0.1218)	(0.1313)	(0.1314)	(0.1871)	(0.0161)	(0.0118)	(0.0763)	(0.0760)
IR Level	10.9581**	2.6859*	2.0624*	0.9401	0.6594	1.1393	0.1438	-0.0118	0.9677	0.6414
	(4.4466)	(1.5575)	(1.1721)	(1.5689)	(1.1305)	(1.8000)	(0.1626)	(0.1000)	(0.8645)	(0.6821)
IR Slope	34.1822***	9.3673***	2.6166	-1.5053	-0.4570	-3.1800	-0.2082	-0.1490	-0.9461	-1.4559
	(4.6811)	(2.2062)	(2.4359)	(3.3162)	(2.6556)	(3.2771)	(0.2612)	(0.1886)	(1.4369)	(1.1136)
ECB Liq	-4.8236	-1.0379	1.1528	2.8819	2.6899**	-9.2444***	-0.7837***	-0.3641***	-2.2420**	-1.3689
	(4.6368)	(1.7294)	(1.4278)	(1.8784)	(1.3216)	(3.2089)	(0.2699)	(0.1296)	(1.1015)	(0.8323)
German CDS	0.0813	0.0713	0.0851**	0.0721	0.0423	-0.0576	-0.0029	-0.0031	-0.0267	-0.0214
	(0.1331)	(0.0444)	(0.0418)	(0.0456)	(0.0395)	(0.0651)	(0.0048)	(0.0035)	(0.0242)	(0.0172)
FG Spread	19.3818**	9.2715**	7.5811**	5.0716	6.0984**	-3.7050	0.4728	0.7186**	2.2386	1.7903
	(8.7216)	(3.6956)	(3.5132)	(3.8316)	(2.9513)	(5.7009)	(0.5711)	(0.3006)	(1.7670)	(1.4261)
ECB RA	3.1487***	1.4336***	0.8754***	0.6006**	0.2812	-0.1232	-0.0229	-0.0344*	-0.1648	-0.0089
	(0.5702)	(0.2484)	(0.1817)	(0.2735)	(0.2109)	(0.3164)	(0.0267)	(0.0190)	(0.1558)	(0.1025)
Adj-R^2	38.20	34.09	21.69	8.71	5.47	12.30	16.20	12.89	7.01	2.92
N	360	360	360	360	360	360	360	360	360	360

OLS robust regressions of the 12M tenor Basis Swap spreads transitory and permanent components. The table reports the OLS results from regressing changes in the transitory and permanent factors of the 12-month Euribor tenor Basis Swap spreads at different maturities against different macro-financial variables. These results correspond to OLS coefficient estimates, robust standard errors and Adjusted R^2 percentage values. The sample period corresponds to weekly data from December 19th 2007 to November 12th 2014. *, ** and *** denote the significance at 10%, 5% and 1%, respectively.

term maturities compared to longer term ones.

Summarizing the previous results we may conclude that liquidity shocks are permanent. At short to medium tenors, they are relevant only in the very short run. Nevertheless, for very long tenors, they are the most important variable capturing permanent component fluctuations for all maturities. Interbank credit risk shocks may be interpreted as permanent at shorter tenors. Nevertheless, at longer tenors their impact changes and it becomes transitory. Other macroeconomic variables are also relevant in explaining the changes in the transitory and permanent components. German CDS spreads capture transitory fluctuations mainly at shorter tenors. The level of instability about economic conditions summarized by the interest rates slope is related to the permanent component at short tenors but, at long tenors, the impact of this variable becomes transitory. The agent's degree of risk aversion is important for both transitory and permanent fluctuations. Remarkably, permanent fluctuations show the highest explanatory power at 1-month and 3-months tenors and transitory shocks are the most prevalent at 6-months and 12-months tenors.

4.6 Concluding remarks

Interbank derivative market quotes have experienced an important structural change in recent years. The market has started to recognize the distinct -credit and liquidity- risks associated to lending at different tenor interbank rates. Although recent literature has found evidence confirming the role of these risks and their impact on different tenor interbank market spreads, further analysis concerning the nature and relative importance of these shocks is missing and necessary to better understand the structural changes that have occurred.

In the present paper, we study the information embedded in interbank market BS spread quotes. We separate the BS changes into transitory and permanent factors. We provide a deep characterization of the liquidity and credit shocks impact on BS spreads by observing the impact of these shocks separately on each of the factors, discriminating their effect from other macroeconomic and financial variables. This allows us to study in more detail the different nature of the shocks and their importance. The results are very interesting and shed light on many relevant issues concerning the different effects of liquidity and credit shocks on different tenors and maturities.
In particular, our findings suggest that for short tenors, both credit and liquidity risks are permanent factors, liquidity shocks have an impact on short maturities and credit shocks on medium-long term maturities. For long tenors, interbank credit risk becomes transitory and liquidity risk remains permanent although its effect is on the entire term structure. The permanent component is relatively more important than the transitory one at short tenors and the opposite happens at long tenors.

The changing nature of interbank market credit variables at long tenors and the liquidity risks behaving as permanent factors are apparently puzzling results. Nevertheless, these are very interesting findings that may change the perception regarding the importance and the relative role of these risks in explaining the post-crisis BS spreads explosion, particularly at longer tenors. Our results interpretation is that although interbank credit risk is the predominant and most common source of fluctuations, impacting on the entire term structure, as tenors increase its impact becomes more transitory and this means that credit shocks experience shorter duration. Liquidity shocks are permanent and this means that their impact is long lasting, although it is relatively more infrequent. Liquidity shocks only matter for shorter tenors at shorter maturities but, importantly, for longer tenors they have an impact on the entire term structure.

Chapter 5

Conclusions and further research

In this dissertation we focus on the information embedded in the different tenor Basis Swap spread curves of the Euro interbank market with the aim of characterizing and quantifying the asset pricing impact of credit and liquidity shocks -among other explanatory variables- and study their role as determinants of the interbank spreads explosion in the post-crisis period. This analysis is carried out considering different approaches that contribute to bring new views and conclusions about the topic.

In the first essay, included in Chapter 2, we show that the main features of the Basis Swap spreads are captured by three components whose dynamic behaviour serves us to study the interbank market curves post-crisis evolution. These components are the Nelson and Siegel (1987) model level, slope and curvature factors. The principal component analysis of each factor across tenors reveals that there exist important commonalities. In particular, the first principal component is the most important summarizing 90% of each factor fluctuations across the different curves. The study of the relationship of these components with credit and liquidity variables -a part from other macroeconomic and financial variables- indicates that the level factors have strong co-variation with credit risk. The model residuals information is also considered by computing the Hu et al. (2013) noise measure. The examination of the information embedded in these residuals shows that they are clearly related to liquidity. Further causality tests and VAR analyses help to highlight credit and liquidity risks as the main drivers of the level and noise series, respectively.

This evidence is important to confirm the existence of the same sources of commonality in the dynamic behaviour of the multiple curves and to associate these underlying drivers to credit and liquidity risks.

The relationship of the model residuals with liquidity confirms that during distressed periods liquidity shortages generate price deviations from fundamental values. These deviations may be expected to be transitory, suggesting that the nature of shocks may be relevant. This issue is explored in more detail in Chapter 4.

In the second essay, contained in Chapter 3, we focus on the counterparty risk information embedded in Basis Swap spread curves associated to different tenor underlying deposit rates. This essay is motivated by Chapter 2 results regarding the importance of a single source factor accounting for the level of the multiple curves. Considering different tenor Basis Swap curves, we estimate distinct tenor counterparty risk intensities, disentangling this information from the term structure of risk-premiums (i.e. compensation due to changes in counterparty risk conditions as a result of variations in economic fundamentals etc.).

The estimation results reveal that counterparty risk intensities have significantly increased during the crisis. During distressed times, they range from 100 to 250 basis points depending on the tenor and they capture the Basis Swap curves level of risk. The level of commonality between the different tenor curves risk intensities is remarkable, given that the first principal component accounts for 82% of their variability across tenors. The determinants of these intensities strongly relate to credit risk, particularly to the German CDS, which can be interpreted as a state variable capturing the level of risk agents are willing to bear in interbank deposit borrowing and lending transactions.

Concerning risk-premiums estimations, they are also significant, particularly at short maturities. They range from 20 to 60 basis points depending on tenor during financial turmoil episodes. The degree of commonality of the different maturities risk-premiums across tenors is also remarkable and the first principal component accounts for 81% of their variance. The determinants of risk-premiums at short tenors are financial sector credit risk variables. At long tenors, agents' risk compensation is also due to liquidity restrictions and risk aversion (i.e. uncertainty perceptions about future financial sector conditions). The data fit of the model regarding risk-premium regressions is very important in the short run, given coefficients of determination of up to 54%.

The analysis of the model residuals information content yields similar conclusions to Chapter 2 given the relationship of the Hu et al. (2013) noise measure to liquidity.

In the third essay, included in Chapter 4, we investigate the nature of the credit and liquidity shocks impact on interbank spread curves. This essay is motivated by the Chapter 2 and Chapter 3 results regarding the relationship of model residuals to liquidity. To examine this relationship in more detail, we infer two -permanent and transitory- latent factor components from the Basis Swap spreads series.

Analyzing these component series we can observe that, although commonalities between these components exist, heterogeneities in the behaviour of these factors across tenors are not negligible.

The examination of the relationship of each tenor and maturity BS spreads' latent component to credit and liquidity variables yields the following conclusions. On one hand, liquidity shocks are permanent meaning that their effect is infrequent but long-lasting. Their impact is only on short maturities at short to medium tenors but on the entire term structure at long tenors. On the other hand, the nature of credit shocks changes according to tenor. These shocks are permanent at short-tenors but transitory at long-tenors, meaning that their effect has shorter duration and it is more frequent at longer compared to shorter tenors. Their impact is always on the entire term structure.

The explanatory power of credit and liquidity -among other financial and macroeconomic variables- increases with tenor and is more noticeable in the short to medium run compared to the long run. The explanatory power associated to permanent factors is remarkable at short tenors while transitory components are more relevant at longer tenors. This suggests that credit shocks play a more important role compared to liquidity.

The results show the importance of disentangling the nature of shocks in the characterization of the impact of credit and liquidity. This distinction helps to identify sources of heterogeneity in these variables effects across tenors and maturities and this allows to provide a more detailed specification of their impact.

Finally, to conclude this dissertation and connecting the results from the different chapters, we would like to emphasize the importance of credit risk as first order effect variable explaining the curves multiplicity spreads. The strong commonalities of the impact of credit risk on the different curves are very remarkable. Despite the importance of credit risk, second order effect sources are not negligible. In particular, it is worth highlighting the significant role of liquidity through its effect on risk premiums and the different nature of its impact compared to credit shocks. Taking into account these second order drivers allows to identify certain heterogeneities in the behaviour of the curves across tenors and maturities. This provides a better and richer understanding of the multiple-curve phenomena guiding the directions of future research. In particular, this dissertation conclusions suggest two main future directions of research. On one hand, deepening into the theoretical foundations of the effects of the multiple curve explanatory sources that we have identified. On the other hand, further analyzing the relevance of accounting for these sources in the design of financial market intervention policies and the planning of investors hedging strategies.

Appendix A

Interest Rate Swaps and the multi-curve framework

Due to multi-curve setting, IRS floating payments do depend on floating rate periodicity. To fix notation, denote as $L(T_{x,j-1},T_{x,j})$ the interbank deposit rate with tenor x associated with an interest rate swap floating leg with date schedule $T_x = \{T_{x,0},..,T_{x,n_x}\}$. Similarly, we denote as K the interest rate corresponding to a swap fixed leg with date schedule $T_z = \{T_{z,0},..,T_{z,n_z}\}$. The interest rate swap cash flows present value is

$$\begin{aligned} Swap(t;T_x,T_z) &= E_t\left(\sum_{j=1}^{n_x} e^{-\int_t^{T_{x,j}} r(s)ds}\tau_x\left(T_{x,j-1},T_{x,j}\right)L\left(T_{x,j-1},T_{x,j}\right)\right) \\ &- K\sum_{j=1}^{n_z} P_d\left(t,T_{z,j}\right)\tau_z\left(T_{z,j-1},T_{z,j}\right), \qquad (A.1) \end{aligned}$$

where r_t is the instantaneous default-free interest rate at time t and $P_d(t,T)$ is the value at time t of the default-free zero-coupon bond with maturity T, $P_d(t,T) = E_t[e^{-\int_t^T r(u)du}]$. $E_t[.]$ is the expectation under the risk neutral measure. Finally, τ_x and τ_z denote the day count fraction between two particular payment dates according to the established calculation basis.

The IRS equilibrium rate is the swap fixed leg interest rate that makes null the swap present value, namely,

$$IRS\left(t;T_x,T_z\right) = \frac{E_t\left(\sum_{j=1}^{n_x} e^{-\int_t^{T_{x,j}} r(s)ds}\tau_x\left(T_{x,j-1},T_{x,j}\right)L\left(T_{x,j-1},T_{x,j}\right)\right)}{\sum_{j=1}^{n_z} P_d\left(t,T_{z,j}\right)\tau_z\left(T_{z,j-1},T_{z,j}\right)}. \qquad (A.2)$$

If we substitute expression (2.1) on the last expression we are assuming that the following replication strategies for IRSs based on a single-curve framework hold. In the pre-crisis context, these replication strategies were consistent with market quotes.

$$Swap(t,T) = \frac{\sum_{i=1}^{n} P(t,T_i)\tilde{F}(t,T_{i-1},T_i)\tau(T_{i-1},T_i)}{\sum_{i=1}^{n} P(t,T_i)\tau(T_{i-1},T_i)} \quad = \quad \frac{P(t,T_0) - P(t,T_n)}{\sum_{i=1}^{n} P(t,T_i)\tau(T_{i-1},T_i)} \tag{A.3}$$

Appendix B

The Basis Swap contract

There exist two types of single-currency BS contracts exchanged in the interbank market. On the one hand, there are the BSs constituted by two vanilla swaps, named here as first type. On the other, the single line items, or second type, which consist of the interchange of two floating rates, the longer tenor Euribor rate against the shorter tenor one plus a spread. The choice of the contract type depends on the infrastructure capability of the financial entities. In any case, there are negligible differences between the quotes of both type of swaps, mainly due to the frequency of compounding and the day count conventions as we will see in more detail below. This paper employs the first type of BS contracts, which is quoted as a portfolio of two standard floating versus fixed swaps with two different floating rates and coincident fixed leg tenors. In this case the BS spread is the difference between the two equilibrium fix-to-float swap rates, and it has the same payment frequency as the shorter tenor swap fixed leg. Then, the value of the BS contract is

$$
\begin{aligned}
\Delta_{x,y} &= IRS\left(t;T_x,T_z\right) - IRS\left(t;T_y,T_z\right) \\
&= \frac{\begin{pmatrix} E_t\left(\sum_{j=1}^{n_x} e^{-\int_t^{T_{x,j}} r(s)ds} \tau_x\left(T_{x,j-1},T_{x,j}\right) L\left(T_{x,j-1},T_{x,j}\right)\right) \\ -E_t\left(\sum_{j=1}^{n_y} e^{-\int_t^{T_{y,j}} r(s)ds} \tau_y\left(T_{y,j-1},T_{y,j}\right) L\left(T_{y,j-1},T_{y,j}\right)\right) \end{pmatrix}}{\sum_{j=1}^{n_y} P_d\left(t,T_{z,j}\right)\tau_z\left(T_{z,j-1},T_{z,j}\right)}, \qquad \text{(B.1)}
\end{aligned}
$$

with $IRS\left(t;T_x,T_z\right)$ and $IRS\left(t;T_y,T_z\right)$ the equilibrium swap rates of fixed versus floating IRS contracts, and the floating legs are linked, respectively, to the x-tenor and y-tenor Euribor reference rates.

In the second type of basis swap contract the longer tenor Euribor rate $L(T_{x,j-1},T_{x,j})$ is exchanged for the shorter tenor Euribor rate $L(T_{y,j-1},T_{y,j})$. The date schedules corresponding to the swap floating legs linked to Euribor rates $L(T_{y,j-1},T_{y,j})$ and $L(T_{x,j-1},T_{x,j})$ are $T_y = \{T_{y,0},..,T_{y,n_y}\}$ and $T_x = \{T_{x,0},..,T_{x,n_x}\}$, respectively. To equilibrium the present value of these legs, a basis swap spread $\Delta_{x,y}$ has to be added to the floating leg with shorter tenor. The second type is structured as a floating vs. floating swap plus spread. In this case, the basis swap spread has the same payment frequency as the shorter tenor leg and is quoted against this leg. In the second type of basis swap contract the longer tenor Euribor rate $L(T_{x,j-1},T_{x,j})$ is exchanged for the shorter tenor Euribor rate $L(T_{y,j-1},T_{y,j})$. The date schedules corresponding to the swap floating legs linked to Euribor rates $L(T_{y,j-1},T_{y,j})$ and $L(T_{x,j-1},T_{x,j})$ are $T_y = \{T_{y,0},..,T_{y,n_y}\}$ and $T_x = \{T_{x,0},..,T_{x,n_x}\}$, respectively. To equilibrate the present value of these legs, a basis swap spread $\Delta_{x,y}$ has to be added to the floating leg with shorter tenor. The value of the Basis Swap contract is as follows,

$$\begin{aligned} BasisSwap(t;T_x,T_y) &= E_t\left(\sum_{j=1}^{n_x} e^{-\int_t^{T_{x,j}} r(s)ds}\tau_x\left(T_{x,j-1},T_{x,j}\right)L\left(T_{x,j-1},T_{x,j}\right)\right) \\ &- E_t\left(\sum_{j=1}^{n_y} e^{-\int_t^{T_{y,j}} r(s)ds}\tau_y\left(T_{y,j-1},T_{y,j}\right)\left(L\left(T_{y,j-1},T_{y,j}\right)+\Delta_{x,y}\right)\right) \end{aligned} \tag{B.2}$$

This equilibrium basis swap satisfies

$$\Delta_{x,y} = \frac{\begin{pmatrix} E_t\left(\sum_{j=1}^{n_x} e^{-\int_t^{T_{x,j}} r(s)ds}\tau_x\left(T_{x,j-1},T_{x,j}\right)L\left(T_{x,j-1},T_{x,j}\right)\right) \\ -E_t\left(\sum_{j=1}^{n_y} e^{-\int_t^{T_{y,j}} r(s)ds}\tau_y\left(T_{y,j-1},T_{y,j}\right)L\left(T_{y,j-1},T_{y,j}\right)\right) \end{pmatrix}}{\sum_{j=1}^{n_y} P_d\left(t,T_{y,j}\right)\tau_y\left(T_{y,j-1},T_{y,j}\right)} \tag{B.3}$$

As can be observed from the previous equations, the difference between the two types of basis swaps lays on the annuity term in the denominator, where the frequency and calculation basis in one case corresponds to the shorter tenor floating leg and in the other case to the swap fixed leg. In particular, the first type of contract basis spread, $\Delta^1_{x,y}$, can be deduced from the one corresponding to the second type of basis swap contract, $\Delta^2_{x,y}$, as follows,

$$\Delta^2_{x,y} = \frac{\sum_{j=1}^{n_z} P_d\left(t,T_{z,j}\right)\tau_z\left(T_{z,j-1},T_{z,j}\right)}{\sum_{j=1}^{n_y} P_d\left(t,T_{y,j}\right)\tau_y\left(T_{y,j-1},T_{y,j}\right)}\Delta^1_{x,y} \tag{B.4}$$

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