The 2007 Subprime Market Crisis Through the Lens of European Central Bank Auctions for Short-Term Funds*

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Abstract

This paper studies European banks' demand for short-term funds during the summer 2007 subprime market crisis. We use bidding data from the European Central Bank's auctions for one-week loans, their main channel of monetary policy implementation. Through a model of bidding, we show that banks' bidding behavior reflects their cost of obtaining short-term funds elsewhere (i.e., in the interbank market) as well as a strategic response to other bidders. We find considerable heterogeneity across banks in their willingness to pay for short-term funds supplied in these auctions. Accounting for the strategic component is important: while a naïve interpretation of the raw bidding data may suggest that virtually all banks suffered a dramatic increase in the cost of obtaining funds in the interbank market, we find that for about one third of the banks, the change in bidding behavior was simply a strategic response. Using a complementary data set, we also find that banks' pre-turmoil liquidity costs, as estimated by our model, are predictive of their post-turmoil liquidity costs and that there is considerable heterogeneity in these costs with respect to the country-of-origin. Finally, among the publicly traded banks, the willingness to pay for short term funds in the second half of 2007 are predictive of stock prices in late 2008.

Keywords: multiunit auctions, primary market, structural estimation, subprime market, liquidity crisis

JEL Classification: D44

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1 Introduction

On August 9, 2007 BNP Paribas announced its decision to freeze three investment funds with exposure to high-grade segments of the U.S. subprime home-loan market. The combined value of the funds was €1.59 billion ($2.19 billion) (The Wall Street Journal August 10-12, 2007). This announcement followed the rescue of a German bank IKB Deutsche Industriebank AG arranged over a weekend meeting on July 27-28, 2007. The crisis was triggered by the problems with subprime mortgages in the U.S. market, which in turn contributed to revealing the vast amount of securities (such as asset backed securities (ABS)) that were likely exposed to much more risk than originally assessed based on their ratings. When the subprime credit crisis hit the Euro money market in August 2007, banks' cost of obtaining short-term uncollateralized loans increased sharply. In figure 1, we plot the spread between the (1 week) EURIBOR[1], a measure of interbank uncollateralized rate, and the (1 week) EUREPO, the rate for fully collateralized loans on the interbank market.[2] After the second week of August 2007 the gap between these rates significantly widened; the premium a lender required for an unsecured loan in the interbank market in the post-August 2007 period increased from around 4 basis points to well over 10 basis points for loans with a maturity of one-week.[3]

In response to similar liquidity problems in the U.S., the Federal Reserve System significantly expanded and diversified its facilities for providing liquidity. On the other side of the Atlantic, the European Central Bank exploited an already existing tool within its operational framework, its weekly "repo auctions".[4]

For many financial market participants seeking access to liquidity, repo auctions of the central

[1]EURIBOR, Euro Interbank Offer Rate, is a daily reference rate based on the averaged interest rates at which banks offer to lend unsecured funds to other banks in the euro interbank market.

[2] Loans at EUREPO have strict requirements on the type and quality of the collateral.

[3]In this paper, our analyses focus mostly on one-week maturity rates as this is the maturity of the regular weekly repo operations of the ECB. However, even more dramatic jumps in the unsecured-secured spread occurred for longer maturity loans. We analyze loans with 3-months maturity in section A.4. Not only did the spreads increase, but also the set of securities that were acceptable as collateral in the interbank market became much smaller which renders the repo rate not directly comparable (see e.g., the BearingPoint Report, 2008).

[4]It is interesting to note that in the U.S. during the early stages of the crisis (2007H2) it was the Federal Home Loan Bank System, not the Federal Reserve System, who was the main provider of liquidity support to the U.S. financial institutions. For example, as documented by Ashcraft, Bech and Frame (2008) Washington Mutual (which failed on September 25, 2008) received liquidity support in Q4 2007 amounting to about $64 billion representing 20% of its total assets. Countrywide ($48 billion in Q4 2007) and Wachovia ($42 billion in Q4 2007) were also among the institutions that received liquidity support from the FHLB System in 2007.

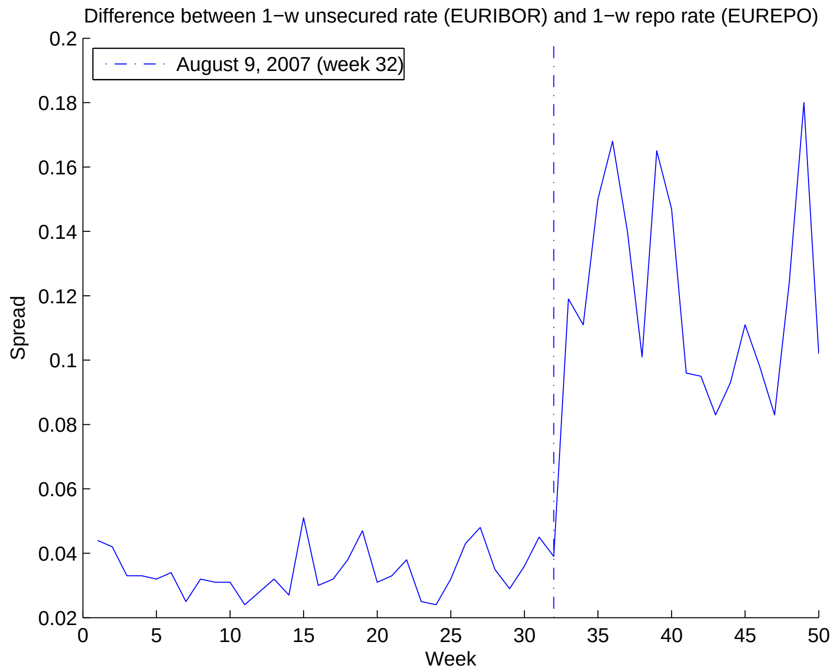


Figure 1: Spread between the unsecured and secured lending rates

bank was an attractive option: the collateral requirements were less strict and (market clearing) interest rates were significantly lower than for unsecured loans in the interbank market. To obtain a loan at the EUREPO rate in the post-turmoil period, the collateral had to be virtually risk-free - basically just high-quality government paper.[5] Therefore for many potential borrowers the better option might have been to obtain liquidity by participating in the auctions run by the central bank where the collateral requirements are not as stringent.[6]

This paper analyzes unique data on bidding behavior in the repo market to shed some light on the turmoil that started in August 2007. Our work complements prior influential analyses of this crisis by e.g. Taylor and Williams (2008, 2009), Michaud and Upper (2008), Wu (2008), and McAndrews, Sarkar and Wang (2008)[7] who have focused on the spread between the secured (collateralized) and unsecured lending rates in the interbank money market.[8] These papers report

[5]For a list of eligible collateral, see http://www.eurepo.org/eurepo/eurepogc.html

[6]Even in the U.S., the U.S. Federal Home Loan Bank System accepted mortgage-backed securities as collateral for its advances to financial institutions.

[7]See Section 2 for a more detailed literature review.

[8]These studies also look at the spread between the overnight interest swap rates and unsecured lending rates.

a large jump in these spreads beginning August 2007, and analyze the impact of various central bank actions on subsequent yield spreads.

While yield spreads paint a useful picture of the market-level impact of the liquidity crisis, and could be used as a "temperature gauge" for assessing the health of credit markets, it is not possible to assess the heterogeneity of the impact of the crisis across the banking system without access to information on individual banks' funding costs. Unfortunately, obtaining high-frequency data on individual banks' borrowing costs is difficult, as most interbank transactions take place on an over-the-counter basis, or through anonymized trading. Bank-level data from ECB's repo auctions provides us with a unique opportunity to understand the distribution of the severity of the liquidity crisis across the banking sector. Every week the ECB auctions loans with 1-week maturity to banks who offer the highest interest rates and are willing to put up the appropriate collateral that will be repurchased[9] after the loan matures. In Section 5 below, we provide a simple economic model to link the participating banks' willingness-to-pay for ECB loans in the repo auctions to their outside options of procuring liquidity through the (unsecured and/or secured) interbank markets. We then utilize recent structural econometric methods developed by the multi-unit auction literature to estimate banks' willingness-to-pay for ECB loans from their bids.

The first striking feature of our data is the sudden change in bidding behavior that occured after the turmoil. Just a quick glance at the aggregate bid curves[10] for auctions before and after August 9th, 2007 reveals a significant change in bidding behavior. The aggregate bid curves (normalized by subtracting the EONIA swap rate[11]) are shown in Figure 2. Before August 9th, 2007 all aggregate bids (depicted with solid lines) were very concentrated around the EONIA swap rate (i.e., around 0 on the vertical axis in the graph), which is regarded as an indicator of industry expectations of the relevant market interest rates since it can be used together with overnight borrowing as an

The correlation between these spreads and the secured/unsecured spread is very high, as documented by Taylor and Williams (2008). We find this in our data as well: a regression of the overnight swap rate (EONIA SWAP)/unsecured (EURIBOR) rate spread and the secured(EUREPO)/unsecured(EURIBOR) spread has coefficient 1.05($t = 15.96$), with $R^2 = 0.84$, which are very similar to results reported by Taylor and Williams (2008) for US equivalents.

[9]Hence the term repo auctions.

[10]The aggregate bid curve in an auction is simply a horizontal sum of individual bid (i.e., demand) curves submitted by all participants in that auction.

[11]An "EONIA swap" is an interest rate swap transaction, where one party agrees to receive/pay a fixed rate to another party, against paying/receiving a floating rate named EONIA (Euro OverNight Index Average) which is an average of all actual overnight unsecured transactions.

alternative to bidding in the repo auctions. After August 9th, 2007, a significant upward shift of all aggregate bid curves is quite evident.

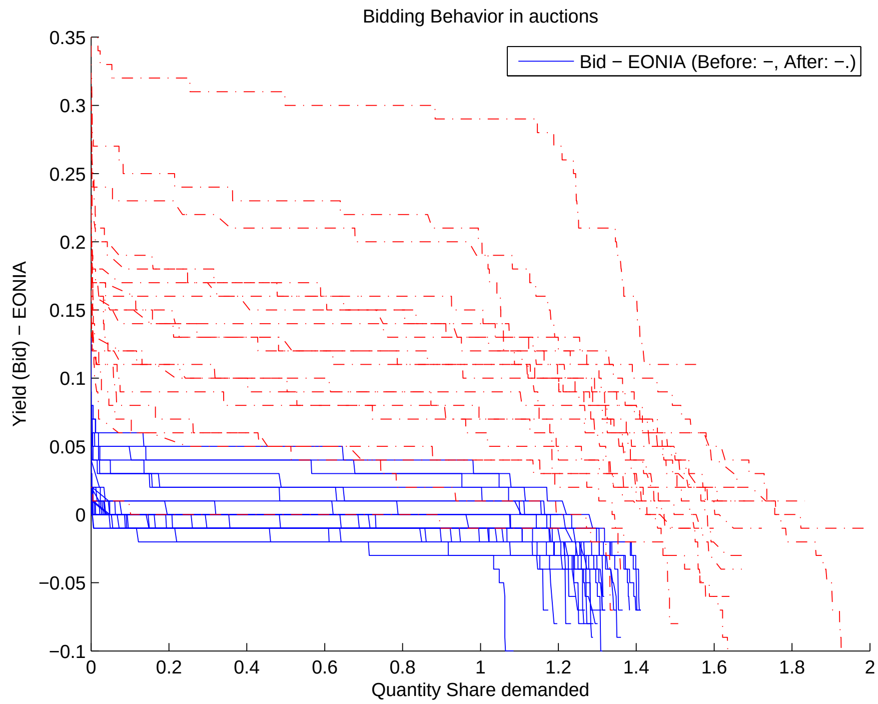


Figure 2: Aggregate quantity-weighted average bid

While the dramatic shift in aggregate bid curves in ECB's liquidity auctions parallels developments in interbank markets, an important result of our analysis is that the distinction between "bids" and "willingness-to-pay" is very important in this market. Although, as we will show in Section 4 and Section 6, virtually all banks' bidding behavior changed dramatically after August 9, this does not necessarily indicate a shift in all banks' *willingness-to-pay* for ECB provided liquidity. Even if some bidders did not experience a change in their costs of short-term funds from alternative sources, presumably due to their solid balance sheets and lack of exposure to problematic assets, these bidders would rationally have to adjust their bids as a best-response to their "distressed" competitors' higher demand for ECB provided liquidity. That is, the shift in bids for ECB liqudity was composed of both a "fundamentals" based shift, based on an increase in the outside funding costs of a subset of banks, and a "strategic" shift, that arose from the best-responses of strategic bidders in a competitive environment. Indeed, we find in Section 6 that for about one third of the participants the observed change in bidding behavior was simply a strategic response. Loosely speaking, while their costs of obtaining short-term funds stayed the same, they increased their bids in order to best-respond to the higher bids of their rivals.

As for the bidders whose willingness-to-pay for ECB provided liquidity increased significantly after August 2007, it is important to understand the determinants of this demand shift. In Section 6.4, we analyze the differences in banks willingness-to-pay for ECB loans based on their country-of-origin in the Eurozone countries. We find significant heterogeneity across member countries, and find that banks from member countries that relied less on ECB funding pre-August 2007 appear to have suffered less from the crisis.

To further investigate what led to the demand shifts at the bank level, in Section 6.5, we use an auxiliary data set on a subset of banks' credit default swap (CDS) rates, and their reserve requirements with the ECB. We provide evidence that this increase in willingness-to-pay for ECB liquidity is linked to a deterioration in credit/default ratings (as measured by CDS rates). We also find that ECB reserve requirements become a more significant determinant of bidding in repo auctions suggesting that access to other liquidity sources became more difficult after August 2007. Moreover, in Section 6.6 we find that banks' willingness-to-pay for ECB loans in the second half of 2007 are predictive of the change in publicly traded banks' stock prices between December 2007 and 2008 – after the "second" liquidity crisis spurred on by Lehman Brothers' collapse. This suggests that bids in ECB auctions contain private information about banks' financial well-being that is not immediately impounded into their stock prices.

Another result of our analysis is that in the period beginning in August 2007, the previously stable relationship between the banks' implied willingness-to-pay and reported interbank rates broke down. In particular, on several occasions after the turmoil, the market clearing interest rate for *collateralized* loans issued through the primary auctions (which constitutes a lower bound on the willingness-to-pay for the marginal bank under normal circumstances) is *higher* than the reported interest rate for the *unsecured* loans issued in the interbank market. This suggests that the reported unsecured interest rates (EURIBOR in the EURO context) failed to reflect the "actual" unsecured borrowing rates (or true market prices) that were faced by a large number of banks in the EURO area. This criticism of LIBOR[12] rates induced the British Bankers' Association (BBA) to publish the consultative paper "Understanding the construction and operation of BBA LIBOR – strengthening for the future" on June 10^{th}, 2008. We pursue several explanations for and implications of this decline in the informativeness of reported market rates in section 6.3.1.

From broader perspective our results suggest that the evolution of banks' willingness-to-pay for liquidity may be useful for many questions policy-makers might be interested in answering. While many of such questions may be answered with balance sheet data, the reliability of such data and its low frequency render the readily available data from bidding in weekly liquidity auction far superior. Recent rapid advances in multiunit auction theory and in empirical methods for modelling of auction markets allow us to recover the willingness-to-pay directly from the bids.[13]

We now move on to describe the growing literature on the financial turmoil in section 2 to provide context for the rest of our paper. We describe the primary repo auctions of the ECB in section 3. In section 4 we describe our data set from these auctions and summarize several interesting facts that these data reveal. We sketch a simple model in section 5, and we use our data in conjuction with our model to recover bidders' willingness-to-pay for ECB loans. For interested readers, we review a more detailed model of a discriminatory auction of a perfectly divisible unit good, its equilibrium characterization and the estimation method which we proposed in our previous work in appendix A.2. In section 6 we present the main results of our estimation and discuss some implications of our findings. Section 7 concludes. Appendix A.1 is devoted to more details about the way ECB conducts its monetary policy and its operations.

2 Turmoil in the Literature

The significance of the financial crisis is perhaps best illustrated by the number of internet blogs by many top economists[14] devoted to it. In winter 2009, almost the whole issue of the Journal of Economic Perspectives has been devoted to the financial crisis. Coval, Jurek and Stafford (2009)

[12]LIBOR, London Interbank Offer Rate, like EURIBOR, is a rate for unsercured interbank loans.

[13]See Athey and Haile (2005) or Hendricks and Porter (2007) for surveys of recent advances in empirical methods and Milgrom (2004) for excellent auction theory overview.

[14]For example, Bob Hall's blog or many articles on Mankiw's or Becker & Posner's blog.

talk about the contribution of the structured financial products to the crisis when the correlation of defaults is ignored. Mayer, Pence and Sherlund (2009) describe the evolution of mortgage defaults in recent years. Brunnermeier (2009) provides a very nice discussion of the origins of the financial crisis. He ties together the worsening balance sheets of financial institutions due to dropping asset prices, drying up of the lending channel as banks become worried aboud access to funds, the associated fear of bank runs and the network effects arising from financial institutions being both lenders and borrowers. Cecchetti (2009) describes the early stages of the crisis from the viewpoint of the central bank. He points out the increase in the interest rate spreads and describes several actions that the FED took in order to fight the crisis.

Some recent papers (for example Taylor and Williams (2008, 2009)) have argued that this increase in the spread between the term[15] swap rates which are used to proxy the expectations of overnight lending rate of financial market participants and the rates for unsecured term loans is likely due to an increase in the counter-party risk. In particular, following the news about the extent of representation of highly risky subprime loans among securities with highest ratings which many banks held in their portfolios, there has been a sudden shift in the probability of default. Looking at the difference between the secured and unsecured loan rates as well, Taylor and Williams argue that indeed the increase in spread seems to be due to this effect.[16]

While the evidence for the increased spread is very convincing, whether this increase is due to counter-party risk or due to liquidity risk, i.e., reluctance of banks to lend liquidity in the secondary market due to their own uncertainty about future liquidity needs, is less clear. In fact, some other papers argued that the increased spread is due to the liquidity risk stemming from increased uncertainty about future liquidity needs of each bank, which in turn increases banks' reluctance to lend long-term (e.g., Wu (2008)).

In a short article, Chari, Christiano and Kehoe (2008) argue that, while there is clear evidence of a financial crisis, some of the often cited sources of this crisis, one of which is the tougher access

[15] 1-week rates for example.

[16] As is the case in the U.S., the secured (EUREPO) and overnight swap rates (EONIA SWAP) are highly correlated in the Euro area. Taylor and Williams (2009) argue that both rates are close to being riskless, and could be considered close to perfect substitutes. Although it is a collateralized rate, there is some risk in EUREPO due to potential problems in the delivery or return of collateral. EONIA swaps are subject to some risk in that one of the parties may default, and the remaining party is subject to the differential in the fixed and overnight components of swap. In our data, EURIBOR-EUREPO spreads and the EURIBOR-EONIA spread are almost perfectly correlated.

to liquidity in the interbank market, are not consistent with publicly available aggregate data. Cohen-Cole et al. (2008) point out that the aggregate figures might be missing a lot of details, but Christiano (2008) mostly disagrees with their arguments. We show in this paper that by looking at aggregate data a researcher might indeed miss the relevant changes in the structure of liquidity demands: while the total demand may have stayed the same, many banks substituted from the secondary (interbank) market to the primary one and the collapse of the secondary market may have important implications for allocative efficiency and credit availability. The increased heterogeneity of values for liquidity in the post-turmoil period and the failure of the interbank market to lead to an efficient allocation of liquidity among banks then renders the primary auctions (or open market operations) of the central banks crucial in improving the performance of the liquidity markets by correcting the misallocation.

Bidding data from repo auctions of the ECB have been previously studied in Bindseil, Nyborg and Strebulaev (2005), who describe many interesting details of this market and compare these auctions to those of treasury bills by studing auctions between June 2000 and June 2001. Among other things, they argue that the common value component seems much less important in the central bank repo auction than in T-bill auctions, which substantiates our using of the private values framework. Unlike them we adopt a structural modeling framework which aims at non-parametric identification of the primitives. A similar approach has been used in Hortaçsu and Kastl (2008) to analyze Canadian T-bill auctions or Chapman, McAdams and Paarsch's (2006) analysis of Canadian Receiver General auctions of cash. While the setting Chapman et al. analyzes is the closest to ours, the objective of their analysis is quite different. Their main interest lies in investigating whether bidders' behavior in these auctions is consistent with best-response assumptions. They found that while violations of best-responses are frequent, the extent of these violations is so minimal (in terms of the expected payoff lost) that assuming that bidders indeed play best-responses may not be a bad assumption. Our approach is to assume bidders play best-responses and our goal is to use the estimated model to analyze the forces behind bidders' choices and to analyze the impact of the financial turmoil by studying the link between the willingness-to-pay in the repo auctions and alternative sources of funding.

3 Primary Auctions of Liquidity in the EURO Area

Our analysis in this paper focuses on the auctions of liquidity, which are part of the Main Refinancing Operations (MROs)[17] of the ECB. They are auctions of collateralized loans with one-week maturity, conducted every week. The main function of the MROs (at least before the turmoil period) is to provide liquidity to the market. They are pivotal in steering interest rates (through the minimum bid rate (MBR)), manage liquidity in markets and signal the stance of monetary policy.

Before each auction, a bank that wants to participate submits bids specifying the rate and the quantity this bank is willing to transact with the ECB at that rate to the NCB[18] of the Member State in which the institution has an establishment (head office or branch). The bids of an institution may be submitted by only one establishment in each Member State. Banks may submit bids for up to ten different interest rate levels and hence a bid in these auctions can be thought of as a demand function. The ECB then collects the bids and determines the maximal rate at which the demand weakly exceeds the supply. All bids for higher rates are satisfied and demands at the marginal rate are rationed proportionally. During the time span of our data set the ECB has used solely the discriminatory auction format, but it has the right to change the mechanism at any time. All winning bidders thus had to pay their full bids (i.e., rates) for the allocated liquidity.

After each auction, the following is revealed about the outcome: % marginal (market clearing) bid rate, allotment at marginal rate, total amount allotted, weighted average allotment rate, total number of participating bidders, minimum rate of all bids, and maximum rate of all bids. Notice that no additional data that would provide information on demands by individual banks are revelead.

The loans obtained in these auctions have to be collateralized. In particular, banks are expected to cover the amounts allotted to them with a sufficient amount of eligible assets (collateral).[19] Penalties can be applied by the NCBs in case of a failure to deliver the collateral. The eligible collateral is broader than collateral generally accepted for loans at the EUREPO rate on the interbank (secondary) market, even more so after the turmoil. Nevertheless the ECB applies

[17]See section A.1.2 in the appendix for more details.

[18]National Central Bank

[19]See section A.1.3 in the appendix for detailed discussion of eligible collateral.

valuation haircuts as risk control measures.

Table 1 shows the relative weight for the categories of eligible assets used by Eurosystem counterparties. It illustrates that banks tend to substitute illiquid collateral (ABS; Uncovered Bank Bonds) for highly liquid collateral (Government bonds).[20] This trend accelerated after the turmoil with a sharp increase in Asset Backed Securities; however it reflects a medium term development that has been ongoing for a while and is not strictly related to the turmoil.

Table 1: Structure of Collateral Pledged Against the MROs

	2004	2005	2006	2007	2008
central government securities	0.52	0.50	0.48	0.46	0.42
regional government securities	0.03	0.03	0.03	0.03	0.03
uncovered bank bonds	0.12	0.14	0.16	0.17	0.20
covered bank bonds	0.16	0.15	0.14	0.12	0.11
corporate bonds	0.09	0.09	0.09	0.09	0.08
asset-backed securities	0.04	0.05	0.06	0.08	0.09
other marketable assets	0.04	0.04	0.04	0.04	0.05
non-marketable assets	0.01	0.01	0.01	0.01	0.02

Now with the relevant background we are ready to describe in detail our data set and go on to estimate a model of bidding in the repo auctions.

4 Data

Our unique data set consists of all submitted bids in 50 regular discriminatory (pay-your-bid) repo auctions of liquidity provided via collateralized loans with 1-week maturity conducted as part of the regular MROs of the ECB between 1/3/2007 and 12/11/2007.

Table 2 offers some important summary statistics of the full sample. On average, there are 341 participating bidders (banks) in an auction. There are 733 unique bidder-identities, which suggests that only about one half of potential bidders participates in any given auction. Participating bidders submit bids with very few steps (price-quantity pairs): only 1.66 on average. The banks demand on average about 1 billion EUR at 3.94%, which is on average about 4 basis points higher than the EONIA rate.

[20]See also Ewerhart and Tapking (2008)

Table 2: Data Summary

Summary Statistics				
Auctions	50			
	Mean	St.Dev.	Min	Max
Bidders	341	28	273	395
Submitted steps	1.66	1.02	1	10
Price bid	3.94	0.22	3.50	4.36
Price bid spread[a]	0.04	0.07	-0.17	0.41
Quantity bid	0.004	0.012	$3 * 10^{-6}$	0.18
Issued Amount (billions €)	259.89	52.77	155	330.5

[a] Spread against EONIA rate.

Table 3 illustrates the change in means and standard deviations following the turmoil of August 2007. The most striking differences are the increase in the number of steps in each bid (from 1.47 to 2.02), the decrease in the amount of liquidity offered for sale (from 292.34 to 202.19 billions EUR) and, most importantly, the increase in the spread between the bids and the EONIA rate (from 0 to 10 basis points). Recall that in a discriminatory auction, a bidder would do the best, if she knew the market clearing rate beforehand and thus were able to submit just a single bid equal to that rate for an amount at which her marginal value equaled this rate. The first difference therefore likely reflects the fact that the bidders were much less certain where the market would clear and thus submitted finer bids.[21] An alternative potential explanation for this phenomenon might be that some bidders simply needed to make sure that they receive at least some minimal level of liquidity in the primary market and therefore they submitted inframarginal bids for which they were willing to pay a premium over the market clearing rate. Both of these explanations may also be consistent with the observed increase in the spread between the bids and EONIA. To distinguish these two potential explanations, we would need to know what the marginal value of that bidder looked like when placing the bids. Obtaining estimates of these marginal values is thus one of the main goals of this article.

After August 2007 bids become much more dispersed as shown by the aggregate bid curves depicted with dashed-dot lines (-.) in Figure 2. The aggregate bid curve in each auction also

[21] Figure 13 shows that there is a clear first-order stochastic dominance relationship between the empirical cumulative distribution functions before and after the turmoil.

Table 3: Data Summary: Before and After August 2007

Summary Statistics				
	Mean		Std Dev	
	Before	After	Before	After
Bidders	348.6	328.1	20.88	34.37
Submitted steps	1.47	2.02	0.73	1.34
Price bid	3.80	4.13	0.20	0.06
Price bid spread[a]	0.00	0.10	0.02	0.08
Quantity bid	0.004	0.005	0.009	0.014
Issued Amount (billion €)	292.34	202.19	1.42	4.51

[a] Spread against EONIA rate.

becomes much steeper relative to the aggregate bid curves before the turmoil which are depicted as solid lines. We hypothesize that access to affordable loans in the secondary market became much tougher for some banks, which can also be thought of as an outward shift in the marginal value for the liquidity obtained in the primary market. This could be due to the above mentioned increase in the counter-party risk, but there is another potential source that emerged during the turmoil, stemming from the lender's uncertainty about its future liquidity needs - leading to unwilingness to lend in the term interbank market.[22] The latter uncertainty is related to the inherent difficulty for banks to evaluate even their own assets, uncertainties related to potential drawings from committed credit lines, set-backs in securitization programmes, and in extreme cases potential bank runs (by depositors and/or investors) triggered by rumours.[23]

5 Model and Estimation Framework

In order to obtain estimates of the marginal values which would rationalize the observed bids we estimate a model of bidding in these discriminatory auctions. Consider first the following simple model of bidding in the primary auction, which links the estimated marginal values to the secondary market secured and unsecured interest rates. Suppose bank i has a liquidity need (possibly due to

[22]Similar incentive to keep liquid assets is in Holmstrom and Tirole's (1998) model of liquidity. In their model enterpreneurs who want to continue a project to a later stage might find themselves sometimes with insufficient returns in the intermediate stage and thus might have a need for liquid assets in order to keep the project afloat.

[23]In a recent paper, Tapking and Eisenschmidt (2008) provide a simple theoretical model for the liquidity risk premia in unsecured interbank transactions which tries to address this channel.

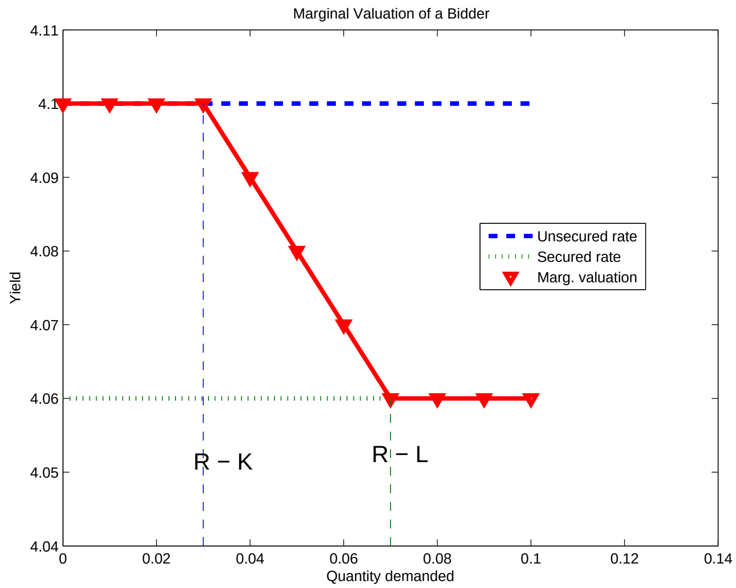
a reserve requirement, to improve its balance sheet or to close a funding gap) of R_i. This has to be fulfilled through 3 alternative channels: 1) ECB primary auctions, 2) unsecured interbank lending, or 3) secured interbank lending.[24,25]

We assume that these methods for fulfillment are perfect substitutes but access to them is limited based on collateral availability. In particular, bank i has $K_i \leq R_i$ units of collateral that is acceptable by the ECB, and $L_i \leq K_i$ units of collateral acceptable by secured interbank lending counterparties. The anecdotal evidence is that, after the subprime crisis, L_i became noticeably less than K_i. Bank i faces interest rate of u_i in the unsecured interbank market and s_i in the secured interbank market, where $u_i > s_i$. In our application, we assume that $\{R_i, K_i, L_i, u_i, s_i\}$ are independent (conditional on variables commonly observed by banks) across banks. The marginal value for obtaining liquidity in the auctions run by the ECB therefore can be thought of as depicted in figure 5. A bank with liquid collateral that is sufficient to cover its needs should not have higher value than s_i, a bank that has no collateral that can be pledged in the interbank repo market should have a marginal value at the bank-specific unsecured rate u_i. For a bank with collateral that is partially liquid (for example one that requires substantial haircuts if used in the interbank repo market), the marginal value should be between u_i and s_i. Later in our application we will work with quantity weighted average marginal value, which should be, by the above arguments, a convex combination of s_i and u_i. We thus define a parameter, α_i, as the weight on the secured rate: a bank with high α has a lot of liquid collateral, as $\alpha \to 0$, bank's usable collateral in the interbank market approaches zero as well.

[24] We abstract from other ways of obtaining liquidity. Managing the maturity mismatch between assets (long-term) and liabilities (short-term) is the essence of banking. Before the crisis a variety of instruments allowed banks to fund their assets without major constraints. Short-term funding was available in the form of interbank loans, issuance of Certificate of Deposits (CDs) and central bank refinancing; longer-term funding was available from bond issuance (covered or uncovered) and through securitization. The securitization and the interbank funding channels were among the most severely disrupted sources of liquidity immediately after August 2007. Bond issuance without government guarantees was also impaired.

[25] The interbank market operates to a large degree as an over-the-counter (OTC) market, for which (to best of our knowledge) there is hardly any transaction level data that could be used for our purposes. The impact of liquidity shocks and other frictions on prices in OTC markets has been studied in Duffie, Gârleanu and Pedersen (2007) whose model of OTC market is based on the search and bargaining model proposed in Duffie, Gârleanu and Pedersen (2005). They provide conditions under which asset prices are adversely affected by frictions in the OTC market, such as increased difficulty to find a counterparty, for example.

Figure 3: Marginal Value for Liquidity in ECB Auctions



5.1 Model of Bidding and Econometric Framework

The previous section provides a simple theory of where banks' marginal valuations for ECB loans may come from.[26] We now describe how banks will bid in the auctions. The ECB allows bidders to place multiple price/quantity bids; bidding, in effect, demand schedules. Our model is therefore based on Wilson's (1979) share auction model, in which bidders compete for one unit of a perfectly divisible good and their choice of quantity is continuous. We view this model as appopriate for our setting as the amount of credit to be sold in each auction is over €2 billion and the minimum bid increment is only €100,000.

Kastl (2008) analyzes a variant of Wilson's model with bidding in step functions, which is the appropriate modification also for our application. He proves that an equilibrium of a discriminatory auction in distributional strategies in this constrained game exists when signals are independent and price is assumed to be continuous and provides its characterization via a set of necessary conditions for each step k at which the marginal valuation function is continuous in q given by (1)

[26]See Ewerhart, Cassola and Valla (2009) for an alternative theory model.

below. The model and its assumptions are formally spelled out in section A.2 in the appendix.

$$v\left(q_k, s_i\right) = b_k + \frac{\Pr\left(b_{k+1} \geq p^c | s_i\right)}{\Pr\left(b_k > p^c > b_{k+1} | s_i\right)}\left(b_k - b_{k+1}\right) \tag{1}$$

Equation (1) serves as the main identification equation in our analysis and it therefore deserves more discussion. This equation simply describes the equilibrium relationship between bids and values. In our earlier discussion, we tied the bid + markup term to the bank's "outside options" of procuring liquidity through secured and unsecured interbank markets.

The intuition for the underlying trade-off is quite similar to that in the single-unit first-price auction. Notice that we can rewrite the optimality conditions as $\Pr\left(b_k > p^c > b_{k+1}|s_i\right)\left(v\left(q_k, s_i\right) - b_k\right) = \Pr\left(b_{k+1} \geq p^c|s_i\right)\left(b_k - b_{k+1}\right)$. This equation simply says that the marginal loss of surplus due to decreasing the demand at price b_k whenever the k^{th} step is the marginal step in i's demand (and thus market clearing price must be between b_k and b_{k+1}) should be traded-off against the possible gains when the k^{th} step is inframarginal (and thus market clearing price must be weakly lower than b_{k+1}) and thus by shifting some demand to the subsequent $(k+1)^{st}$ step would decrease the payment by the difference between the bids (times the quantity shifted). It is important to emphasize that these necessary conditions given by (1) have to hold at each step k. Therefore, we do not need to directly model the choice of the number of steps, $\hat{K}\left(s_i\right)$, that bidder i submits. Notice that if signals were independent, the probabilities in (1) would not be conditional on s_i as knowing one's signal would not be informative about the distribution of rivals' signals, but the probabilities would still be, of course, a function of the submitted bid curve.

Since in practice, the continuity in q of the marginal valuation function might be questionable at the last step, to identify the marginal value corresponding to the last step in a bid function we use the optimality equation with respect to bid given by equation (A-3) in the appendix.

Using these necessary conditions, we obtain point estimates of marginal values at submitted quantity-steps nonparametrically using a resampling method as described in our earlier work.[27]. The resampling method that we employ is based on simulating different possible states of the world

[27] See Hortaçsu and Kastl (2008) for formal treatment of the estimation and Athey and Haile (2005) for a recent survey of nonparametric estimation techniques for auction data.

(realizations of the vector of private information) using the data available to the econometrician and thus obtaining an estimator of the distribution of the market clearing prices. It works as follows:

Suppose there are N potential bidders that are (ex ante) symmetric. Fix a bidder's bid. From the observed data, draw (with replacement) $N-1$ actual bid functions. This simulates one possible state of the world from the perspective of the fixed bidder, a possible vector of private information, and thus results in one potential realization of the residual supply. Intersecting this residual supply with the fixed bid we obtain a market clearing price. Repeating this procedure a large number of times we obtain an estimate of the full distribution of the market clearing price conditional on the fixed bid. Using this estimated distribution of market clearing price, we can obtain our estimates of marginal values at each step submitted by the bidder whose bid we fixed using (1).

Hortaçsu and Kastl (2008) show that this estimator is asymptotically normally distributed and well-behaved so that its asymptotic distribution can be approximated by bootstrap, which is how we obtain standard errors also in this application.

5.1.1 Supply Uncertainty

While in the pre-turmoil period the actual amount of liquidity allocated in the auction by the ECB differed only slightly from the pre-announced supply, as figure 18 illustrates, the deviations became quite substantial in the post-turmoil period. We assume that bidders rationally expected the ECB to deviate from the announced benchmark. To incorporate this feature into our estimation framework, we use the empirical distributions of deviations from the pre-announced supply in the pre- and post-turmoil period and at each iteration of our resampling algorithm, we resample independently from the corresponding empirical distribution of supply deviations. More details about the way supply in the weekly repo auctions is determined are provided in section A.3 in the appendix.

5.1.2 Asymmetric bidders

Since one of the goals of this paper is to identify bidders (banks) that have been likely hit harder by the financial turmoil than their rivals, in the sense that their value for liquidity obtained in the primary market increased, assuming that all banks are ex-ante symmetric might not be appropriate and doing so might bias the results. Instead, we adopt an iterative procedure and estimate an asymmetric model with two groups of banks as follows: In the first step we estimate the model assuming ex-ante symmetry of bidders. In the second step, we use the estimated values to find a subset of bidders which experienced an increase in their estimated values for liquidity in the post-turmoil period. Recall that one of our goals is to separate bidders that experience financial distress, which in our model is captured as a shift in the distribution of marginal values - perhaps in the sense of first-order stochastic dominance, but also possibly accompanied with a shift in the support. There are multiple ways how to check for this shift, and the test we employ is based on comparing means of the distributions before and after turmoil for each bidder. This test is operationalized by regressing the quantity-weighted average of the marginal value estimates (normalized by EONIA to take out the level effect of interest rates[28]) on the turmoil dummy separately for each bidder. If the estimated coefficient on the turmoil dummy is significant at 5% level, i.e., if the mean marginal value increased, we classify this bidder as one who experienced financial distress in the post-turmoil period. In the third step of our algorithm we re-estimate the model using the two groups of bidders, where the resampling method is modified accordingly to allow for two groups of bidders whithin which they are symmetric. In the fourth step we again estimate which subset of bidders experienced an increase in their values using the estimates from the asymmetric model and if this subset coincides with the two groups used in step 3, we stop, otherwise we repeat step 3 again.[29] In practice, we stop the algorithm when weakly less than 5 bidder identities switch groups.[30] We are able to classify 482 bidder identities out of 733 appearing in our data. The remaining bidder identities do not submit bids both before and after turmoil.

[28]See Piazzesi (2003) for a thourough discussion of recent literature on the structure of interest rates.

[29]While we do not have a formal proof of whether this method converges, if it does, it is easy to see that the resulting estimates constitute consistent estimates of primitives of the asymmetric model. In the actual application it turns out that already after very few iterations, the two groups of bidders are very stable - both in terms of size and in terms of identities of bidders contained in each of them. The asymmetry therefore seems not to play as an important role in the estimation stage, which is probably due to the large number of participants. We also experimented with a random initial assignement of bidders into the two groups and after very few iterations we obtained virtually the same bidder groups as those arrived at when starting with the symmetric model.

[30]Varying this criterion has virtually no effect on the estimated marginal values.

6 Results

The change in bidding behavior documented in figure 2 is not necessarily a direct consequence of the turmoil making it harder to access liquidity in the interbank market. In particular, two effects are at play. On the one hand, for some banks the primary market may have become the main source of liquidity to cover their needs, and therefore their value for liquidity offered in these primary auctions may have risen, which in turn may have caused the upward shift in their individual bid curves. On the other hand, when some bidders change their bidding strategies due to a change in their values for the auctioned good, in equilibrium it is very likely that all other bidders will change their bidding strategies as well since they need to be playing best responses against a different set of bidding strategies. Our first main goal is thus to separate the strategic adjustment effect, i.e., bidders adjusting their bidding strategies in response to changes in the strategies of their rivals, from the effect of changing values which might indeed signal financial distress for a bank. To achieve this goal, we estimate the model of bidding in these auctions outlined in section 5 and described in more detail in appendix A.2.

Figures 4 and 5 depict an example of a randomly chosen bidder with the associated estimated marginal values for two auctions - one before and one after the turmoil. There are two interesting observations: (i) the quantity that this bidder demanded increased substantially - from less than 2% of the supply before the turmoil, to over 3% of the supply after the turmoil[31] and (ii) this bidder likely wanted to be fairly certain that she gets allocated at least 3% of the supply after turmoil since her bid for that amount exceeded the eventual market clearing price substantially (by 4 basis points) and, moreover, her marginal value decreased by about 2 basis points between her highest and lowest bids after turmoil. Recall that if a bidder knew with certainty that the market would clear at a price p^* in a discriminatory auction, then the optimal bidding strategy would be to submit only one bid at this price and for a quantity, such that the marginal value of the expected allocation after rationing would be equal to p^*. Finally, notice that the estimated marginal value before the turmoil is just slightly higher than the EONIA swap rate (which corresponds to 0 on the vertical

[31] Recall that the supply declined by about one third after the turmoil, which makes the demand increase perhaps not as large, but still an increase of 0.3 percentage points of the supply demanded post-turmoil amounts to about €600 million.

axis). This suggests that indeed buying the fixed leg of the SWAP and borrowing overnight was an option for many banks. After the turmoil, however, the estimated marginal values are significantly above the EONIA swap rate, suggesting that this particular bank valued the liquidity obtained in the repo auctions of the ECB more, perhaps because its access to the EONIA rate may have been limited and/or perhaps because it did not have enough high-quality collateral to participate in the collateralized interbank market to obtain loans at EUREPO rate. This change in values and thus indirectly the implied ability of an individual bank to access liquidity in the interbank market would be missing if we were to analyze aggregate data such as the study of Chari, Christiano and Kehoe (2008).

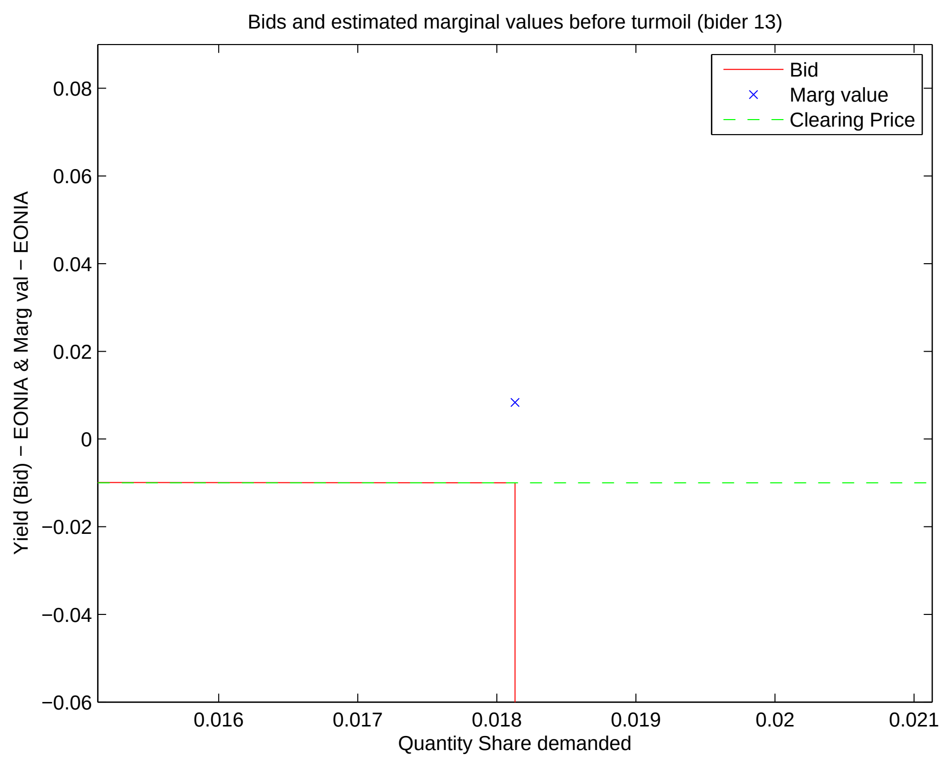


Figure 4: Bid and Estimated Marginal Value (Before Turmoil)

Overall, we find a profound effect of the August 2007 turmoil on marginal valuations that bidders attach to liquidity offered for sale in the primary markets. Figure 6 illustrates this effect in more detail. The solid lines depict estimated aggregate (i.e., horizontal sum of) marginal valuation

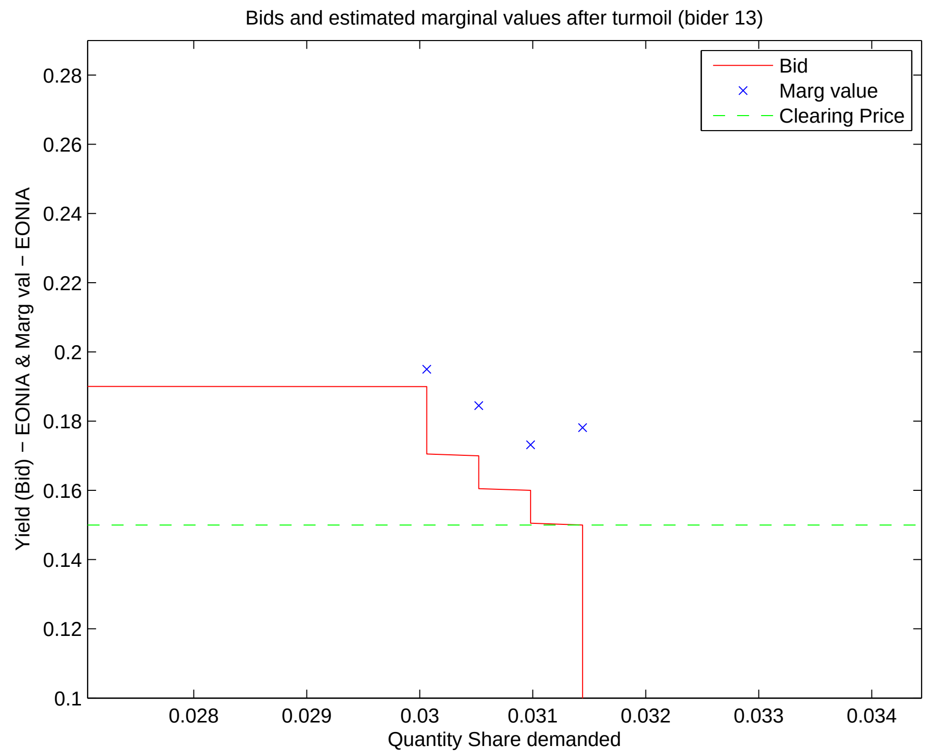


Figure 5: Bid and Estimated Marginal Value (After Turmoil)

curves before the turmoil (normalized by subtracting the EONIA swap rate), whereas the dash-dotted lines (-.) depict the estimated aggregate marginal valuation curves after the turmoil of August 2007. It is evident that an outward shift of marginal values (towards north-east) has taken place, which suggests that at least for some bidders the liquidity provided in the primary market became very valuable relative to the period before August 2007.

To illustrate this effect further, consider figures 9 and 10 which depict the aggregate bid curves and aggregate marginal valuation curves for two auctions - one before and one after the turmoil. It again clearly illustrates that the EONIA swap rate which played a role of a reference point for bidding in the pre-turmoil period most likely no longer served this role after the turmoil. More importantly, the amount of shading (the area between the aggregate marginal value and the aggregate bid curves) increased in most auctions substantially. For example, at the market clearing price (i.e., where the vertical line at $Q = 1$ intersects the marginal value and bid curve), the amount

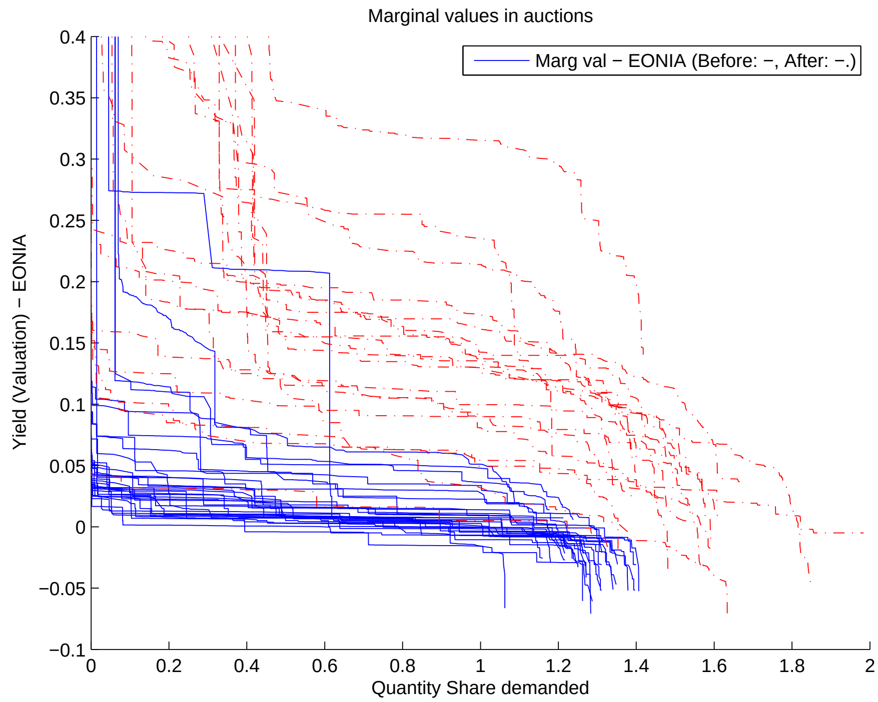


Figure 6: Estimated Aggregate Marginal Valuation Curves

of shading in figure 9 is less than 1 basis point, whereas in figure 10 it increases to almost 3 basis points. This is a consequence of the change in the slope of the aggregate bid curves and hence of increased market power of marginal bidders and/or uncertainty about the market clearing price. More importantly, in auction 32 before turmoil the bidding is concentrated on the EONIA and repo rates and the market clears exactly at the repo rate. After turmoil (in auction 44), however, neither EUREPO, EONIA, or EURIBOR seem to be a focal point of bids. Moreover, the market clears significantly above all three rates.[32]

6.1 Identification of "Distressed" Bidders

Figure 7 depicts the estimated quantity-weighted average marginal values in each auction normalized by subtracting the corresponding EONIA swap rate (a very similar pattern obtains if we

[32]Since the goal of the ECB is to target the overnight interest rate, of which the 1-w EONIA swap rate is an expectation, this suggests that the ECB might have faced some problems with achieving its objectives in the post-turmoil period.

subtract the EUREPO rate). The emerging pattern again suggests that the (normalized) marginal values for liquidity provided in the primary market increased substantially following the turmoil in August 2007. In fact, it still seems to be increasing, reaching in the most recent auctions in our data over 20 basis points premium over the EONIA swap rate. Even more importantly, the marginal values have become quite heterogeneous which is evidenced by the increased slope.

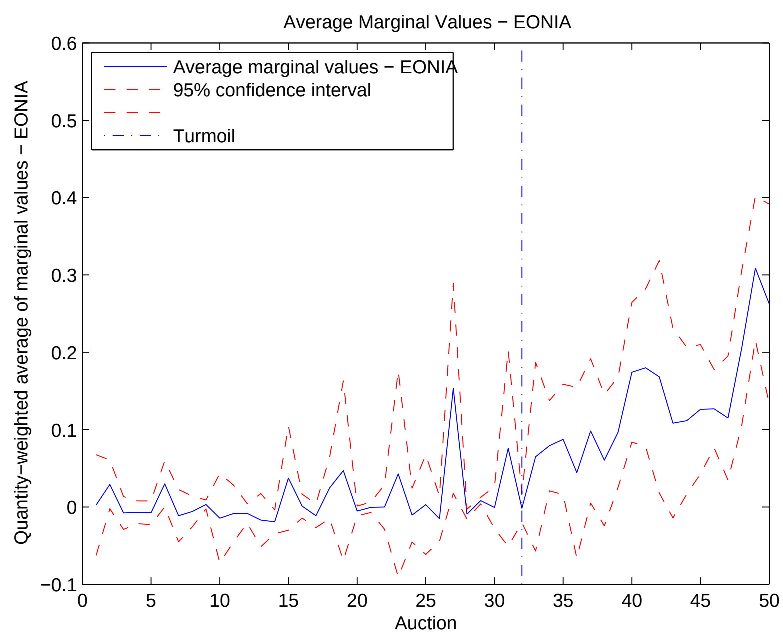


Figure 7: Quantity-weighted average marginal values (across all bidders)

Having estimated the marginal values for each bidder before and after the turmoil, we can now look for the effect of the turmoil on these values. In particular, we regress the quantity-weighted estimates of marginal values for each bidder on a turmoil dummy. Figure 8 plots the histogram of the significant coefficients from these regressions. For almost 100 bidders the (normalized) marginal values have risen by more than 20 basis points in the post-turmoil period. This exercise reveals another important point: the turmoil seemed to be accompanied by an increase in marginal value for liquidity in the primary market for about $\frac{2}{3}$ of the participants, whereas the remaining $\frac{1}{3}$ experienced no significant increase. Our conclusions might be quite different if we base the analysis solely on bids. Running the same type of regressions, but using quantity-weighted bids (again normalized by EONIA) rather than marginal values results in significantly positive relationship for virtually all bidders. Table 4 shows that the predictions differ for over 20% of the banks. Given the amounts that are often mentioned in connection with helping the struggling banking sector, whether or not 20% of banks seem to be healthy might potentially be quite important.

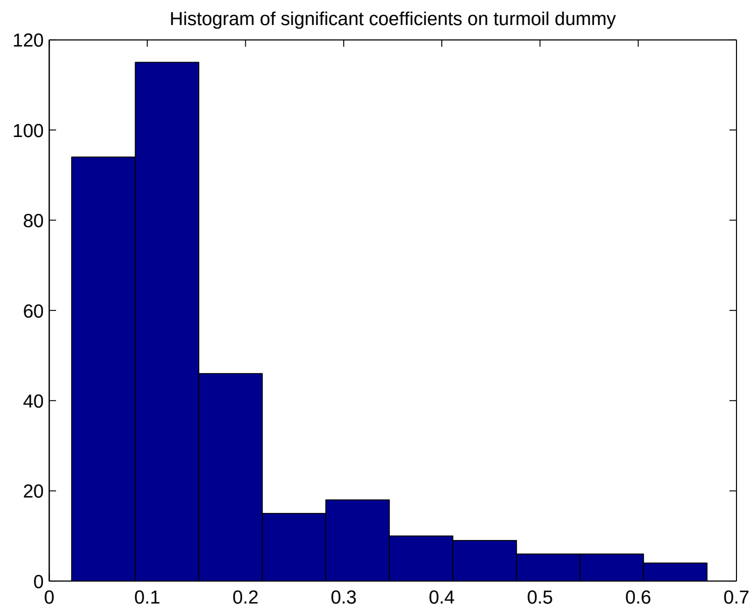


Figure 8: Histogram of Significant Turmoil Effects

Table 4: Predicting Potential Problems

Based on		Bids	
		Yes	No
Values	Yes	326	5
	No	96	55

As a placebo test of the last exercise, we also tried focusing exclusively on the time period before the turmoil (we observe 32 auctions before the turmoil in our data) and splitting this subset of data into two halves, before and after auction 16. Regressing bids and values, respectively, on a dummy for auctions $16 - 32$ results in both data on bids and values showing no effect for 398 banks, both exhibiting a significant effect for 6 banks, and 19 and 20 banks, respectively, seem to have been significantly affected based either on bids or on values data, but not both. This exercise suggests that the difference in predictions based on values and bids reported in Table 4 appears likely not by chance. In fact, it suggests that the turmoil had an important effect which caused significant changes in bids for most banks, but the underlying values actually changed only for a smaller subset of banks.

Figure 15 shows a histogram of participation for bidders for whom the turmoil effect on marginal values is significant and larger than the median significant effect. It clearly demonstrates that the most significantly affected bidders are also the most frequent participants in these auctions. The same pattern emerges when we look at participation just in the pre-turmoil period.

On the other hand, figure 16 shows that bidders whose values have not been significantly affected by the turmoil exhibit fairly uniform participation. On average such a bidder participates in about 23 auctions out of 50 in our sample, with the median participation being 24.

6.2 Degree of Shading

As we have seen, the turmoil in the financial markets increased both the variability of bids and the variability of marginal values. Due to more variation in bidding strategies, the uncertainty about where the primary market would clear also increased. Using our estimates of marginal values, we now examine how the turmoil affected the degree of shading, where shading is defined as the difference between the marginal value and the bid. Using our estimates, the average amount of shading over the whole sample period was about 6.6 basis points with a standard deviation of 20 basis points. Looking at shading before and after the turmoil offers a different picture, however. In particular, the mean shading before the turmoil was only about 4 basis points with a standard deviation of 11.5 basis points. After the turmoil, the mean shading increased to 11.2 basis points with a standard deviation of 30.5 basis points.

The increased variability of shading supports our finding that some bidders were likely affected by the subprime crisis significantly more than others. Regressing the estimated shading on the turmoil dummy reveals that for 99 bidders, the turmoil resulted in a significant change in the amount of shading. For 7 bidders, shading decreased by an average of 2 basis points, while for the

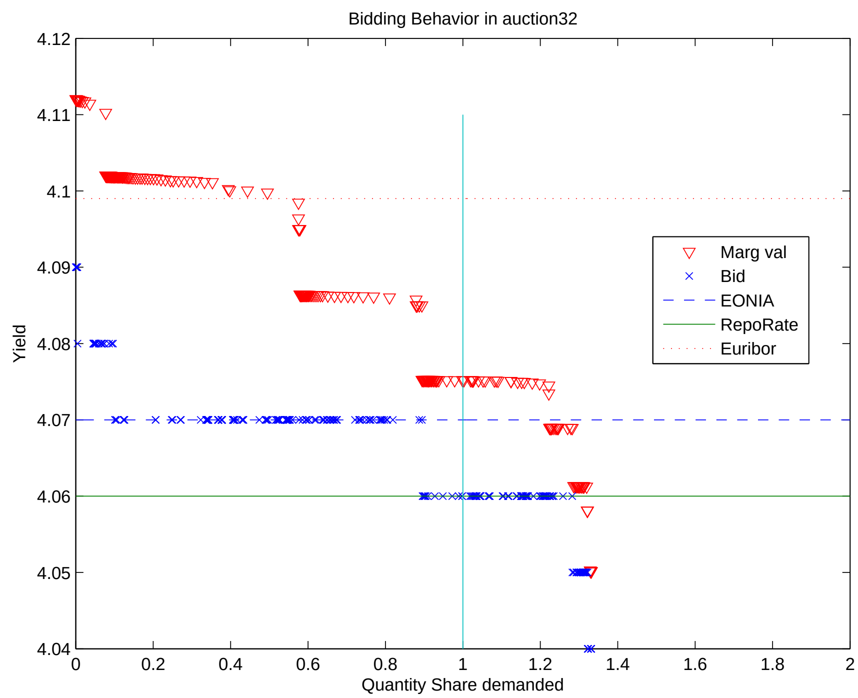


Figure 9: Aggregate Bid and Estimated Aggregate Marginal Values Curve (Before Turmoil)

remaining 92 bidders it increased on average by over 18 basis points.

6.3 Bidders' Marginal Valuations and Secondary Market Rates

Our application is also naturally suited to subjecting the estimates from the structural model to a quick reality check. In particular, as we motivated in section 5, the bid plus markup values of each bank should lie between the fully unsecured lending rate (the most risky one) and the risk-free rate whenever these rates reflect the true market clearing prices. We will use EURIBOR as the unsecured lending rate and EUREPO as the risk-free as only the highest quality collateral (such as government treasury bills) may be used against loans obtained at this rate.[33] Indeed, in figure 9 the estimated marginal values are for the most part bounded from above by EURIBOR rate and from below by EUREPO. This suggests that the estimates produced by our structural model are reasonable. In many auctions in the post-turmoil period, however, this relationship fails (see figure 10). In particular, as figure 11 illustrates there are many auctions which clear at rates that are

[33]Results are similar if we use the EONIA SWAP rate instead of the EUREPO.

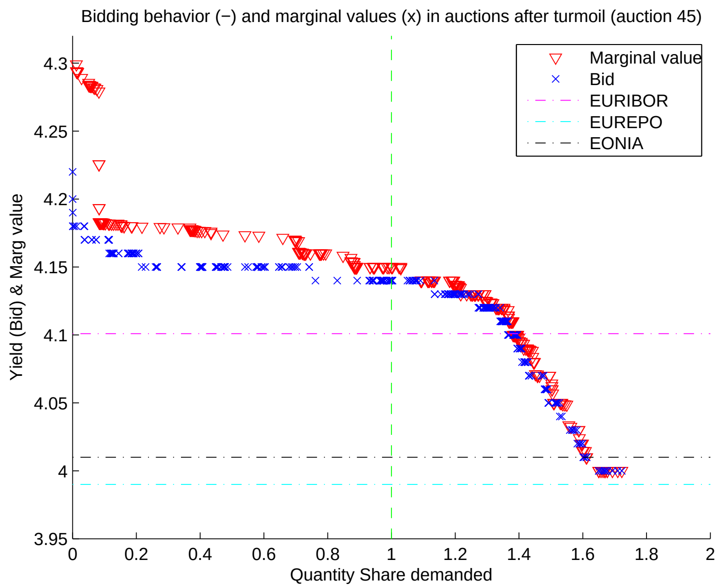


Figure 10: Aggregate Bid and Estimated Aggregate Marginal Values Curve (After Turmoil)

above the unsecured rate (EURIBOR) which suggests that this rate is not the rate at which any bank can borrow.

We used our estimates to ask what α_i's would make the convex combination of the secured rate, EUREPO, and the unsecured rate, EURIBOR, equal to the estimated values. To do this, we use the (quantity-weighted average) estimates of bid+markup/marginal values. This hypothetical exercise therefore assumes that everybody could get a loan at the reported unsecured rate, which is, however, highly unlikely. If that was the case, our estimates of α should lie between 0 and 1, yet we quite often obtain negative values. This suggests that the unsecured interest rate that would rationalize banks' marginal value in the primary auction lies above EURIBOR - the reported unsecured rate – which suggests that these banks could not borrow at this rate, a fact that we will provide further support for in section 6.3.1. Restricting attention to $\alpha \in (-1, 1)$ and taking the mean of α_i across all bidders pre-turmoil, we get 0.17, with a median of 0.29. In the post-turmoil period, the average α decreased to -0.01, and the median to -0.02 which suggests that the average bank did not have usable collateral in the interbank market, and many could not borrow unsecured at EURIBOR, either.

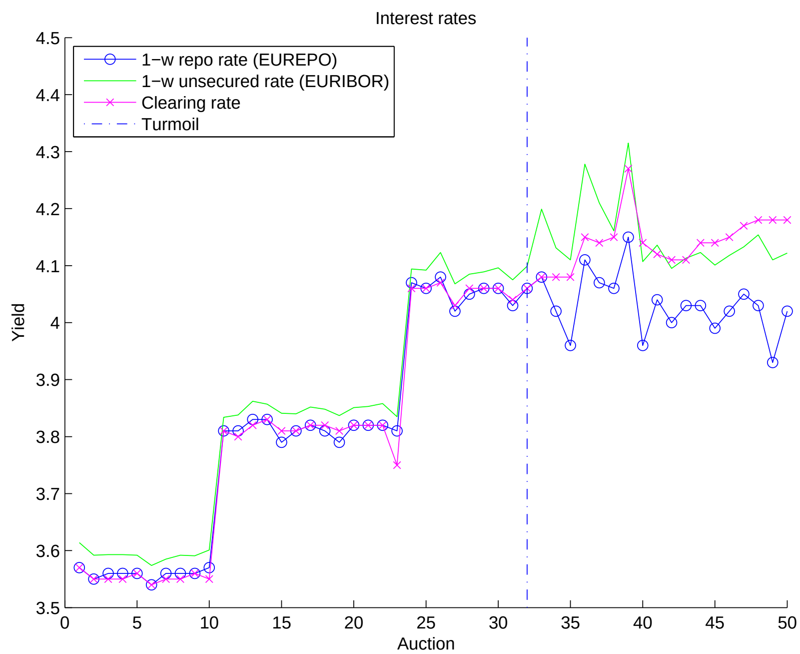


Figure 11: EUREPO, EURIBOR and primary auction clearing rates

A more interesting finding obtains, however, when we decompose these changes in the hypothetical collateral structure based on our classification of bidders: the ones that we labeled as financially distressed after the turmoil (due to a significant increase in marginal values) see a change in mean α_i from 0.18 to -0.02 and the median α_i decreases from 0.28 to -0.04. This suggests that indeed the bidders who we label as significantly affected suffered from a big hit in the way their collateral pool was valued in the secondary market. The "non-distressed" bidders' mean α in fact even slightly increases from 0.466 to 0.474, but the median decreases from 0.18 to 0.10.[34]

In our second exercise we abandon the assumption that everybody can get a loan at the unsecured interest rate and instead compare directly the estimated v_i's and the published secured and unsecured rates at the time of the auction. We normalize our results by dividing by the number of auctions (since we have 32 auction pre-turmoil and 18 post-turmoil). Averaging across all auctions,

[34] Recall that we were able to classify only 482 bidders (out of the total of 733 identities appearing throughout our sample). While we have estimated α_i also for the remaining bidders as we have estimated their marginal values whenever they submitted a bid, they did not submit both pre- and post-turmoil bids, and therefore our procedure cannot classify them. This explains why the reported means of both the insignificantly and significantly affected bidders lie above the overall mean α across all bidders.

we have 156 bidders per auction whose values exceed the unsecured interest rate, EURIBOR, and 184 whose values fall short of it. We find that before turmoil, about 138 bidders have values higher than the reported EURIBOR, which suggests that even before turmoil not every bank was able to borrow at the reported unsecured rate. After turmoil, this number increases by almost 40% to 189 bidders per auction! Given that on average there is slightly more than 330 participants in an auction, this means that over 50% of participating bidders cannot transact at the published EURIBOR. Again decomposing this increase, we found that among the significantly affected bidders, the number increased from 92 to 137, while for insignificantly affected bidders it even slightly decreased from 34 to 33. Similarly, the number of bidders whose estimated marginal value falls short of the unsecured rate, $v_i \leq u$, drops from 209 pre-turmoil to 138 post-turmoil. This change is mainly due to changes among the bidders who have been significantly affected by the turmoil: there are 158 such bidders per auction pre-turmoil and only 93 post-turmoil, whereas among the insignificantly affected ones the drop is only from 38 to 34.

We can also compare estimated marginal values with the secured rate in the secondary market, s (EUREPO). Doing so, we find that for over 322 bidders in an auction $v_i \geq s$ (325 pre-turmoil and 318 post-turmoil), while for only 18 the reverse is true. This suggests that s indeed places a lower bound on the marginal value of liquidity obtained in the primary market.

6.3.1 Does the EURIBOR provide an accurate view of interbank lending?

As we found above, many of the marginal valuations, especially in the post-turmoil period, suggest that the EURIBOR is not representative of the unsecured interest rate at which many banks can borrow. Indeed, we have even more direct evidence for this from the fact that several auctions in the latter part of our sample cleared above the EURIBOR. Figure 11 is a clear indication that there must have been excess demand for uncollateralized loans at the EURIBOR rate. Thus, evaluation of policy actions based on levels or changes of secured and unsecured interest rates (such Taylor and Williams (2008, 2009), Wu (2008)) may be more problematic than may initially appear. The main source of the problems is that the used rates may not necessarily reflect market clearing prices and, moreover, might not even be comparable over time when a crisis such as the subprime turmoil hits the economy.

Since the EURIBOR (or its counterpart, LIBOR) also play a crucial role in anchoring most of the consumer loans, such as mortgages, it is important to understand why this rate may have failed to reflect a market clearing price. The first potential explanation is that the EURIBOR is not actually a market clearing rate by virtue of its construction. Indeed, the EURIBOR is not based on actual transactions, but on a survey of a subset of banks: "A representative panel of banks provide daily quotes of the rate, rounded to two decimal places, that each panel bank *believes* one prime bank is quoting to another prime bank for interbank term deposits within the euro zone." Note that the EURIBOR is based on the declared beliefs of banks regarding market transactions, and that the rate pertains to transactions between a selected group of banks with superior credit ratings. Thus, in times of uncertainty, it is likely that the EURIBOR will not accurately represent the unsecured loan rates available to a large number of non-prime banks.

A second and related explanation is that of a market failure in the form of credit rationing due to increased informational asymmetries after the turmoil as in the model of Stiglitz and Weiss (1981). We might thus expect rationing of unsecured loans at the reported rates, with the unfulfilled demanders seeking liquidity at the ECB repo auctions instead. However, the market for unsecured loans may have failed to function due to reasons other than informational asymmetries, especially since credit rationing equilibria are typically difficult to generate quantitatively (Arnold and Riley (2008)).[35]

All of these factors suggest that the EURIBOR is likely not a reliable indicator of the severity of demand shifts in the money markets. In the next section, we will utilize the disaggregate bidding data to analyze the demand shifts in more detail.

[35] Brunnermeier (2009) argues that the troubles in the interbank lending market in 2007 is due to the precautionary hoarding by individual banks. He argues that banks funding highly leveraged investment funds (who bet on asset-backed securities) became more worried about these funds drawing on their credit lines. This increased each bank's uncertainty about their own liquidity needs. At the same time, banks became more uncertain as to whether they could rely on the interbank market, as it was not known to what extent other banks faced similar problems. Thus the supply of liquidity decreased and demand for liquidity increased at the same time, driving up interbank rates. However, although this provides an explanation as to why the EURIBOR-EUREPO spreads increased, it does not explain why the primary auction rate for secured loans exceeded the EURIBOR rate.

6.4 Cross-country differences in banks' marginal values

Our data allows us to identify the country-of-origin for the bidders in our data set. Although we are not allowed to report the identities of countries, it is instructive to investigate whether banks in different countries in the Euro system were affected differently by the crisis.

In Figure 12, we plot the mean α values across bidders before and after the crisis by country. Recall that α is close to 1 if a bidder's marginal value for ECB loans is close to EUREPO, the interbank secured interest rate, and close to 0 if the bidder's marginal value is the EURIBOR, the interbank unsecured interest rate. An α value that is negative indicates that the bidder has marginal value above the reported EURIBOR; i.e. the bidder can not satisfy its funding needs at the EURIBOR rate.

In the figure, we see that there is considerable heterogeneity across countries both pre and post-crisis. First, notice that pre-crisis, some countries' banks have α values close to 1, while others have banks with α values close to zero (in one case, slightly negative). There is high positive correlation between pre- and post-crisis αs; the Pearson correlation coefficient is 0.9. After the crisis, α values appear to have declined across the board, with the low α countries' banks being pushed into the negative α zone.

Due to non-disclosure requirements, we can not investigate how country characteristics, especially attributes of their respective financial systems, are correlated with the funding costs of their banks. However, the above exercise may be instructive in that α values are quite highly correlated before and after the crisis: the countries whose banks are likely to suffer are those whose banks had high liquidity funding costs to begin with.

6.5 Sources of bidders' private values

We motivated our model with private values by arguing that banks' values for liquidity obtained in the primary market is likely driven to a large extent (i) by the collateral value of each bank's asset portfolio and (ii) by the private information of each bank about its liquidity position, i.e., its needs to satisfy the prescribed reserve requirements. To test these assumptions, we complement our data set and our estimates of marginal values with additional detailed bank-level data for a

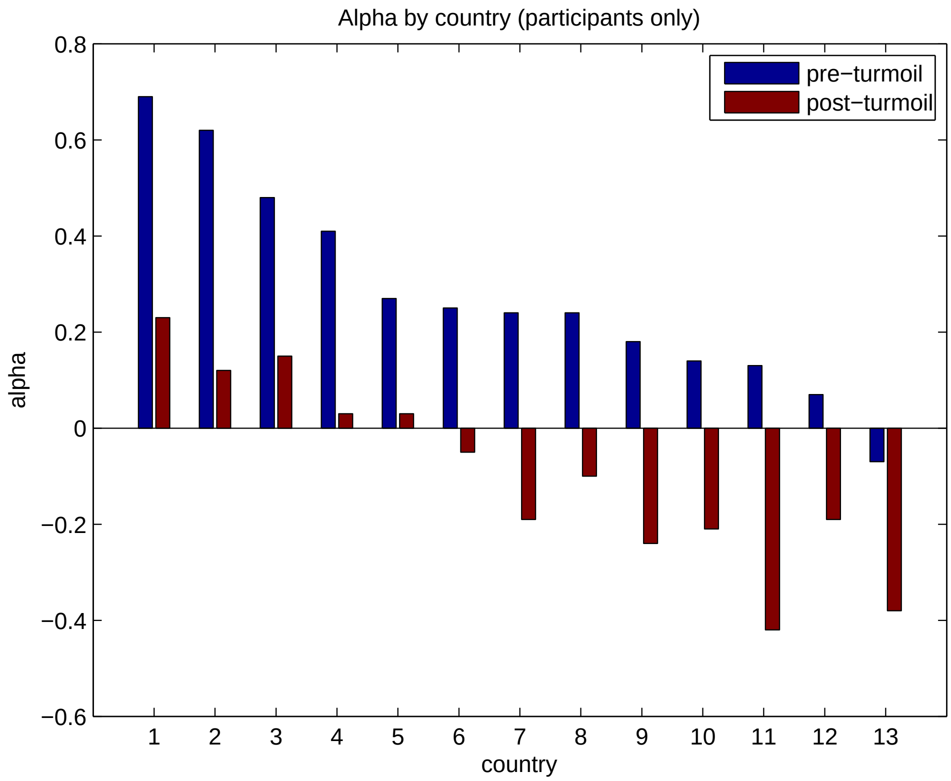


Figure 12: Pre and Post-Crisis Marginal Values across Euro-zone Countries

subsample of banks. We use two types of data in this exercise: (1) data that is common to all banks and specific to each tender - one-week Eurepo rate[36]; and (2) bank specific data, some of which is publicly available - bank's CDS and asset sizes, and (3) non-public data - volumes allotted at ECB's long-term refinancing operations (LTRO), banks' current accounts with the national Central Banks (NCBs) and reserve requirements.[37] In what follows we project our estimates of marginal values on these variables (or their functions) accounting for their panel structure in various ways.

We now briefly summarize which effects we expect from each variable included in the analysis below. As mentioned earlier, the *one-week Eurepo rate* normally sets the floor for bid rates (if above the minimum bid rate) and marginal values as its measures the cost of "alternative" funding in the secondary market against highly liquid collateral. This rate thus sets the common floor level

[36]See Piazzesi (2003) for an argument why it is very important to control for the levels of interest rates.

[37]The source for these data are: Bloomberg (bank assets); ECB (DG-M/MOA: current accounts; DG-M/FO: LTROs and MROs bidding data); Reuters (Eurepo rate); and KMV (CDS).

of bids and marginal values for all banks.

The (relative) *CDS premium* captures the impact of credit risk premia in the inter-bank market; higher values of this variable should lead to an increase in the bids and marginal values of liquidity at the central bank auctions. We use CDS on the day before each auction, and define a relative credit default swap variable as the bank's CDS minus the average of all banks' CDS to purge possible trends correlated with other variables used: $RCDS_{it} = CDS_{it} - \frac{\sum_{j \neq i} CDS_{jt}}{N_{j \neq i}}$.

Volumes allotted at the LTROs capture the impact of term liquidity funding pressure. With a liquid interbank lending market, the term-liquidity that a bank receives from the central bank (LTROs) should have little or no impact on the marginal value for liquidity in the short-term auction (MRO). However, if the ECB becomes the primary funding source for a bank, we may expect a noticeable linkage between the two auctions. Accordingly, our $LTROout_{it}$ variable measures the outstanding volume of loans obtained in LTROs bank i owns in week t (in billion €).

Reserve deficiency is calculated from banks' current accounts with the NCBs: the marginal value of liquidity should increase in the amount that a bank has to accumulate until the end of the reserve maintenance period. The reserve deficiency of a bank varies with unexpected liquidity shocks which may be driven by unexpected mismatches between cash inflows and outflows from that bank's accounts; and it may also reveal the failure to guarantee a targeted allotment at a previous auction. The *Deficiency* variable is calculated, for each bank i, as follows. First we calculate:

$$D_{it} = T * RR_i - \sum_{s=1}^{t} CA_{is}$$

where D_{it} is, on day t, for bank i, the accumulation of reserves needed, until the last day of the reserve maintenance period, in order to fulfill its requirement. RR_i is the daily average reserve requirement of bank i (set by the ECB at the beginning of each reserve maintenance period) and T is the number of days in the maintenance period; $T - t$ is the number of days until the end of the reserve maintenance period. If a bank follows a smooth (linear) reserve fulfilment path, it targets as its daily current account the daily average reserve requirement D^*_{it}:

$$D^*_{it} = T * RR_i - t * RR_i \Leftrightarrow \frac{D^*_{it}}{RR_i} = T - t$$

Deficiency is thus defined as:

$$Deficiency_{it} = \frac{D_{it}}{RR_i} - \frac{D^*_{it}}{RR_i} = \frac{D_{it}}{RR_i} - (T - t)$$

A bank is said to be front-loading its reserve fulfilment path if $Deficiency < 0$; and it is back-loading if $Deficiency > 0$. The frontloading liquidity policy followed by the ECB, after August 2007, should have led to an average negative value of $Deficiency$. We use the $Deficiency$ value on the day before the MRO. This is a normalized variable that has a days in the reserve maintenance period dimension.

Finally, *Turmoil* is a dummy variable equal to 1 in the post-turmoil period. We also included interactions of all variables with this dummy.

We estimated Fixed Effects (FE) and Random Effects (RE) Panel Data Models. The estimates for the specification with Eurepo 1-week and the alternative interest rate measures as explanatory variables are reported in table 5 below.[38]

We performed the Breusch-Pagan test (for specification (1) in table 5). The random effects model is not rejected at the 5% level; however it is rejected at the 10% level. The results reported in the table suggest that the estimates from a RE and FE models are both qualitatively and quantitatively very similar. The estimates show that the Eurepo 1-week rate explains the level of marginal values before the turmoil very well. Indeed, as the constant term is insignificant, our model predicts highly concentrated bidding before the crisis at rates between the level of the Eurepo 1-week rate and 3 basis points above it. Marginal values increased significantly after the crisis. Liquidity shocks (captured by deficiency) have a positive and statistically significant impact on marginal values only after the crisis. The impact of the outstanding volumes in LTROs is not statistically significant for marginal values either before or after the crisis. Nevertheless the change in sign of these coefficients pre- and post-turmoil period might be suggestive of the LTROs being a substitute for MROs before the turmoil, but complementary source of liquidity in the post-turmoil period. The credit risk variable (measured by the relative CDS) is statistically significant. A bank

[38]Since not all banks participate in every auction, we also used a two-step Heckman selection model (Heckman (1976, 1979)). The estimates obtained with correction for sample selection are very similar to those obtained with FE and RE and can be obtained upon request.

Table 5: Analysis of Marginal Values

	Marginal Value			
	(1)	(2)	(3)	(4)
EUREPO	1.03***			1.033***
	(0.04)			(0.036)
EUREPO*Turmoil	-0.35*			-0.39**
	(0.19)			(0.19)
EONIA		1.02***		
		(0.04)		
EONIA*Turmoil		-0.53***		
		(0.16)		
EURIBOR			1.02***	
			(0.04)	
EURIBOR*Turmoil			-0.32**	
			(0.16)	
Turmoil	1.53**	2.28***	1.36**	1.70**
	(0.77)	(0.65)	(0.67)	(0.77)
Deficiency	0.000008	0.00017	-0.0001	-0.003
	(0.002)	(0.002)	(0.002)	(0.002)
Deficiency*Turmoil	0.0226***	0.0226***	0.023***	0.024***
	(0.003)	(0.003)	(0.003)	(0.003)
LTROout	-0.006	-0.005	-0.006	-0.013
	(0.008)	(0.008)	(0.008)	(0.01)
LTROout*Turmoil	0.009	0.008	0.01	0.016
	(0.008)	(0.008)	(0.008)	(0.01)
RCDS	0.001	0.001	0.001	0.0005
	(0.001)	(0.001)	(0.001)	(0.002)
RCDS*Turmoil	0.006***	0.006***	0.0059***	0.006***
	(0.001)	(0.0015)	(0.0015)	(0.0018)
Constant	-0.08	-0.04	-0.1	-0.09
	(0.14)	(0.14)	(0.13)	(0.14)
Observations	690	690	690	690
Random effects	19	19	19	
Fixed effects				19
Within R^2				0.74

[a] Specifications (1)-(3): Bank random effects GLS regression
[b] Specification (4): Bank fixed effects regression
[c] Standard errors clustered at the bank level in parentheses.
[*] Significant at 10% level.
[**] Significant at 5% level.
[***] Significant at 1% level.

with CDS above the average tends to have higher marginal valuations for liquidity. The liquidity and credit risk factors seem to capture only partially the increase in the spread between marginal valuations and the reference rate (Eurepo 1-week) after the crisis, as the turmoil dummy variable is significant even when these variables are added to the regression. These results are robust to changing the reference rate in the regression, as shown by the different specifications[39]. We also performed a Hausman test to test the equality of the coefficient estimates of RE and FE models. We failed to reject that the coefficients are equal across the two models (p-value of 0.33).

In order to assess the economic significance of the results we calculated the predicted difference between the marginal valuations for two banks under the following assumptions: Eurepo rate 1-week at its highest in-sample value (4.15%); one bank with CDS differential at highest in-sample value (44.64); the other bank at minimum sample value (-30.91); one bank with deficiency at highest in-sample value (21.22 days); the other bank at zero. These assumptions are intended to capture the hypothetical situations of "good" and "bad" banks in the sample. The FE model predicts a marginal value of 4.07% for the "good" bank and a marginal value of 5.05% for the "bad" bank, a one percentage point difference in short term funding costs across these two banks. Note that in relative terms, after the crisis, the Eurepo 1-week rate "explains" only 52% of the marginal valuation, the deficiency 9%, the cds differential 6%, and the turmoil dummy 33%.

6.6 Relationship between marginal values and the evolution of stock prices through 2008

In the previous analysis, we linked the marginal values that we recovered from the bidding behavior in the primary repo auctions to the credit rating and reserve deficiency of each bank. We argued that banks that are more "sound", i.e., that have healthier balance sheets and thus easier access to alternative sources of funding than only the primary markets (and thus access to loans at or close to the low secured EUREPO rate) are less pressed to bid aggressively and thus their implied marginal values are lower. On the other hand, if we observe a bank whose marginal values substantially increased after the turmoil, it could perhaps be linked to some underlying problems that this bank might be facing. For a very small subset of our bidders (only 19) we were able to obtain stock

[39]Same results were obtained when estimating the fixed effects models with different interest rates.

Table 6: Correlations between changes in stock prices, marginal values and CDSs

	Δ Stock Price	Δ CDS Price	Δ Marginal Value	Δ MV Spread
Δ Stock Price	1			
Δ CDS Price	-0.75	1		
Δ Marginal Value	-0.46	0.37	1	
Δ MV Spread	-0.25	0.05	0.84	1

prices and prices of credit default swaps. Using these data, we look at the relationship between three variables: "Δ Stock Price" which is defined as the difference between the mean prices in the first half of 2007 and mean prices in the year and half following the turmoil (August 2007-December 2008) normalized by the mean price pre-turmoil, similary defined "Δ CDS Prices", and the difference between the mean quantity weighted marginal value before and after the turmoil. The raw correlations between the change in the stock prices and changes in marginal values and changes in the prices of CDSs indeed provide evidence for our interpretation of an increase in marginal values as suggesting distressed banks. As table 6 shows the correlation is negative for stock prices, marginal values and spreads of marginal values of EONIA swap rate, suggesting that the higher the increase in marginal values pre- and post turmoil, the bigger the decline in stock prices post turmoil. Since the prices of credit default swaps reflect the default risk directly, their increase is also accompanied by a decline in stock prices and they are positively correlated with the difference in marginal values.

Our sample is not big enough to draw definitive conclusions.[40] It points, however, towards the link between the change in the stock prices, which captures the information about the financial soundness of each bank becoming public information, and the change in marginal value for liquidity obtained in the primary market which captures the at-that-point private information of each bank relevant to its alternative sources of liquidity.[41]

[40]While a simple linear regression of the change in (estimated) marginal values on the change in stock prices results in a negative coefficient that is statistically significant, the same regression with the independent variable being the change in (estimated) spreads results in a negative, but insignificant coefficient.

[41]The same correlations hold for changes in marginal values in LTROs.

7 Conclusion

In this paper we utilized an economic model of bidding in the ECB's main refinancing operations to recover participant banks' marginal valuations for ECB provided short term loans, which can also be linked to the banks' outside funding opportunities in the interbank market. Our econometric approach allows us to decompose the dramatic upward shift in banks' bids starting in August 2007 into two main effects: a "fundamental" effect linked to a genuine increase in demand for ECB loans due to dwindling funding opportunities elsewhere, and a "strategic" effect, in which banks without a demand shift best-respond to their competitors' more aggressive bidding behavior. We showed that the "strategic" effect is non-negligible – while a naive analysis of bids would indicate that all bidders' demand for short term ECB funding increased due to the subprime crisis, accounting for the strategic effect reveals one third of the bidders as not having experienced a statistically significant demand shift.

Our results also shed light into the linkages between primary and secondary money market rates, and the shortcoming of "survey" based market rate reporting. We showed that before August 2007, participant banks' marginal valuations are in close agreement with the EUREPO and EURIBOR; published secured and unsecured lending rates reported based on surveys of money-center banks. After August 2007, however, we find that banks' marginal valuations and, sometimes, bids for secured ECB loans far exceed the EURIBOR; which suggests that a large number of banks were not able to borrow at published rates. These results suggest that monitoring primary market activity may allow policymakers and market observers to gain a more detailed understanding of the depth of similar financial crises.

Primary market activities of banks also allowed us to paint a more disaggregated picture of the 2007 subprime crisis. We noted that there was considerable heterogeneity banks' willingness-to-pay for ECB loans across different Eurozone countries. Perhaps more significantly, banks from member countries that relied less on ECB funding pre-August 2007 appear to have suffered less from the crisis. We also projected the estimated marginal valuations of banks on bank-level covariates that proxy for the banks' creditworthiness (as measured by the bank's credit default swap rates) and reserve requirements. We find that both factors began to play a significant role in banks' bidding behavior during the 2007 crisis. Moreover, we were able to provide a quantitative link between the rise in a bank's CDS rate and its reserve deficiency and the banks' marginal cost of short-term funding. Finally, we showed that banks' marginal valuations for ECB funding during the 2007 crisis predict a portion of the decline in these banks' stock prices throughout 2008. Thus, primary market data contains private information about the bidders that is persistent and not immediately impounded into share prices, and could potentially be monitored as leading indicators for distress in crisis situations.

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A Appendix

A.1 Institutional Background

A.1.1 Objectives and Tools of the ECB

The operational framework for monetary policy implementation by the ECB has three main objectives: signalling of the monetary policy stance, steering of very short-term interest rates, and provision of refinancing to the banking system in an efficient way and under all circumstances. The ECB has three main tools to implement its objectives: minimum reserve requirements with averaging provision, standing facilities, and open market operations. The main focus of this paper is on open market operations, but below we briefly describe each of the three components because all are quite relevant for banks' behavior in the open market operations .

Reserve requirements have two main functions. They contribute to stabilise money market interest rates and enlarge the structural liquidity shortage of the banking system. Euro area banks have to keep minimum reserves (current accounts with NCBs[42]). They are computed on a lagged accounting basis by applying a reserve ratio (currently at 2%) to the reserve base. The reserve base

[42] National Central Banks

includes short-term liabilities of banks (deposits and debt securities with maturity below or equal to two years). Reserves must be kept on average over a maintenance period (averaging mechanism) which has approximately one month duration. Required reserves are remunerated - at a rate linked to the marginal rate of the Main Refinancing Operations (MROs) described below. Current account holdings beyond the minimum requirement are not remunerated (excess reserves).

There are two types of *standing facilities*, one providing liquidity (against collateral), which is a marginal lending facility and another, absorbing liquidity, which is a deposit facility. Both are overnight facilities taken at the discretion of the banks, and, in general, there are no limits set by the ECB to their recourses by banks. Standing facilities have penalty rates: marginal lending +100 basis points above the Minimum Bid Rate (henceforth MBR, which is a policy rate, see below for more details) and deposit facility -100 basis points below the MBR.[43] These two rates set a corridor for the interbank market overnight interest rate.

There are three main types of *open market operations*. The Main Refinancing Operations (MROs), which are the main focus of our analysis, The Longer Term Refinancing Operations (LTROs) are liquidity providing reverse transactions, with three-month maturity, conducted once a month, every month. The main function of the LTROs is to provide additional longer-term liquidity to the market. They are not intended to signal the (future) stance of monetary policy. Fine Tuning Operations (FTOs) provide or absorb liquidity. They have neither fixed frequency nor maturity. Provision of liquidity is made via reverse transactions or foreign exchange swaps, and absorption of liquidity is normally achieved via collection of fixed term deposits or foreign exchange swaps. The main function of the FTOs is to smooth the effects on interest rates caused by unexpected liquidity fluctuations in the market. Since 2005 the ECB conducts (almost) systematically an FTO on the last day of each reserve maintenance period.

A.1.2 More Details on the Main Refinancing Operations

MROs are executed weekly according to an indicative calendar published by the Eurosystem. Normally, the announcement of the operation is on Monday[44], the execution on Tuesday[45] and set-

[43] The interest rate corridor was narrowed to ±50 basis points as of October 9, 2008.
[44] Info in Reuters page ECB16.
[45] Info in Reuters page ECB17.

tlement on Wednesday. On the announcement day (Monday) the ECB publishes an estimate of the average autonomous factors[46] from the announcement day until the maturity of the operation (9 days ahead forecast) as well as the benchmark allotment. On the execution day (Tuesday) the ECB publishes a revised estimate of the average autonomous factors and benchmark amount.

As we mentioned earlier, a bid may consist of up to ten interest rates and associated quantities a bank is willing to transact with the ECB. The interest rate bid must be expressed as multiples of a basis point, i.e., of 0.01 percentage points. The minimum bid amount is EUR 1,000,000. Bids exceeding this amount must be expressed as multiples of EUR 100,000. The ECB may impose a maximum bid limit in order to prevent disproportionately large bids.

In the allotment, bids are listed in descending order of offered interest rates. Bids with the highest interest rate levels are satisfied first and subsequently bids with successively lower interest rates are accepted until the total liquidity to be allotted is exhausted. If at the lowest interest rate level accepted (i.e., the marginal interest rate), the aggregate amount bid exceeds the remaining amount to be allotted, the remaining amount is allocated pro rata among the bids according to the ratio of the remaining amount to be allotted to the total amount bid at the marginal interest rate (a.k.a. rationining rule pro-rata on-the-margin). The amount allotted to each bank is rounded to the nearest euro.

The ECB may apply either single rate (uniform price) or multiple rate (discriminatory) auction procedures. So far only the latter has been used, and thus our data includes only discriminatory auctions. In a discriminatory auction, the allotment interest rate is equal to the interest rate offered by each individual bid. Since October 15 2008 the weekly main refinancing operations have been carried out with a fixed-rate tender procedure with full allotment.

A.1.3 Collateral (Eligible Assets)

All Eurosystem liquidity-providing operations (including marginal lending and intraday credit) are based on underlying assets that must fulfill certain criteria in order to be eligible. A European credit assessment framework (ECAF) has been set up in order to evaluate the eligible collateral.

[46] Defined as Autonomous factors (AF) = Net Foreign Assets (NFA) + Net Assets Denominated in Euro (NDA) - Banknotes (BN) - Government deposits (GOV) - Other (O).

The collateral accepted by the Eurosystem is very broad. Two types of assets are included in the list: marketable and non-marketable. The ECB publishes daily a list of eligible marketable assets on its website.[47] Marketable assets must be debt instruments meeting high credit standards which are assessed by the ECAF rules. The issuers can be central banks, public sector, private sector, and international institutions; the place of issue must be EEA[48], the place of establishment of the issuer must be the EEA and non-EEA G10 countries, the currency must be EUR.[49] Both regulated and non-regulated markets are considered; the latter must be, however, accepted by the ECB. Non-marketable assets are credit claims and Retail Mortgage Backed Debt Instruments (RMBD). For credit claims the debtor/guarantor must meet high credit standards which are assessed by the ECAF rules. The debtor/guarantor can be public sector, non-financial corporations, and international institutions; the place of establishment of the debtor/guarantor must be the euro area and the currency must be EUR. Minimum size rules apply. For RMBD the asset must meet high credit standards which are assessed by the ECAF rules. The issuers can be credit institutions; the place of establishment of the issuer must be the euro area, and the currency must be EUR. A bank may not submit as collateral any asset issued or guaranteed by itself or by any other entity with which it has close links.

In the assessment of credit standard of eligible assets the Eurosystem takes into account the following sources: external credit assessment institutions (ECAIs), NCBs in-house credit assessment systems (ICAS exist in Deutsche Bundesbank, Banco de España, Banque de France and Oesterreichische Nationalbank), counterparties internal ratings-based systems (IRB) or third-party providers rating tools. The Eurosystems credit quality threshold is defined in terms of a "single A" credit assessment (meaning "A-" by Fitch or S&P; or "A3" by Moody).[50] The Eurosystem considers a probability of default (PD) over a one-year horizon of 0.10% as equivalent to a "single A" credit assessment. Prudential information can be used by the Eurosystem as a basis for rejecting assets. In countries, in which RMBDs are mobilised, the respective NCB must implement a credit

[47] Eligible assets are listed at: `https://mfi-assets.ecb.int/dla_EA.htm`

[48] European Economic Area

[49] Since November 14, 2008 the list of eligible marketable debt instruments was enlarged to include instruments denominated in US dollar, yen and sterling, issued by EEA issuers.

[50] As of October 25 2008 and until December 2009 the ECB lowered the threshold to BBB- (except for ABS still A-).

assessment framework for this type of asset. The performance of the credit assessment systems is reviewed annualy. It consists of an ex post comparison of the observed default rate for the set of all eligible debtors and the credit quality threshold defined by the benchmark PD.

Risk control measures are applied to protect the Eurosystem against the risk of a financial loss if underlying assets have to be realised owing to the default of a counterparty. The following measures are applied: i) valuation haircuts (increasing with the maturity and illiquidity of the asset); ii) margin calls (i.e. marking to market): if the value of the underlying collateral falls below a certain level the NCB will require the counterparty to supply additional assets or cash. The Eurosystem may apply limits to the exposure vis-a-vis issuers/debtors or guarantors and may exclude certain assets from use in its monetary policy operations. The last two are, however, currently not applied.[51]

In pooling systems the counterparty makes a pool of sufficient underlying assets available to the NCB to cover the related credits thus implying that individual assets are not linked to specific credit operations. In an earmarking system each credit operation is linked to specific identifiable assets. Assets are subject to daily valuation.

A.2 Model of Bidding in the Primary Market for Liquidity

The basic model underlying our analysis is based on the share auction model of Wilson (1979) with private information, in which both quantity and price are assumed to be continuous.[52] In summary, there are N (potential) bidders, who are bidding for a share of a perfectly divisible good. Q denotes the amount of liquidity offered for sale by the central bank, i.e., the good to be divided between the bidders. Q might itself be a random variable if it is not announced by the auctioneer ex ante, or if the auctioneer has the right to augment or restrict the supply after he collects the bids. We assume that the distribution of Q is common knowledge among the bidders. Furthermore,

[51] Additional haircuts will be applied to all newly eligible marketable assets.

[52] Since the main goal of this article is not to provide tools and methodology for estimating this type of models, we refer the reader to our earlier work for more detailed discussion and analysis. The discriminatory auction version of Wilson's model with private values has been studied in Hortaçsu (2002a) in the context of Turkish treasury bill auctions. Kastl (2008) extends this model to an empirically relevant setting, in which bidders are restricted to use step functions with limited number of steps as their bidding strategies. The estimation of this extended model (which is also utilized in this paper) and the relevant asymptotic behavior of the resulting estimates are described in detail in Hortaçsu and Kastl (2008). Several related theoretical papers on divisible good auctions, such as Ausubel and Cramton (2002), Back and Zender (1993) or Wang and Zender (2002) focus on properties of equilibria.

the number of potential bidders participating in an auction, N, is also commonly known. This assumption is reasonable in the context of our empirical application as all participants have to register with the auctioneer before the auction and the list of registered participants is publicly available. Each bidder receives a private (possibly multidimensional) signal, s_i, which is the only private information about the underlying value of the auctioned goods. The joint distribution of the signals will be denoted by $F(\mathbf{s})$. We assume independent private values (IPV) paradigm.[53] In this case the s_i's are distributed independently across bidders, and bidders' values do not depend on private information of other bidders, i.e., the marginal valuation function has the form $v_i(q, s_i)$.

Assumption 1 *Bidder i's signal s_i is drawn from a common support $[0,1]^M$, where $M = dim(s_i)$, according to an atomless marginal d.f. $F_i(s_i)$ with strictly positive density $f_i(s_i)$.*

Assumption 2 *$v_i(q, s_i)$ is measurable and bounded, strictly increasing in (each component of) s_i $\forall q$ and weakly decreasing in q $\forall s_i$.*

$V_i(q, s_i)$ denotes the gross utility: $V_i(q, s_i) = \int_0^q v_i(u, s_i)\, du$. Bidders' pure strategies are mappings from private signals to bid functions: $\sigma_i : S_i \to \mathcal{Y}$. Since in most divisible good auctions in practice, including the liquidity auctions of the ECB, the bidders' choice of bidding strategies is restricted to non-increasing step functions with an upper bound on the number of steps, $\overline{K} = 10$, we impose the following assumption:

Assumption 3 *Each player $i = 1, ..., N$ has an action set:*

$$A_i = \left\{ \begin{array}{c} \left(\vec{b}, \vec{q}, K\right) : \dim\left(\vec{b}\right) = \dim(\vec{q}) = K \in \{0, ..., 10\}, \\ b_{ik} \in B = \{l\} \cup \left[0, \bar{b}\right],\ q_{ik} \in Q = [0,1],\ b_{ik} \geq b_{ik+1}, q_{ik} \leq q_{ik+1} \end{array} \right\}$$

Therefore the set $\mathcal{Y}$ includes all non-decreasing step functions with at most 10 steps, $y : \mathbb{R}_+ \to [0,1]$, where $y_i(p) = \sum_{k=1}^{K} q_{ik} I(p \in (b_{ik+1}, b_{ik}])$ where I is an indicator function. A bid function

[53] Bindseil, Nyborg and Strebulaev (2005) provide some econometric evidence that private values might be appropriate in case of repo auctions.

for type s_i specifies for each price p, how big a share $y_i(p|s_i)$ of the securities offered in the auction (type s_i of) bidder i demands.

Finally, since bidders use step functions, a situation may arise in which multiple prices would clear the market. If that is the case, we assume consistently with our application that the auctioneer selects the most favorable price from his perspective, i.e., the highest price.

Assumption 4 *If in any auction $\exists\ \underline{p}, \overline{p}$ such that $\forall p \in [\underline{p}, \overline{p}] : TD(p) = Q$, then the market clearing price, p^c, satisfies $p^c = \overline{p}$, where $TD(p)$ denotes total demand at price p.*

Because bidders' strategies are step functions, the residual supply will be a step function and hence but for knife-edge cases any equilibrium will involve rationing with probability one. Consistently with our application, we only consider the rationing rule pro-rata on-the-margin, under which the auctioneer proportionally adjusts the marginal bids so as to equate supply and demand.

Assumption 5 *The rationing rule employed is pro-rata on-the-margin, under which the rationing coefficient satisfies*

$$R(p^c) = \frac{Q - TD_+(p^c)}{TD(p^c) - TD_+(p^c)}$$

where p^c is the market clearing price, $TD(p^c)$ denotes total demand at price p^c, and $TD_+(p^c) = \lim_{p \downarrow p^c} TD(p)$. Only the bids exactly at the market clearing price are adjusted.

These last two assumptions, which are both consistent with our application, make sure that no bidder would prefer to tie with another bidder when gaining strictly positive marginal surplus at the quantity allocated after rationing.

Our solution concept is Bayesian Nash Equilibrium. The expected utility of type s_i of bidder i who employs a strategy $y_i(\cdot|s_i)$ in a discriminatory auction given that other bidders are using $\{y_j(\cdot|\cdot)\}_{j \neq i}$ can be written as:

$$EU_i(s_i) = E_{Q,s_{-i}|s_i} \left[\begin{array}{c} \int_0^{q_i^c(Q,\mathbf{s},\mathbf{y}(\cdot|s))} v_i(u, s_i)\, du \\ -\sum_{k=1}^{K} \mathbf{1}\left(q_i^c(Q,\mathbf{s},\mathbf{y}(\cdot|s)) > q_k\right)(q_k - q_{k-1})\, b_k \\ -\sum_{k=1}^{K} \mathbf{1}\left(q_k \geq q_i^c(Q,\mathbf{s},\mathbf{y}(\cdot|s)) > q_{k-1}\right)\left(q_i^c(Q,\mathbf{s},\mathbf{y}(\cdot|s)) - q_{k-1}\right) b_k \end{array} \right] \tag{A-1}$$

where $q_i^c(Q, \mathbf{s}, \mathbf{y}(\cdot|s))$ is the (market clearing) quantity bidder i obtains if the state (bidders' private information and the supply quantity) is $(\mathbf{s}, Q)$ and bidders bid according to strategies specified in the vector $\mathbf{y}(\cdot|s) = [y_1(\cdot|s_1), ..., y_N(\cdot|s_N)]$, and similarly $p^c(Q, \mathbf{s}, \mathbf{y}(\cdot|s))$ will denote the market clearing price associated with state $(\mathbf{s}, Q)$, which turns out to be the random variable that is most crucial to the analysis. The first term in (A-1) is the gross utility the type s_i enjoys from his allocation, the second term is the total payment for all units allocated at steps at which the type s_i was not rationed and the final term is the payment for units allocated during rationing. A Bayesian Nash Equilibrium in this setting is thus a collection of functions such that almost every type s_i of bidder i is choosing his bid function so as to maximize his expected utility: $y_i(\cdot|s_i) \in \arg\max EU_i(s_i)$ for a.e. s_i and all bidders i. Part (i) of the following proposition proved in Kastl (2008) provides necessary conditions characterizing the equilibrium in discriminatory auctions with private values when marginal valuation function is continuous in q. Since continuity of the marginal valuation function might be questionable at the last step (in particular for bidders who submit just one step), we make use of the necessary conditions for optimality with respect to the bid (part (ii)).

Proposition 1 *Under assumptions 1-5 in any Bayesian Nash Equilibrium of a Discriminatory Auction, for almost all s_i, with a bidder of type s_i submitting $\hat{K}(s_i) \leq 10$ steps, every step k in the equilibrium bid function $y_i(\cdot|s_i)$ has to satisfy:*

(i) $\forall k < \hat{K}(s_i)$ such that $v(q, s_i)$ is continuous in a neighborhood of q_k for a.e. s_i:

$$v(q_k, s_i) = b_k + \frac{\Pr(b_{k+1} \geq p^c|s_i)}{\Pr(b_k > p^c > b_{k+1}|s_i)}(b_k - b_{k+1}) \tag{A-2}$$

and at $K(s_i)$:

$$b_K = v(\overline{q}, s_i)$$

where $\overline{q} = \sup_{(Q,s_{-i})} q_i^c(Q, \mathbf{s}, \mathbf{y}(\cdot|s))$, i.e., the largest quantity allocated to bidder i in equilibrium.

(ii) $\forall k \leq \hat{K}(s_i)$ such that $v(q, s_i)$ is a step function in q at step k such that $v(q, s_i) = v_k$ $\forall q \in (q_{k-1}, q_k]$ for a.e. s_i and signals are independently distributed:

$$v_k = b_k + \frac{\Pr(b_k > p^c|s_i)}{\frac{\partial \Pr(b_k > p^c|s_i)}{\partial b_k}} \tag{A-3}$$

In practice, we use equation (A-2) to identify the marginal values at all, but last step and we use equation (A-3) at the last step.[54] Note that as $K \rightarrow \infty$, (A-2) and (A-3) coincide in the limit.[55]

A.3 Liquidity demand and supply

To put the liquidity auctions of the ECB into perspective and understand the supply policy of the ECB, let us first look at the simplified balance sheet of the Eurosystem, for example on June 29, 2007 (Table 7 and Table 8).

Table 7: Balance sheet of the Eurosystem on June 29, 2007

Assets		**Liabilities**	
1. Net Foreign Assets	325,703	5. Banknotes	630,777
2. Net Assets Denominated in EUR	282,041	6. Current Accounts	194,530
3. Liquidity Providing Open Market Operations	463,501	7. Government Deposits	69,621
4. Marginal Lending Facility	5	8. Deposit Facility	80
		9. Other	176,242
Total Assets	1,071,250	Total Liabilities	1,071,250

* Values in million EUR.

Table 8: Structure of the balance sheet of the Eurosystem on June 29, 2007

Assets	%	**Liabilities**	%
1. Net Foreign Assets	30	5. Banknotes	59
2. Net Assets Denominated in EUR	26	6. Current Accounts	18
3. Liquidity Providing Open Market Operations	43	7. Government Deposits	6
4. Marginal Lending Facility	0	8. Deposit Facility	0
		9. Other	16
Total Assets	100	Total Liabilities	100

On the Liabilities side the main items are Banknotes and Current Accounts (together represent 77% of total Liabilities), the latter including the minimum reserve requirement. On the Assets side there are two large items: Net Foreign Assets and Net Assets Denominated in Euro (representing 56% of total Assets). The former relates to foreign exchange reserve holdings of the Eurosystem (in

[54] Using (A-3) at all steps leads to qualitatively very similar results, but the estimates turn out to be less precise due to the necessity to numerically estimate the derivative of the distribution of the market clearing price.

[55] The formal argument is in Kastl (2008).

gold and US Dollar) managed by the ECB. The latter reflects the investment portfolio holdings of NCBs (managed in a decentralised manner according to agreed rules). It is important to note that this is not a monetary policy portfolio. Liquidity providing OMO represent 43% of the Assets of the Eurosystem. This is the item that is adjusted/managed by the ECB and relevant for monetary policy implementation.

The liquidity needs of the banking system can be calculated from the balance sheet as follows:

+ Assets (other than 3 and 4) provide liquidity

- Liabilities (other than 8) create liquidity needs.

Thus:

Liquidity Deficit = Autonomous factors (AF) + Current Accounts (CA).

Where:

Autonomous factors (AF) = Net Foreign Assets (NFA) + Net Assets Denominated in Euro (NDA) - Banknotes (BN) - Government deposits (GOV) - Other (O).

Current Accounts include the reserve requirement (RR) plus very small excess reserves (XR).

Example 1 *From the balance sheet data (Table 7) we can see that AF = -268,896 million EUR, and CA = -194,530 million EUR. Therefore the aggregate liquidity deficit in the euro area was AF+CA=-463,426 million EUR or approximately 463 billion EUR, of which 58% was due to the so-called autonomous factors and 42% was due to the reserve requirement (current accounts).*

Alternatively one could express the liquidity needs as follows (Table 9): Outright portfolio - Reserve Base - Other = -463,426 million EUR, where Reserve Base = Banknotes + Current Accounts and Outright Portfolio = NFA + NDA - GOV.

Table 9: Simplified balance sheet of the Eurosystem on June 29, 2007

Assets	%	**Liabilities**	%
1. Outright Portfolio	538,125	3. Reserve Base	825,307
2. Repo Operations	463,501	4. Net Standing Facilities	75
		5. Other	176,242
Total Assets	1,001,624	Total Liabilities	1,001,624

* Values in million EUR.

As shown in Table 7 (also Table 9) the ECB provides liquidity to the banking system mainly via its regular *open market operations*, which satisfy: [56]

OMO + ML - DF = AF + CA. And OMO = MRO + LTRO.

Before the turmoil the MROs represented about 70% of the refinancing and the LTROs only 30%. Thus, the bulk of the liquidity was provided by MROs on a short-term basis (weekly) and was rolled-over every week. For example, on June 29, 2007, the outstanding volumes in OMO consisted of: (i) Main refinancing operations (MROs: 313,499 million EUR) and (ii) Longer-term refinancing operations (LTROs: 150,002 million EUR).

In general, the liquidity policy of the ECB is quantity-oriented even if the objective is to steer the overnight interest rate. It is a rules-based approach where the benchmark allotment plays a central role.

The benchmark allotment in a MRO is the allotment amount which allows counterparties to smoothly fulfill their reserve requirements until the day before the settlement of the next MRO, when taking into account the following liquidity needs:

- Liquidity imbalances that have occurred previously in the same reserve maintenance period and which were not anticipated in the preceding MRO
- ECB's forecast of the autonomous factors
- ECB's forecast of excess reserves which are assumed to be the same on each day of the reserve maintenance period

The weekly benchmark allotment is (in simplified terms) given by:

$$MRO^{benchmark} = AF^{forecast} + \underline{RR} + XR^{forecast} + \{Forecast\ error\ of\ previous\ week\}$$

Assuming: $ML - DF = 0$. The reserve requirement is fixed as it is calculated on a lagged accounting basis.

The underlying idea of the benchmark allotment is that if the ECB's forecast errors are unbiased and the forecast error variance is small compared to the reserve requirement, then the overnight

[56]The provision of liquidity via the marginal lending facility is negligible.

rate on the last day in the reserve maintenance period should be expected to be close to the middle of the interest rate corridor defined by the rates on the standing facilities. With a symmetric interest rate corridor this policy should keep the overnight rate close to the policy rate.

In fact, on the last day of the reserve maintenance period we get the aggregate liquidity imbalance equal to the forecast error made by the ECB, the former being either a net recourse to marginal lending (liquidity shortage) or to the deposit facility (liquidity surplus).

$$ML - DF = Forecast\ Error$$

.

If the overnight rate is expected to be close to the policy rate on the last day of the RMP, then on any other day in the reserve maintenance period it should also be close to the policy rate by applying the martingale hypothesis.

Empirical evidence before the turmoil matches these predictions very closely (figure 14).

Figure 17 shows that the liquidity needs of the banking system evolved very smoothly before the turmoil between 400 and 450 billion EUR. The MROs had a volume of around 300 billion EUR and the LTROs about 100-150 billion EUR. Deviations from benchmark were negligible as illustrated in figure 18.

Figure 17 further illustrates how the ECB managed liquidity during the turmoil. Four aspects are shown: i) the total volume of refinancing was kept on trend, albeit with somewhat more volatility; there was a significant increase at the end of the year mainly for seasonal reasons; ii) there was an increase in the absolute volume and relative weight of LTROs in total refinancing. However, the volume of MROs declined so that the total volume was kept on trend; iii) the ECB conducted more frequent and sizable fine-tuning operations (FTOs), both providing and draining liquidity; the latter (draining) were more frequent and sizable; A final aspect is illustrated in figure 18: iv) At the MROs deviations from benchmark became very sizable and time-varying (larger at the first MRO in the RMP and somewhat smaller in subsequent MROs in the same RMP).

A.4 Long Term Refinancing Operations

We also obtained data on ECB's LTROs. We have 19 auctions covering 10/2006 to 3/2008. As described in the institutional background, these auctions are run only once a month and they are for loans with 3-months maturity. These data are summarized in table 10 and the pre- and post-turmoil means and standard deviation in table 11. The patterns in general correspond to those from the main refinancing operations studied in the main body of this paper. The important differences are (i) the much starker increase the price bid spread against the EONIA rate following the turmoil (from 1 to 47 basis points) which is about five times the increase in the MROs and (ii) the number of participants is less than a half of those in MROs. This is probably mainly due to the overlapping maturities of the loans (monthly auction frequency and 3-month maturity) since the set of banks participating in both types of refinancing operations is very similar. This last observation allows us to perform the same exercise as in the case of MROs and use the estimated values to classify bidders into more and less distressed groups. Doing so, we obtain a similar pattern as in the MROs: only about $\frac{2}{3}$ of bidders experienced an increase in their mean (quantity-weighted) marginal value, while almost all banks significantly increased their bid spreads against EONIA suggesting more aggressive bidding strategy.

Table 10: Data Summary - LTROs

Summary Statistics				
Auctions	50			
	Mean	St.Dev.	Min	Max
Bidders	148	19	96	175
Submitted steps	2.29	1.68	1	10
Price bid	4.20	0.44	3.20	5.05
Price bid spread[a]	0.26	0.26	-0.48	1.02
Quantity bid	0.01	0.02	$1 * 10^{-5}$	0.28
Issued Amount (billions €)	49.74	8.58	40	75

[a] Spread against EONIA rate.

Following the same procedure as in MROs, we estimated the marginal values that would rationalize the observed bids in LTROs. We also repeated the same exercise as in the case of MROs to classify the bidders in LTROs into the distressed and not distressed groups. The results are summarized in table 12. Due to less participation frequency (we have only 11 auction pre-turmoil and

Table 11: Data Summary LTROs: Before and After August 2007

Summary Statistics	Mean		Std Dev	
	Before	After	Before	After
Bidders	150.6	143.4	10.66	26.53
Submitted steps	1.76	3.04	0.94	2.15
Price bid	3.78	4.55	0.26	0.16
Price bid spread[a]	0.01	0.47	0.02	0.17
Quantity bid	0.009	0.013	0.024	0.023
Issued Amount (billion €)	46.36	54.38	5.05	9.82

[a] Spread against EONIA rate.

8 auctions post-turmoil) we were able to classify only 200 bidder identities. Very similar pattern arises for those, however, as in the case of MROs. Virtually all participants significantly increased their bids, but for $\frac{49}{189}$ (or 26%) of those, this does not seem to have been accompanied by an increase in values.

Table 12: Predicting Potential Problems - LTROs

Based on		**Bids**	
		Yes	No
Values	Yes	140	4
	No	49	7

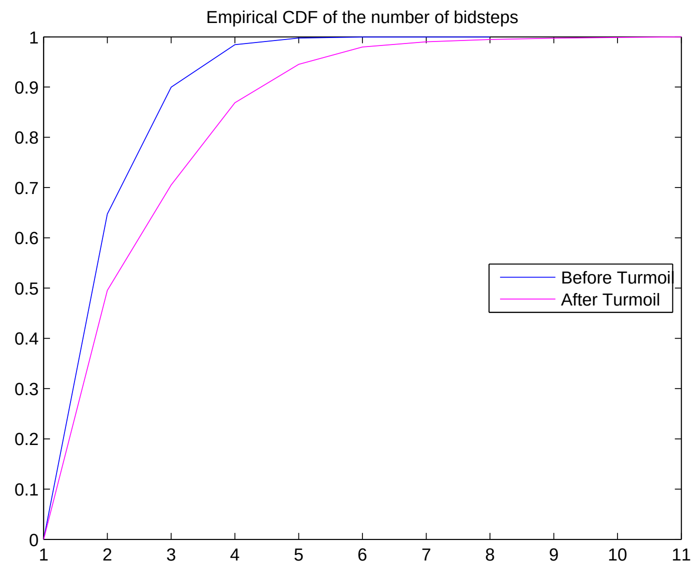

Figure 13: Distribution of the number of steps in a bid curve before and after the turmoil

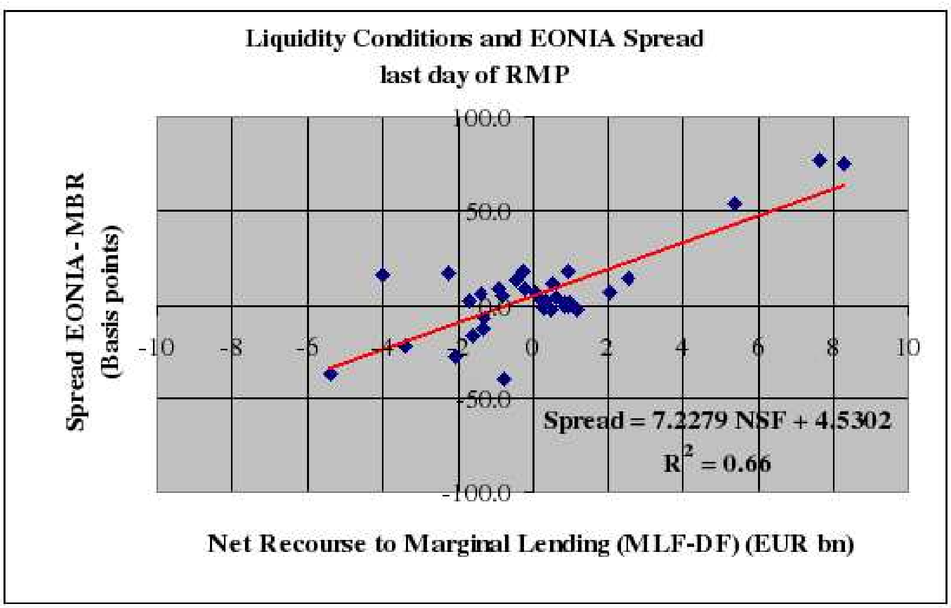

Figure 14: EONIA Spread and Liquidity Conditions on the Last Day of the RMP

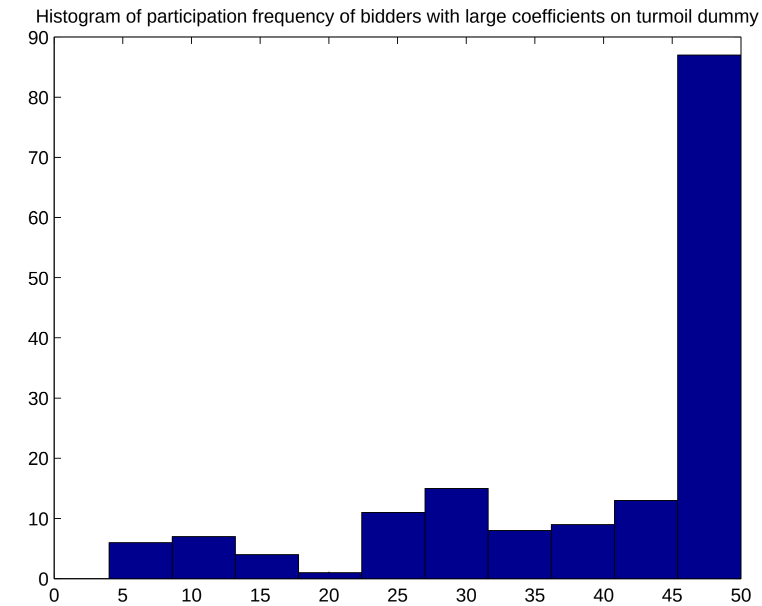

Figure 15: Histogram of Participation by Bidders with Large Turmoil Effects

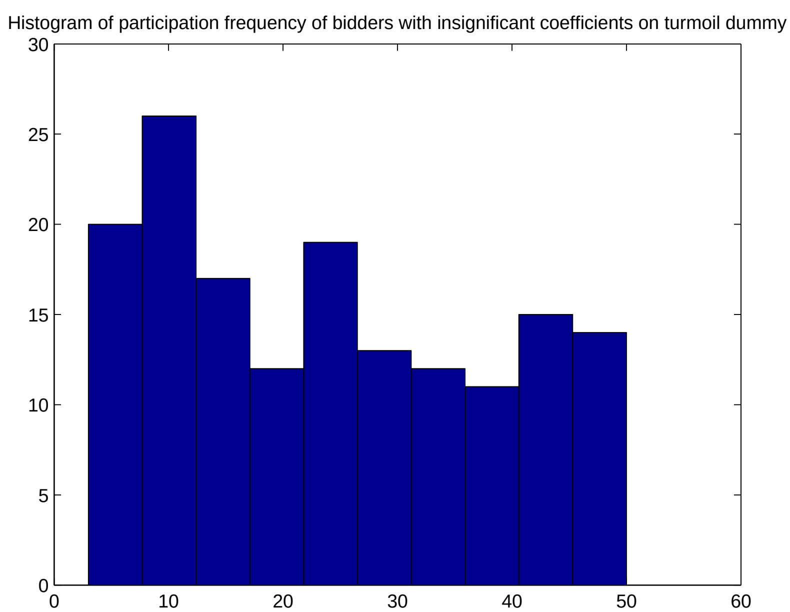

Figure 16: Histogram of Participation by Bidders with Insignificant Turmoil Effects

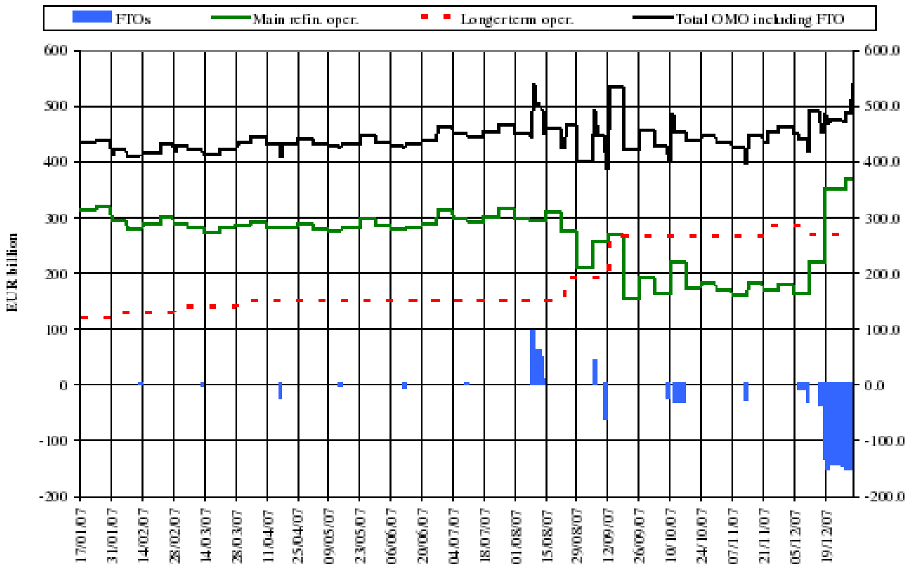

Figure 17: Liquidity Provision by the ECB in 2007

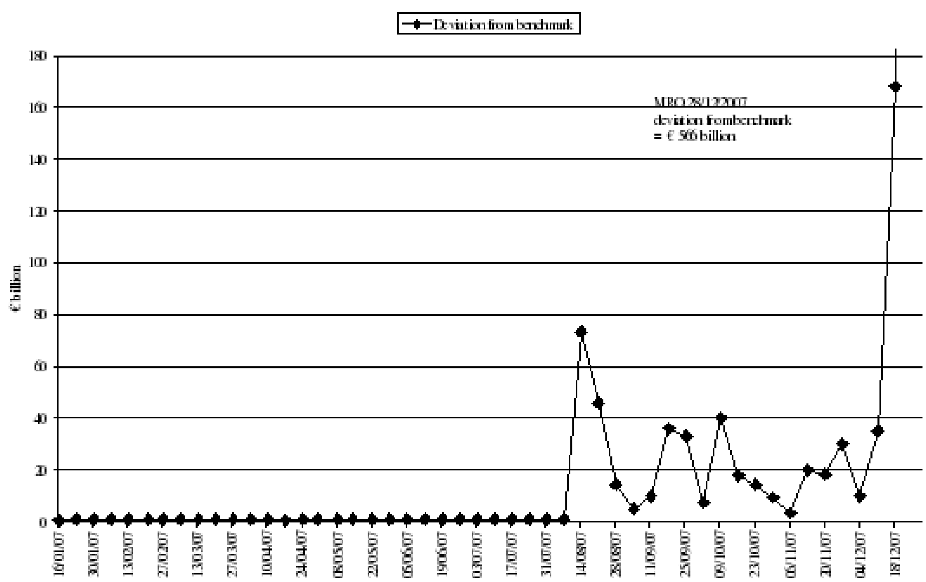

Figure 18: Deviation from Benchmark at the MROs in 2007