

The 2007 Subprime Market Crisis in the EURO Area Through the Lens of ECB Repo Auctions*

Nuno Cassola[†]

Ali Hortaçsu[‡]

Jakub Kastl[§]

February 1, 2009

Abstract

We study the sudden change in bidding behavior in primary auctions of liquidity run by the European Central Bank which followed the spillover of the subprime market crisis in August 2007 to the EURO area. A direct analysis of changes in the bidding patterns suggests that virtually all banks suffered from a decrease in liquidity access in the secondary markets and started bidding more aggressively in the primary market. Using an estimated model of bidding in these auctions we find that for about one third of participants this change in bidding behavior was simply a strategic response. For the other two thirds this change was indeed spurred by an increase in their values for liquidity obtained in the primary market. This change in values occurred likely due to either (i) an exposure of some banks to risky asset-backed securities, which either required a substantial risk premium or could not be used as collateral in the interbank liquidity market, or (ii) increased uncertainty about future liquidity needs. Both of these effects in turn caused the primary market to be a comparatively cheaper and more certain source of liquidity. We also show that the primary auctions of liquidity may have played an important role in improving the efficiency of the allocation when the secondary markets failed to serve this role. Using a smaller complementary data set, we further analyse the changes in private values using data which likely was part of the private information set of each bank when submitting the bid.

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

JEL Classification: D44

*We would like to thank Manuel Amador, Tim Bresnahan, Liran Einav, Nir Jaimovich and seminar participants at Chicago, NYU, Stanford, UCLA and Wisconsin for helpful comments. The views expressed in this paper are our own and do not necessarily reflect the view of the European Central Bank. All remaining errors are ours.

[†]Research Department, European Central Bank

[‡]Department of Economics, University of Chicago and NBER

[§]Department of Economics, Stanford University

1 Introduction

The second week of August 2007 marked the beginning of a turmoil in the financial markets that was probably more far-reaching than any other distress in financial markets in recent history. The main purpose of this paper is to document and shed some light on the impact of this turmoil through an analysis of the behavior of banks in the primary market for liquidity, the weekly repo auctions held by the European Central Bank, using a unique detailed data set.

The primary indicator for the impact of the subprime crisis that has been utilized by previous analyses of the subprime crisis (Taylor and Williams (2008 (a) and (b)), Wu (2008)), McAndrews, Sarkar and Wang (2008)) has been the spread between the secured (collateralized) and unsecured lending rates in the interbank money market.¹ These studies document a large jump in these spreads beginning August 2007. Moreover, industry reports suggest that the type of collateral accepted in the interbank market for secured loans changed significantly.² These developments suggested that it became much costlier for banks to obtain the liquidity needed to finance their (longer-term) investment portfolios, and spurred central banks to provide additional term lending operations.

An important question that is not addressed by the market-level/aggregated analyses of the crisis period is the extent of the liquidity squeeze across the banking system. The ECB's repo auctions provide us with a unique opportunity to answer this question. The ECB uses these auctions to provide 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 repurchased³ 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. Indeed, in "normal" times, banks' willingness-to-pay is expected to lie between (indeed, be a convex combination of) reported secured and unsecured

¹These studies also look at the spread between the overnight interest swap rates and unsecured lending rates. The correlation between these spreads and the secured/unsecured spread is very high, as documented by Taylor and Williams (2008b). 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 (2008b) for US equivalents.

²See e.g., the BearingPoint Report, 2008.

³Hence the term repo auctions.

loan rates.

The period beginning in August 2007 was hardly “normal,” however, and the cozy 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. We pursue several explanations for and implications of this decline in the informativeness of reported market rates in section 6.1.1.

Bids in the ECB repo rates allow us to paint a more detailed picture about the condition of the banking sector than is allowed by trends in market rates. First, as we document in section 4, virtually all participants in these auctions became much more aggressive in their bidding. While this suggests that *all* banks’ willingness-to-pay for liquidity obtained in the primary market increased significantly and these higher values in turn led to higher bids, we in fact argue that for about one third of the participants this change in bidding behavior is simply a strategic response. Loosely speaking, while their values (or outside options) stayed the same, they increased their bids in order to best-respond to the higher bids of their rivals.

As for the two-thirds of 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. Using an auxiliary data set, we provide evidence that this increase in values for ECB liquidity is linked to a deterioration in credit/default ratings (as measured by CDS rates). Moreover, we find that ECB reserve requirements appear to become a more significant determinant of bidding in repo auctions; suggesting that access to other liquidity sources became more difficult after August 2007.

Our reconstruction of individual banks’ willingness-to-pay for ECB loans also allows us to assess the efficiency of the auction mechanism, where we define an efficient allocation as one in

which banks' whose willingness-to-pay is the largest win the auction. Note that efficiency is not an immediate outcome of the utilized discriminatory auction mechanism, as pointed out by Ausubel and Cramton (2002). We find that there were efficiency losses due to the mechanism especially in the post-crisis periods. However, these efficiency losses need to be contrasted with the allocative performance of the interbank market, which appears to have failed to match liquidity to banks who had high value for it.

We now move on to describe the financial turmoil in more detail in section 2, focusing on when and how it started. The reader familiar with the events of 2007 may wish to skip to subsection 2.2, where we put the main object of analysis in this paper, the primary repo auctions of the ECB in 2007, in the appropriate context of the existing literature. 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 use these data to estimate a model of bidding in these auctions which allows us to recover values which bidders attach to obtaining loans from the ECB in the primary market. For interested reader, we review the 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 Financial Markets in 2007

2.1 Beginning of the Turmoil

The subprime credit crisis hit the Euro money market on August 9, 2007. On this day 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 thus 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,

or ABS) that were likely exposed to much more risk than originally assessed based on their ratings.

The impact on the money market was swift with an increasing spread between collateralized and uncollateralized loans. In figure 1, we plot the spread between the (1 week) EURIBOR (Euro Interbank Offer Rate), 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, and the (1 week) EUREPO, the rate for fully collateralized loans on the interbank market, which have strict requirements on the type and quality of the collateral.⁴ As evidenced in figure 1, after the second week of August 2007 the gap between these rates significantly widened. In particular, the premium a lender required for an unsecured loan in the interbank market in the post-August 2007 period increased substantially - from around 4 basis points to well over 10 basis points for loans with a maturity of one-week.⁵ 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.⁶

As similar liquidity problems in the U.S. revealed to be more persistent than initially thought, the Federal Reserve System significantly expanded and diversified its liquidity supporting facilities. On the other side of the Atlantic, the European Central Bank exploited the possibilities already afforded by its operational framework. For many banks, and in particular for those that were exposed to the risks associated with the U.S. subprime market, an easier way to gain access to liquidity was through the primary markets, i.e., repo auctions of liquidity held by the central banks.⁷

It is reasonable to believe that for many financial market participants seeking access to liquidity, repo auctions of the central bank became relatively more attractive: the collateral requirements were less strict and interest rates 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 has to

⁴See <http://www.eurepo.org/eurepo/eurepogc.html> for a list of securities accepted as collateral.

⁵Our analyses focus only on one-week maturity rates as this is the maturity of the regular weekly repo operations of the ECB. However, similar, perhaps even more dramatic jumps in the unsecured-secured spread occurred for longer maturity loans as well.

⁶See e.g., the BearingPoint Report, 2008.

⁷It 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.

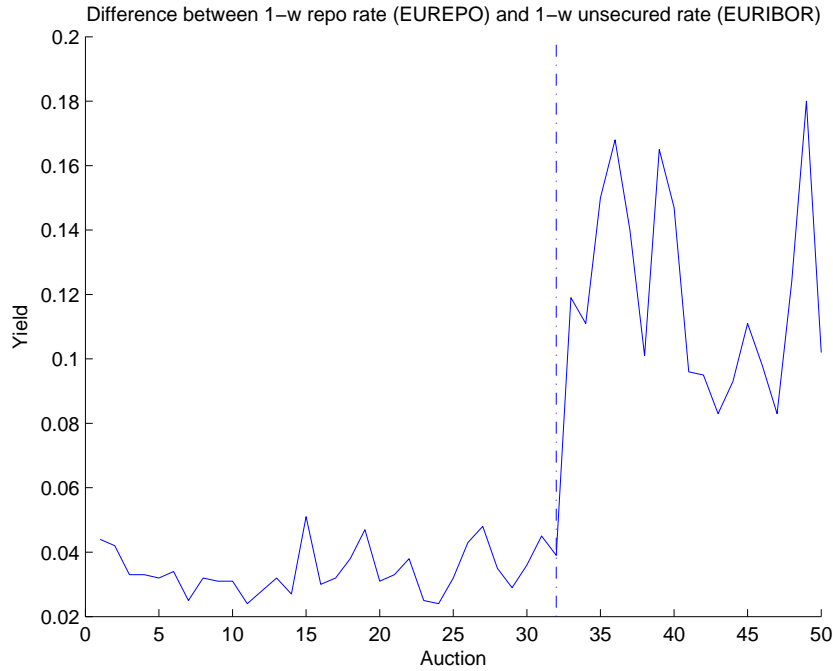


Figure 1: Spread between the unsecured and secured lending rates

be virtually risk-free - basically just high-quality government paper.⁸ Therefore for many potential borrowers the best option might indeed have been to obtain liquidity in the primary market by participating actively in the auctions run by the central bank as the requirements on the collateral are not as stringent.⁹ Since the alternative of obtaining the liquidity in the secondary market became practically infeasible at least for some banks (perhaps due to the structure of their available collateral), the bidding behavior of such banks in the primary markets changed. Of course in an environment in which a subset of bidders are drastically adjusting their bidding strategies in response to the changes in their outside options, the remaining bidders will also adjust their bids as best responses even though their outside options or “values for liquidity in the primary market” might not have changed.

⁸For a list of eligible collateral, see <http://www.eurepo.org/eurepo/eurepogc.html>

⁹Even in the U.S., the U.S. Federal Home Loan Bank System accepted mortgage-backed securities as collateral for its advances to financial institutions.

2.2 Turmoil in the Literature

Some recent papers (for example Taylor and Williams (2008a),(2008b)) have argued that the increase in the spread between the term¹⁰ 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.¹¹

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 bank 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 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

¹⁰1-week rates for example.

¹¹As 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 (2008a) 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.

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 studying 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. We instead 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 main goal is to use the estimated model to analyze the forces behind bidders' choices and to analyze the impact of the financial turmoil.

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)¹² of the ECB. They are liquidity providing, reverse transactions, with one-week maturity, conducted every week. The main function of the MROs (at least before the turmoil period) is to provide a bulk of liquidity to the market. They are pivotal in steering interest rates (such as the minimum bid rate (MBR)), manage the liquidity situation in markets and signal the stance of monetary policy.

¹²See section A.1.2 in the appendix for more details.

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 NCB¹³ 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 is revealed.

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).¹⁴ Penalties can be applied by the NCBs in case of a failure to deliver the collateral. After the turmoil, the eligible collateral is broader than collateral generally accepted for loans at the EUREPO rate on the interbank (secondary) market. Nevertheless, the ECB applies valuation haircuts to adjust the value of collateral for which there is no obvious market price.

Figure 2 shows the relative weight for three 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). 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.

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.

¹³National Central Bank

¹⁴See section A.1.3 in the appendix for detailed discussion of eligible collateral.

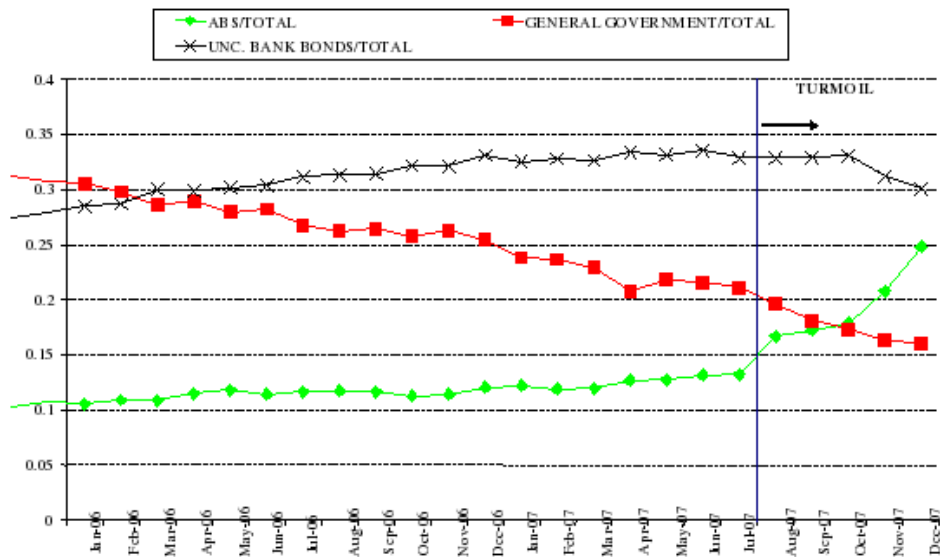


Figure 2: Use of Collateral by Asset Type (2006-2007)

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.

The first striking feature of this data is the sudden change in bidding behavior that occurred after the turmoil. Just a quick glance at the aggregate bid curves¹⁵ 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 are shown in Figure 3. 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 by many as an indicator of industry expectations of the relevant market interest rates since as mentioned above it can be used together with overnight borrowing as an alternative to bidding in the repo auctions. After August 9th, 2007, a significant upward shift of all aggregate bid curves is quite evident.

Table 1 offers some important summary statistics of the full sample. On average, there are 341

¹⁵The 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.

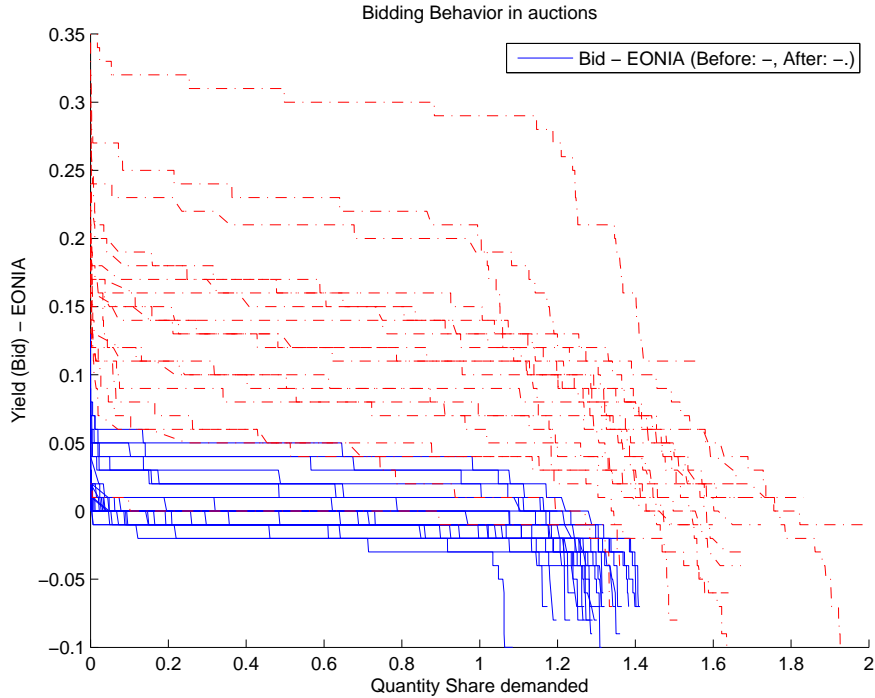


Figure 3: Aggregate quantity-weighted average bid

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%.

Table 1: 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
Quantity bid	0.004	0.012	$3 * 10^{-6}$	0.18
Issued Amount (billions €)	259.89	52.77	155	330.5

Table 2 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) and the decrease in the amount of liquidity offered for sale (from 292.34 to 202.19 billions EUR). 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. Another potential explanation could 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. 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.

Table 2: 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
Quantity bid	0.004	0.005	0.009	0.014
Issued Amount (billion €)	292.34	202.19	1.42	4.51

After August 2007 bids become much more dispersed as shown by the aggregate bid curves depicted with dashed-dot lines (-.) in Figure 3. The aggregate bid curve in each auction also 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 unwillingness to lend in the term interbank market. 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. 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.

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 a reserve requirement) 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.

We assume that these methods are fulfillment are perfect substitutes but access is limited to them 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 $u_i > s_i$. We assume that $\{r_i, k_i, l_i, u_i, s_i\}$ are independent (conditional on variables commonly observed by banks) across banks.

For simplicity, assume that banks place a single bid b_i in the EB auctions. In reality, banks can submit multiple price-quantity bids corresponding to a demand schedule, and we will relax this in the next subsection, though a large number of banks submit single bids.¹⁶ Assuming $s_i < b_i < u_i$, the bank's best-response problem is to maximize:

$$\max_{b_i} [k_i(v_i - b_i) + (r_i - k_i)(v_i - s_i)] \Pr(\text{win}|b_i) + [l_i(v_i - s_i) + (r_i - l_i)(v_i - u_i)] (1 - \Pr(\text{win}|b_i))$$

¹⁶59% of all bids have just one step.

where v_i is bank i 's private willingness-to-pay for liquidity and $\Pr(\text{win}|b_i)$ is bank i 's belief that her bid of b_i will win the auction. Note, however, v_i does not play a role in the optimal bidding decision problem, as it cancels out when we take the first-order condition:

$$b_i + \frac{\Pr(\text{win}|b_i)}{\frac{\partial \Pr(\text{win}|b_i)}{\partial b}} = (1 - \alpha_i)u_i + \alpha_i s_i$$

where $\alpha_i = l_i/k_i$, i.e. the fraction of the ECB-acceptable collateral that is acceptable in the interbank secured lending market. Notice that the left-hand side is the bid + markup term which governs bidding in a regular first price auction. This shows that the bids in these auctions can be connected, through the markup term, to a convex combination of the secured and unsecured rates in the secondary market *at which this bank could transact*. The weights in this convex combination are determined by the ratio of “good” vs “bad” collateral, α_i , on bank i 's balance sheet. As α_i gets smaller, the bid + markups in the ECB auction should get closer to unsecured loan rates. If α_i is close to one, bid + markup should be very close to secured loan rates.

5.1 A More Realistic Model and an Econometric Framework

We now consider the more realistic setting where bidders are allowed to place multiple price/quantity bids; bidding, in effect, demand schedules. The model is 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 appropriate 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 in distributional strategies in this game exists when signals are independent and provides its characterization via a set of necessary conditions for each step k given by (1) below.¹⁷

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

¹⁷The model and its assumptions are formally spelled out in section 5 in the appendix.

Equation (1), which is the analog of equation (5) in our simplified model, 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 simple model above, 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 the same as in the single-unit first-price auction. Recall that the equilibrium bidding rule in a single unit first price auction with independent private values prescribes a bidder with private value v to bid according to $v = b + \frac{G(b)}{(N-1)g(b)}$, i.e., to mark down the value by the inverse hazard ratio of the bid distribution evaluated at the bid. The trade-off of whether or not increasing the bid by \$1 is thus between the change in the probability of losing the unit and thus not obtaining the surplus $v - b$, which is the density of the first order statistic of the $N - 1$ rivals’ bids, $(N - 1)G^{N-2}(b)g(b)$ versus saving that \$1 which would occur with probability that all rivals’ bids were lower, $G^{N-1}(b)$. 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, $\hat{K}(s_i)$, that bidder i submits. Notice that if signals were independent, the probabilities in (1) would not be conditional on s_i , but would still be, of course, a function of the submitted bid curve. Using this necessary condition, we obtain point estimates of marginal values at submitted quantity-steps nonparametrically using a resampling method as described in our earlier work.¹⁸ The resampling method that we employ is based on simulating different possible states of the world (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

¹⁸See Hortaçsu and Kastl (2008) for formal treatment of the estimation.

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.

5.2 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. The classification is achieved by regressing the quantity-weighted average of the marginal value estimates normalized by EONIA on the turmoil dummy separately for each bidder. If the estimated coefficient on the turmoil dummy is significant at 5% level, we classify this bidder as one who experienced an increase in marginal values in the post-turmoil period. In the third step 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 which 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.¹⁹

¹⁹While 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 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.

6 Results

The change in bidding behavior documented in figure 3 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. 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 turmoil²⁰ 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 axis). This suggests that indeed buying the fixed leg of the SWAP and borrowing overnight was an

²⁰Recall 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.

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).

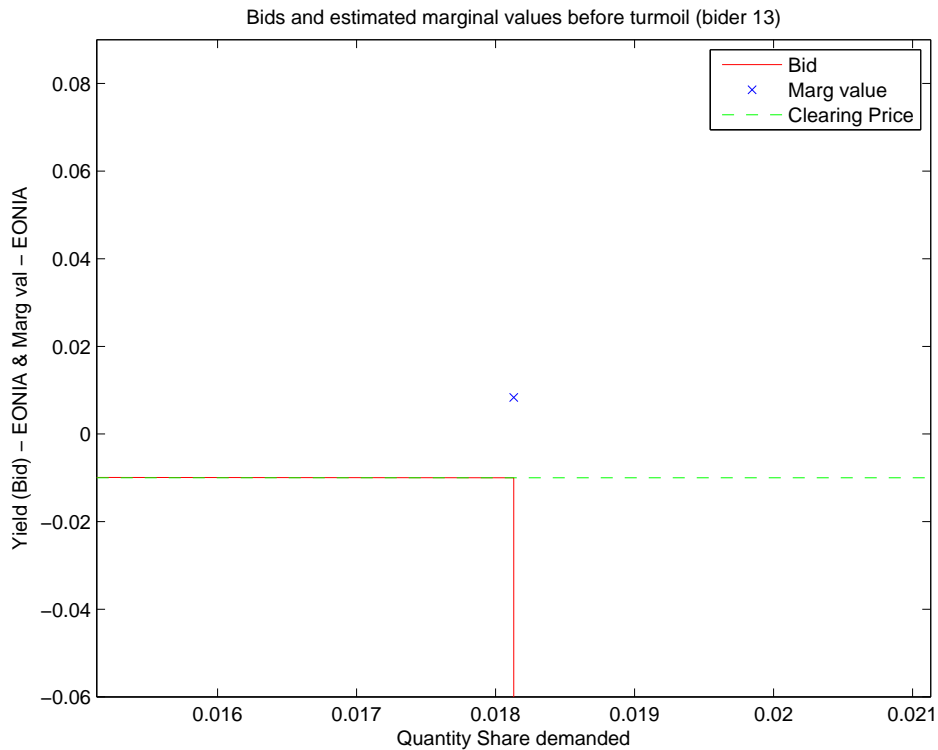


Figure 4: Bid and Estimated Marginal Value (Before Turmoil)

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 curves before the turmoil (normalized by subtracting the EONIA swap rate), whereas the dash-

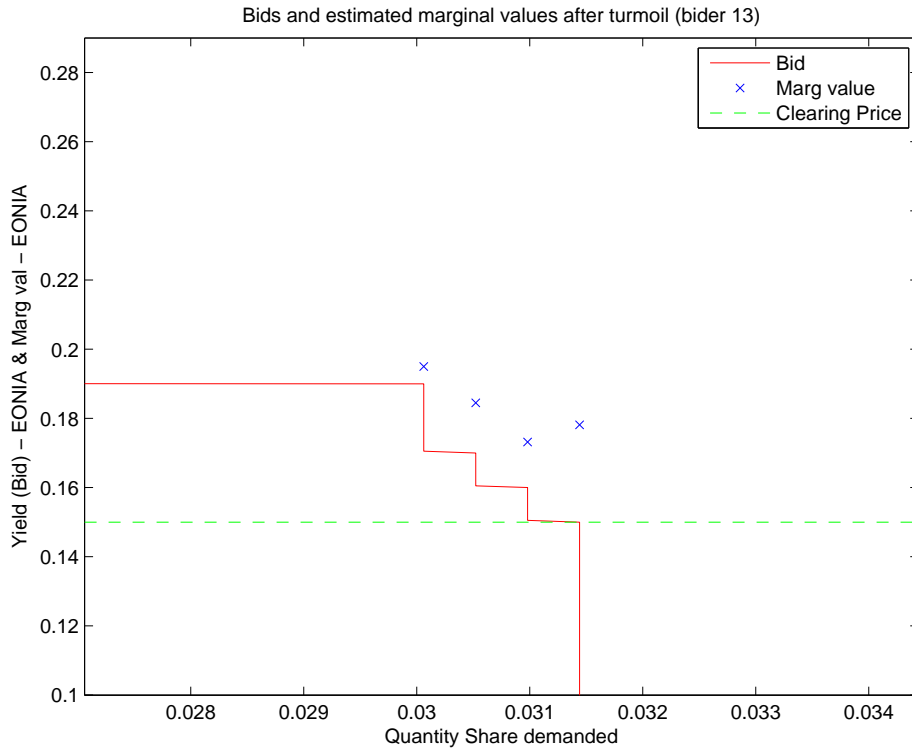


Figure 5: Bid and Estimated Marginal Value (After Turmoil)

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 7 and 8 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 of shading in figure 7 is less than 1 basis point, whereas in figure 8 it increases to about 3 basis

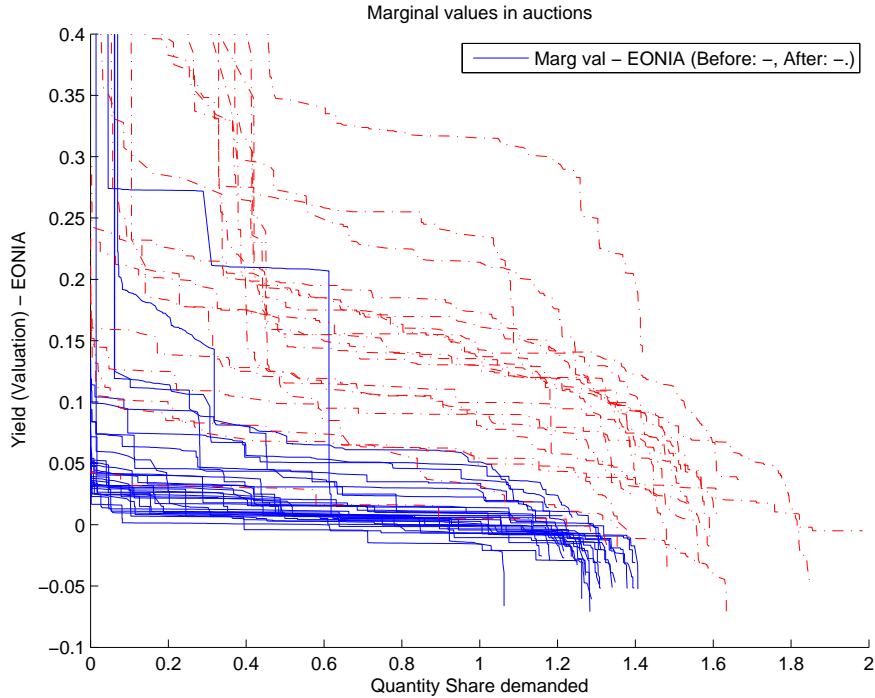


Figure 6: Estimated Aggregate Marginal Valuation Curves

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.

6.1 A Reality Check

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 + 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. In our application, 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.²¹ Indeed, in figures 7 and 8 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

²¹Results are similar if we use the EONIA SWAP rate instead of the EUREPO.

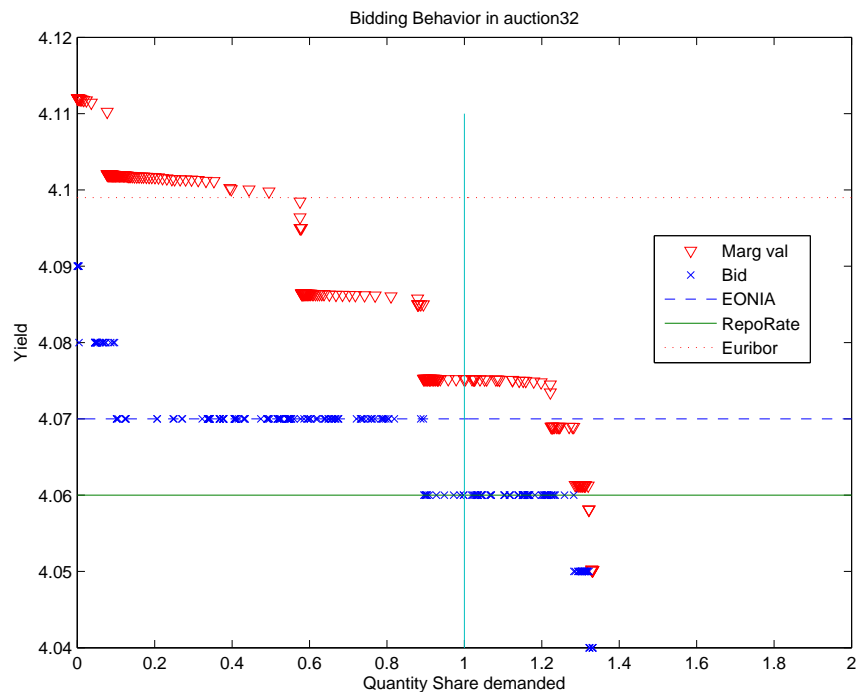


Figure 7: Aggregate Bid and Estimated Aggregate Marginal Values Curve (Before Turmoil)

our structural model are reasonable. In many auctions in the post-turmoil period, however, this relationship fails. In particular, as figure 9 illustrates there are many auctions which clear at rates that are above the unsecured rate (EURIBOR) which suggests that this rate is not the rate at which any bank can borrow.

Taking the model in Section 5 somewhat more seriously, we asked 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 suggesting that the unsecured interest rate that would rationalize that banks marginal value in the primary auction lies above EURIBOR - the reported unsecured rate. Restricting attention to $\alpha \in (-1, 1)$ and taking the mean of α_i across all bidders pre-turmoil, we get 0.17, i.e., that the ratio of ‘bad’ to ‘good’ collateral was about 6:1. The median bank’s α is 0.29, hence our estimates suggest that for over half of

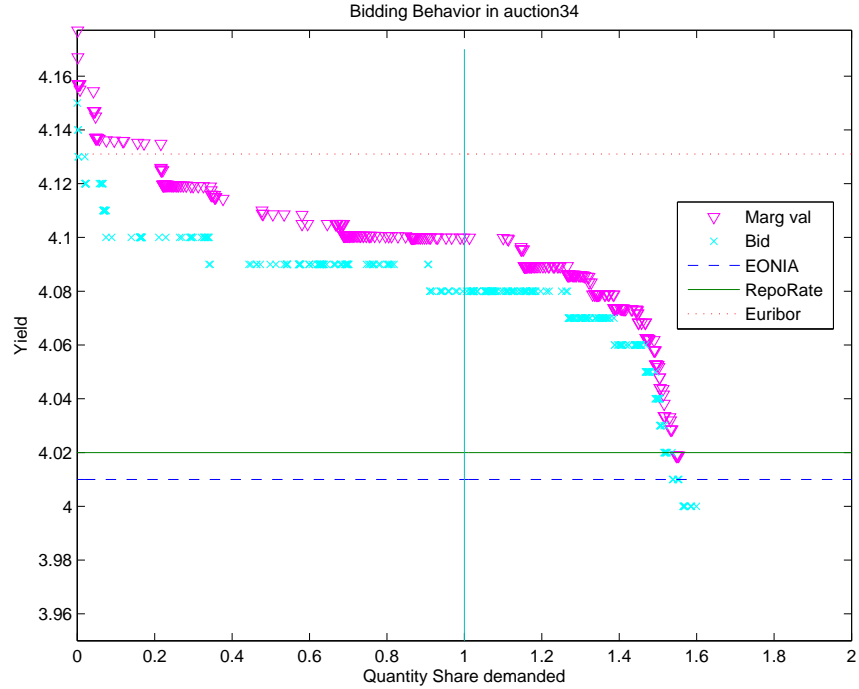


Figure 8: Aggregate Bid and Estimated Aggregate Marginal Values Curve (After Turmoil)

the banks the ratio of “good to bad” collateral was about 1:3 in the pre-turmoil period. In the post-turmoil period, the average α decreased to -0.01 , and the median to -0.02 which suggests that even an average bank was not able to borrow at EURIBOR. The most interesting finding is, however, when we decompose these changes in the hypothetical collateral structure based on our classification of bidders: the ones that we labeled as being significantly affected by 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 insignificantly affected bidders’ mean α in fact even slightly increases from 0.466 to 0.474, but the median decreases from 0.18 to 0.10.²²

In our second exercise we abandon the assumption that everybody can get a loan at the unse-

²²Recall 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, we do not have both their pre- and post-turmoil bids, and therefore 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.

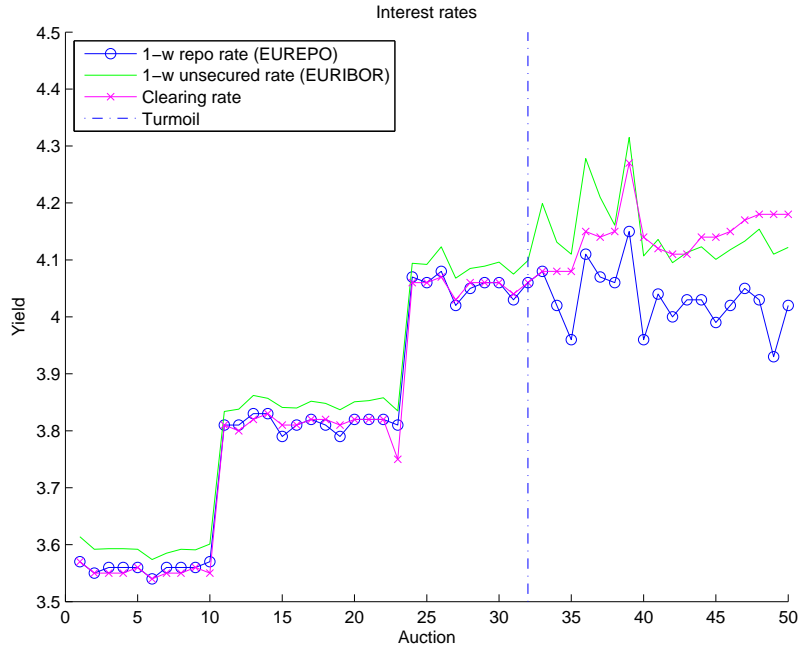


Figure 9: EUREPO, EURIBOR and primary auction clearing rates

cured interest rate and instead compare directly the estimate 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, 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 is 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 indeed s places a lower bound on the marginal value of liquidity obtained in the primary market as we would expect.

6.1.1 A Reality Check on EURIBOR

As the found above, many of the bids, 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, the fact that many auctions in the latter part of our sample cleared above the EURIBOR (in figure 9) is a clear indication that there must have been excess demand for uncollateralized loans at the EURIBOR rate. Thus, any evaluation of policy actions based on levels or changes of secured and unsecured interest rates (such Taylor and Williams (2008a and b), 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) 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. 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)).²³

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.

6.2 Identification of “Distressed” Bidders

Figure 10 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 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.

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 11 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

²³Brunnermeier (2008) 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, 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.

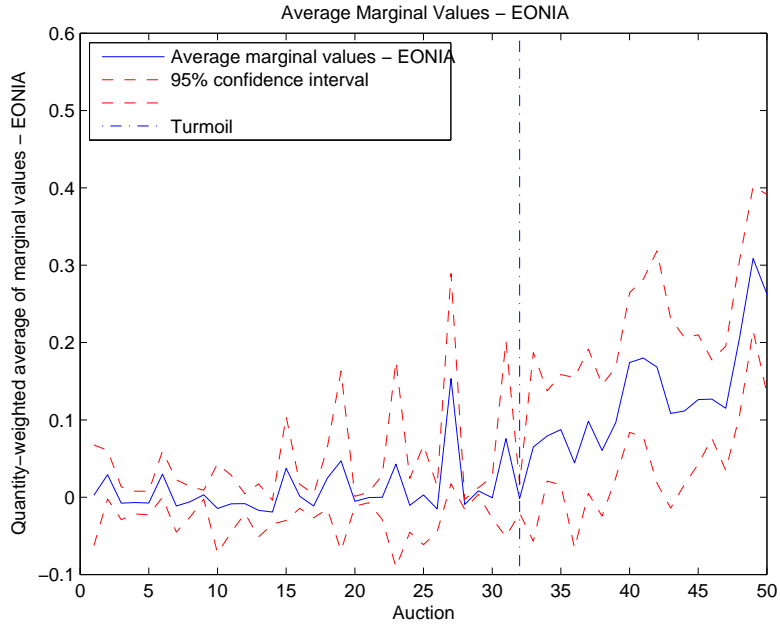


Figure 10: Quantity-weighted average marginal values (across all bidders)

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 3 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.

Table 3: Predicting Potential Problems

Based on	Bids	
	Yes	No
Values	Yes	326
	No	96

As a placebo test of the last exercise, we also tried focusing exclusively on the time period

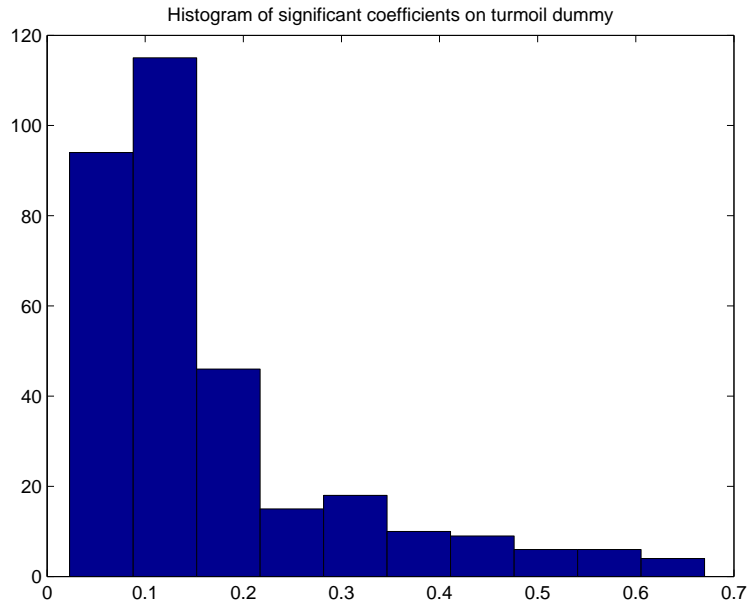


Figure 11: Histogram of Significant Turmoil Effects

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 3 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 participation among 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.

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

6.4 Allocative Efficiency of the Auction Mechanism

Using the estimated marginal values, we can also evaluate whether the allocations implemented in each auction were efficient. In particular, we can compute the (estimated) surplus from an allocation in which banks with highest values would be awarded the liquidity and compare this surplus to the surplus from the actual allocation. Figure 12 shows the results from this exercise, where we plot the ratio of the actual surplus to the efficient one. It is immediately noticeable from this figure that the average efficiency of the allocation achieved via the discriminatory auction in the

primary market significantly declined following August 2007. In fact, the misallocation of liquidity can amount to as much as 5% of the achievable surplus. These results should be interpreted with caution, however, because as we argued above the turmoil was likely accompanied with a significant increase in heterogeneity of marginal values. Since with homogenous marginal values even a random allocation would be efficient, the fact that we observe a decline in efficiency could simply be a consequence of this increase in value heterogeneity. For this reason we also conducted another experiment: we compared the surplus achieved by the allocation implemented by each discriminatory auction to the surplus from a random allocation. Figure 13 illustrates that the fact that the central bank was running auctions in the primary market in the pre-turmoil period led to very small gains relative to allocating liquidity for example by running a lottery. In the post-turmoil period, however, the auction became an important tool how to elicit information about bidders' values and thus the discriminatory auctions achieved a much higher surplus than a lottery would have achieved. We might take away from this exercise that since the turmoil increased heterogeneity of values, the way liquidity gets allocated in the primary market has important implications for overall market efficiency.

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 structure of each bank's balance sheet and its wish to improve it and (ii) by the private information of each bank about its liquidity position, i.e., its needs to satisfy the prescribed reserve requirements. We now would like to argue that the first source of private information, i.e., the state of a bank's portfolio, which after the outbreak of the subprime crisis might, for example, exhibit too much exposure to the asset-backed securities risk is relatively more important in driving the variation of the values. In order to make our argument, we complement our data set and our estimates of marginal values with additional detailed bank-level data for a 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; and (2) bank specific data, some of which is publicly available - bank's CDS and asset sizes, and other which

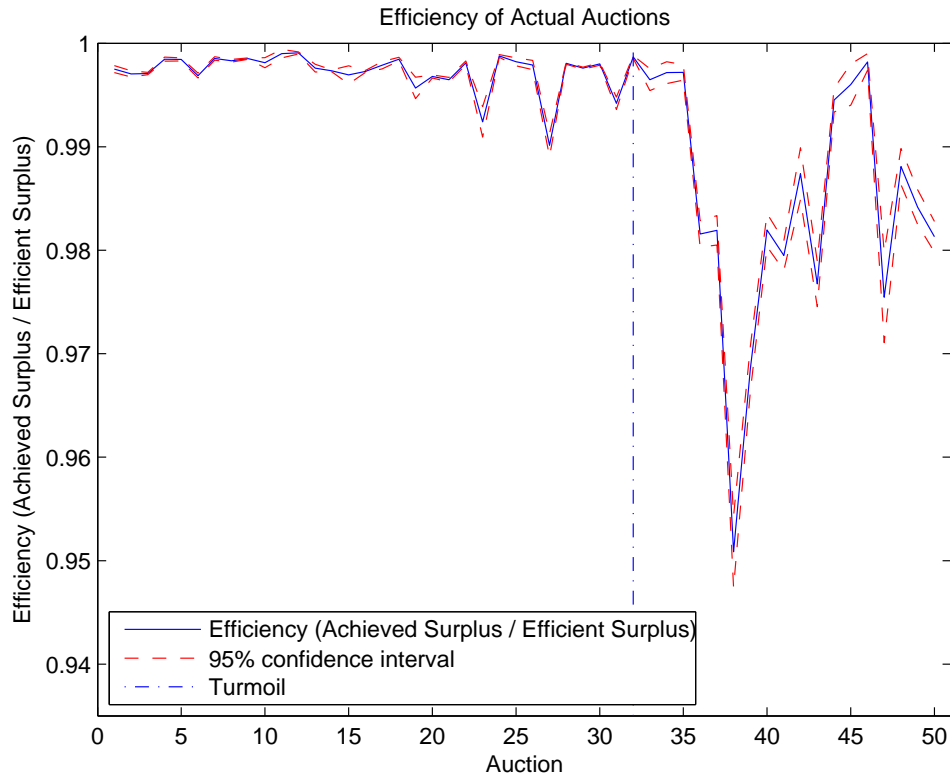


Figure 12: Efficiency of Allocation

is non-public data - volumes allotted at the LTROs, banks' current accounts with the NCBs and reserve requirements. 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).

We now briefly summarise which effects we expect from each variable included in the analysis below: one-week EUREPO rate, Deficiency, LTROs and CDS.

As mentioned earlier, the *one-week Eurepo rate* normally sets the floor for bid rates (if above the MBR) 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 of bids and marginal values for all banks. The *CDS premium* captures the potential impact of asymmetric information in the inter-bank market - credit risk and credit rationing on the bidding behaviour of a bank and marginal valuations. Higher values of this variable should lead to an increase in

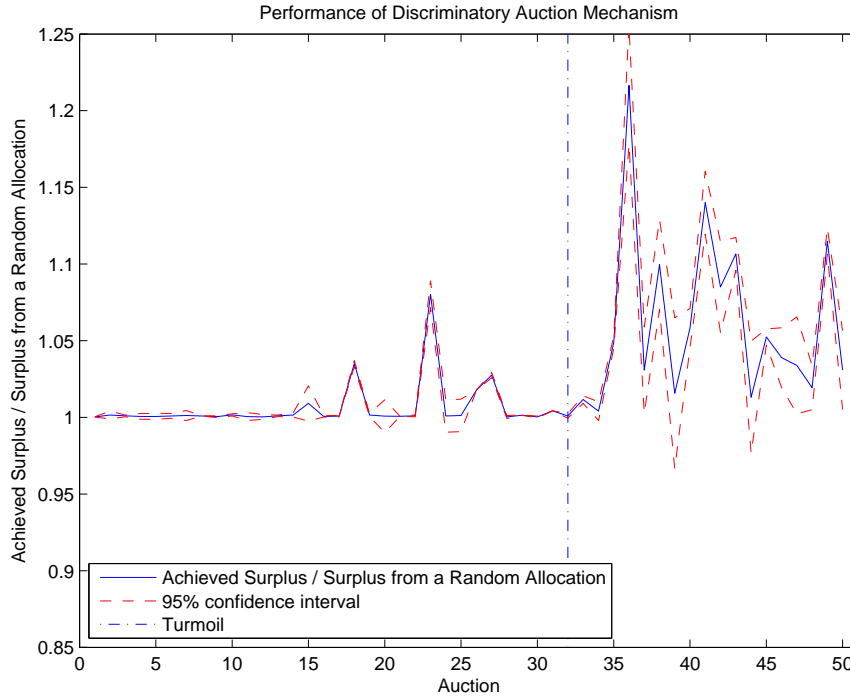


Figure 13: Performance of the Discriminatory Auction

the bids and marginal values of liquidity at the central bank auctions. *Volumes allotted at the LTROs* capture the impact of term liquidity funding pressure. The higher the term-liquidity a bank receives from the central bank (LTROs), the smaller the marginal value for liquidity in the short-term auction (MRO). This captures the phenomena often mentioned by market participants that term funding dried-up during the turmoil; *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.

All variables are self explanatory except *Deficiency* and *CDS*. The *Deficiency* variable is calcu-

lated, 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 (for each bank it is fixed within the maintenance period, and varying across maintenance periods) 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.

The Credit Default Swap variable, CDS_{it} , is based on daily data for traded CDS for each bank, and therefore is determined by the market. We use CDS on the day before the MRO. We define a relative credit default swap variable as CDS relative to the average of all other banks to purge possible trend correlated with other variables used: $RCDS_{it} = \frac{CDS_{it}}{\frac{\sum_{j \neq i} CDS_{jt}}{N_{j \neq i}}}$

Since not all banks participate in every auction, we use the two-step Heckman selection framework (Heckman 1976, 1979) to model the quantity-weighted average marginal value of bank i in auction t . The characteristics, X_{it} , included in the outcome equation which influence the observed outcome, v_{it} , are both bank-varying ($Deficiency_{it}$, $RCDS_{it}$, $LTRO_{it}$) and auction-varying char-

acteristics ($EUREPO_t$) observable to all market participants and a turmoil dummy (as well as interactions of this dummy with the aforementioned variables). The vector W_{it} , which enters the selection equation, contains characteristics of the banks and the market that we think can affect the decision of a bank to participate, which are all variables included in X_{it} and two additional ones: lagged participation variable and the total assets of bank i in auction t (bank size). The bank size is included because larger banks have higher reserve requirements to fulfill and therefore are more likely to participate in the auctions than their smaller counterparts. Also, a bank that participates in an MRO is more likely to participate again if bidding has some (entry) costs (e.g. a bank in the market knows the market better).

The results of the analysis of the weighted marginal value of each bank are presented in table 4. We interacted all variables with a turmoil dummy, T , ($T = 1$ for MRO tenders after August 9th, 2007; $T = 0$ otherwise). In the specifications with auction fixed effects, the EUREPO rate is omitted. The estimates show that the EUREPO 1-week rate explains marginal values both before and after the turmoil since there is no significant change in the estimated coefficient. After the turmoil, deficiency (which is each bank's private information) has a positive impact on marginal values after the turmoil suggesting that banks with a lot of reserves to accumulate until the end of the maintenance period have higher marginal values for liquidity obtained in the primary market. Liquidity received at the longer-term refinancing operations has a negative impact on the marginal valuations at the weekly operation before the turmoil. This shows funding substitutability as banks that received a lot at the LTRO are less pressed to get liquidity at the MRO. Interestingly, after the turmoil (LTRO*Turmoil), there is evidence of funding complementarities - banks with high allocations at LTROs also tend to have high marginal values for obtaining liquidity also at the MROs. RCDS has a positive, but statistically insignificant impact on marginal values (recall that RCDS is public information); banks that pay a higher premium to insure investors against default tend to have higher marginal value for liquidity obtained in the primary market. The Mills lambda is not significant, which suggests that there is no evidence of sample selection bias. All results are robust to the inclusion of bidder-specific and auction-specific fixed effects.

Table 4: Analysis of Marginal Values

	Marginal Value		Participation Equation	
	(1)	(2)	(1)	(2)
Constant	0.16 (0.85)	3.85*** (69.43)	-3.51* (-1.86)	-3.16*** (-2.6)
Turmoil	1.49 (1.35)	0.39*** (5.85)	-13.04* (-1.71)	-0.41 (-0.67)
EUREPO	0.97*** (18.97)	-	0.04 (0.93)	-
EUREPO* Turmoil	-0.33 (-1.22)	-	3.24* (1.71)	-
Deficiency	0.0001 (0.03)	-0.001 (-0.21)	0.05 (1.60)	0.051 (1.47)
Deficiency*Turmoil	0.02*** (5.09)	0.02*** (4.34)	-0.02 (-0.48)	-0.012 (-0.27)
log(LTRO)	-0.00003*** (-3.95)	-0.0000*** (-3.56)	0.0002** (2.26)	0.000 (1.46)
log(LTRO)*Turmoil	0.0315*** (3.39)	0.03*** (3.10)	-0.27** (-2.36)	-0.21 (-1.61)
RCDS	0.001 (0.50)	0.001 (0.59)	-0.003 (-0.19)	-0.015 (-0.78)
RCDS*Turmoil	0.0055*** (2.60)	0.005** (2.44)	0.007 (0.41)	0.017 (0.85)
log(Total Assets in 2006)			0.19** (2.42)	0.22*** (2.57)
Lagged Participation			2.36*** (18.38)	2.66*** (16.66)
Mills Lambda	-0.026 (-0.96)	-0.034 (-1.25)		
Auction and bidder FE	No	Yes	No	Yes
Uncensored obs	691			
Censored obs	228			

^a z-statistics in parentheses

* Significant at 10% level.

** Significant at 5% level.

*** Significant at 1% level.

7 Conclusion

In this paper we document the effect of the turmoil in financial markets from August 2007 that was related to the outbreak of the subprime market crisis on bidding behavior in primary auctions of liquidity conducted by the European Central Bank. Estimating a model of bidding in these auctions we found that the change in bidding behavior was to a large extent caused by an outward shift in marginal values for liquidity obtained in the primary market for many bidders, which suggests that the outside option of obtaining liquidity in the secondary market became for many banks much less accessible. Since the ECB (the auctioneer in the primary market) accepted collateral, which might not have been accepted in the secondary market against a loan at a reasonable rate, the liquidity obtained in the primary market became quite attractive. We estimate that large banks, which usually are the most frequent participants in the primary market auctions, are also the ones for whom the marginal values increased the most. We argue that ignoring the equilibrium effect by analyzing only the bid data would lead to wrongfully concluding that virtually all banks that participate in the primary auctions suffered from the above described effect of the turmoil, i.e., from the harder access to liquidity.

References

- [1] Arnold, Lutz, and Riley, John, “On the Possibility of Credit Rationing in the Stiglitz-Weiss Model,” *The American Economic Review*, forthcoming, 2008
- [2] Ashcraft, A., M. Bech, W. S. Frame, “The Federal Home Loan Bank System: The Lender of Next to Last Resort?”, mimeo, 2008.
- [3] Athey, S., and Haile, P., “Nonparametric Approaches to Auctions,” forthcoming in J. Heckman and E. Leamer, eds., *Handbook of Econometrics, Vol. 6*, Elsevier, 2005
- [4] Ausubel, Lawrence, and Cramton, Peter, “Demand Reduction and Inefficiency in Multi-Unit Auctions,” mimeo, 2002

- [5] Back, Kerry, and Zender, Jamie, “Auctions of Divisible Goods: On the Rationale for the Treasury Experiment,” *The Review of Financial Studies*, Vol. 6., No. 4, pp. 733-764, 1993
- [6] Bindseil, Ulrich, Nyborg, Kjell and Strebulaev, Ilya, “ Bidding and Performance in Repo Auctions: Evidence from ECB Open Market Operations,” mimeo 2005
- [7] Brunnermeier, Markus, “Deciphering the Liquidity and Credit Crunch 2007-08,” mimeo 2008.
- [8] Brunnermeier, Markus, and Pedersen, Lasse, “Market Liquidity and Funding Liquidity,” *The Review of Financial Studies*, forthcoming, 2009
- [9] Caballero, Ricardo, and Krishnamurty, Arvind, “ Financial System Risk and Flight to Quality,” mimeo 2005
- [10] Chapman, James, McAdams, David, and Paarsch, Harry, “Bounding Best-Response Violations in Discriminatory Auctions with Private Values,” mimeo, 2006
- [11] Chari, V.V., Christiano, Lawrence, and Kehoe, Patrick, “ Facts and Myths about the Financial Crisis of 2008,” mimeo 2008
- [12] Christiano, Lawrence, “Looking Behind the Aggregates: A Reply to “Facts and Myths About the Financial Crisis of 2008” ,” mimeo, 2008
- [13] Cohen-Cole, Ethan, Duygan-Bump, Burcu. Fillat, Jose, and Montoriol-Garriga, Judit, “Looking Behind the Aggregates: A Reply to “Facts and Myths About the Financial Crisis of 2008” ,” Federal Reserve Bank of Boston, 2008
- [14] Duffie, Darrell, Garleanu, Nicolae, and Pedersen, Lasse, “Over-the-Counter Markets,” *Econometrica*, Vol. 73, pp. 1815-1847, 2005
- [15] Duffie, Darrell, Garleanu, Nicolae, and Pedersen, Lasse, “Valuation in Over-the-Counter Markets,” *The Review of Financial Studies*, Vol. 20, pp. 1865-1900, 2007
- [16] Eisenschmidt, Jens and Tapking, Jens, “ Liquidity Risk Premia in Unsecured Interbank Money Markets,” mimeo, 2008

- [17] Ewerhart, Christian, Cassola, Nuno, and Valla, Natacha, “Declining Valuations and Equilibrium Bidding in Central Bank Refinancing Operations,” mimeo 2008
- [18] Ewerhart, Christian, and Tapking, Jens “Repo Markets, Counterparty Risk and the 2007/2008 Liquidity Crisis,” ECB Working Paper No. 909, June 2008
- [19] Garleanu, Nicolae, and Pedersen, Lasse, “Liquidity and Risk Management,” *The American Economic Review*, P&P, Vol. 97, pp. 193-197, 2007
- [20] Heckman, James “The common structure of statistical models of truncation, sample selection, and limited dependent variables and a simple estimator for such models,” *Annals of Economic and Social Measurement*, 5, 475492, 1976
- [21] Heckman, James, “Sample selection bias as a specification error,” *Econometrica*, 47(1), pp. 153-161, 1979
- [22] Holmstrom, Bengt, and Tirole, Jean, “ Private and Public Supply of Liquidity,” *Journal of Political Economy*, Vol. 106, No. 1, pp. 1-40, 1998
- [23] Hortaçsu, Ali, “Mechanism Choice and Strategic Bidding in Divisible Good Auctions: An Empirical Analysis of the Turkish Treasury Auction Market,” mimeo, 2002
- [24] Hortaçsu, Ali and Kastl, Jakub, “Do Bidders in Canadian Treasury Bill Auctions Have Private Values?,” mimeo 2008
- [25] Kastl, Jakub, “Discrete Bids and Empirical Inference in Divisible Good Auctions,” mimeo, 2006
- [26] Kastl, Jakub, “On the Properties of Equilibria in Private Value Divisible Good Auctions with Constrained Bidding,” mimeo, 2008
- [27] McAdams, David, “Monotone Equilibrium in Multi-Unit Auctions,” *Review of Economic Studies*, forthcoming, 2006a
- [28] Michaud, Francois-Louis, and Upper, Christian, ”What drives interbank rates? Evidence from the Libor panel,” *BIS Quarterly Review*, March 2008

- [29] Taylor, John, and Williams, John, “A Black Swan in the Money Market,” mimeo, 2008
- [30] Taylor, John, and Williams, John, “Further Results on a Black Swan in the Money Market,” mimeo, 2008
- [31] Wang, Jim and Zender, Jamie, “Auctioning Divisible Goods,” *Economic Theory*, 19, pp.673–705, 2002
- [32] Wilson, Robert, “Auctions of Shares,” *Quarterly Journal of Economics*, 1979
- [33] Wu, Tao, “On the effectiveness of the Federal Reserve’s new liquidity facilities,” Federal Reserve Bank of Dallas Working Paper 0808, 2008

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 NCBs²⁴). They are computed on a lagged accounting basis by applying a reserve ratio (currently at 2%) to the reserve base. The reserve base includes short-term liabilities of banks (deposits and debt securities with maturity below or equal

²⁴National Central Banks

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.²⁵ 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 Monday²⁶, the execution on Tuesday²⁷ and settlement on Wednesday. On the announcement day (Monday) the ECB publishes an estimate of

²⁵The interest rate corridor was narrowed to ± 50 basis points as of October 9, 2008.

²⁶Info in Reuters page ECB16.

²⁷Info in Reuters page ECB17.

the average autonomous factors²⁸ 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. rationing 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 (ECAAF) has been set up in order to evaluate the eligible collateral. The collateral accepted by the Eurosystem is very broad. Two types of assets are included in the

²⁸Defined as Autonomous factors (AF) = Net Foreign Assets (NFA) + Net Assets Denominated in Euro (NDA) - Banknotes (BN) - Government deposits (GOV) - Other (O).

list: marketable and non-marketable. The ECB publishes daily a list of eligible marketable assets on its website.²⁹ 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 EEA³⁰, the place of establishment of the issuer must be the EEA and non-EEA G10 countries, the currency must be EUR.³¹ 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).³² 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 assessment framework for this type of asset. The performance of the credit assessment systems is

²⁹Eligible assets are listed at: https://mfi-assets.ecb.int/dla_EA.htm

³⁰European Economic Area

³¹Since 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.

³²As of October 25 2008 and until December 2009 the ECB lowered the threshold to BBB- (except for ABS still A-).

reviewed annually. 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.³³

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.³⁴ 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, the number of potential bidders participating in an auction, N , is also commonly known. This

³³Additional haircuts will be applied to all newly eligible marketable assets.

³⁴Since 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).

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.³⁵ 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: $\sigma_i : S_i \rightarrow \mathcal{Y}$. 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, $\bar{K} = 10$, we impose the following assumption:

Assumption 3 Each player $i = 1, \dots, N$ has an action set:

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

Therefore the set \mathcal{Y} includes all non-decreasing step functions with at most 10 steps, $y : \mathbb{R}_+ \rightarrow [0, 1]$, 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 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.

³⁵Bindseil, Nyborg and Strebulaev (2005) provide some econometric evidence that private values might be appropriate in case of repo auctions.

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 $\exists \underline{p}, \bar{p}$ such that $\forall p \in [\underline{p}, \bar{p}] : TD(p) = Q$, then the market clearing price, p^c , satisfies $p^c = \bar{p}$, 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:

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

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 $\mathbf{y}(\cdot|s) = [y_1(\cdot|s_1), \dots, y_N(\cdot|s_N)]$, 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 . The following proposition proved in Kastl (2008) provides necessary conditions characterizing the equilibrium in discriminatory auctions with private values.

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 :

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

and at $K(s_i)$:

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

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

(ii) if $v(q, s_i)$ is a step function in q 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, then $\forall k \leq \hat{K}(s_i)$:

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

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 5 and Table 6).

Table 5: 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 6: 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 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 5) 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 7): *Outright portfolio - Reserve Base - Other = -463,426 million EUR*, where *Reserve Base = Banknotes + Current Accounts* and *Outright Portfolio = NFA + NDA - GOV*.

Table 7: 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 5 (also Table 7) the ECB provides liquidity to the banking system mainly via its regular *open market operations*. (The provision of liquidity via the marginal lending facility is negligible.)

$OMO + ML \hat{=} DF = AF + CA$. And

$MO = MRO + LTRO$.

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 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).

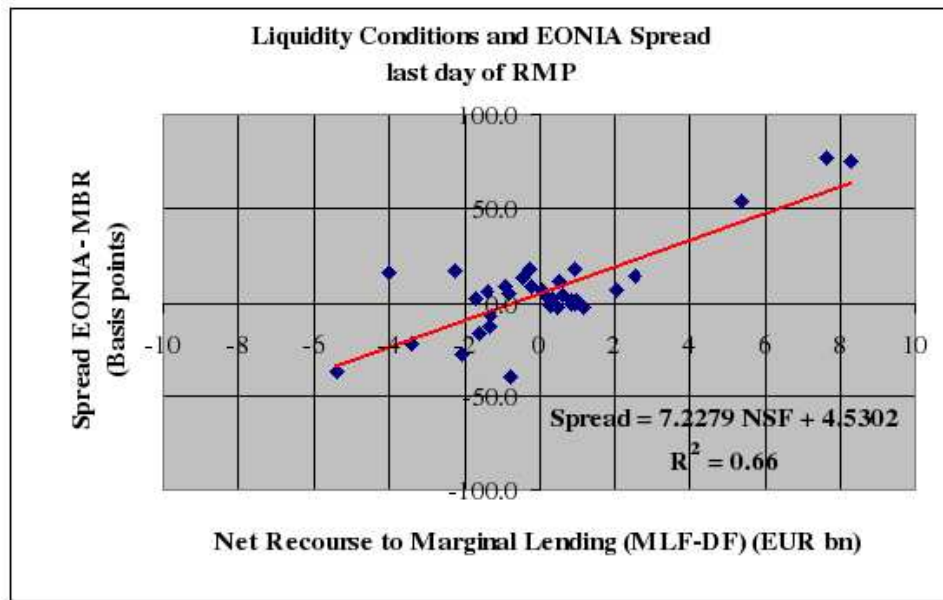


Figure 14: EONIA Spread and Liquidity Conditions on the Last Day of the RMP

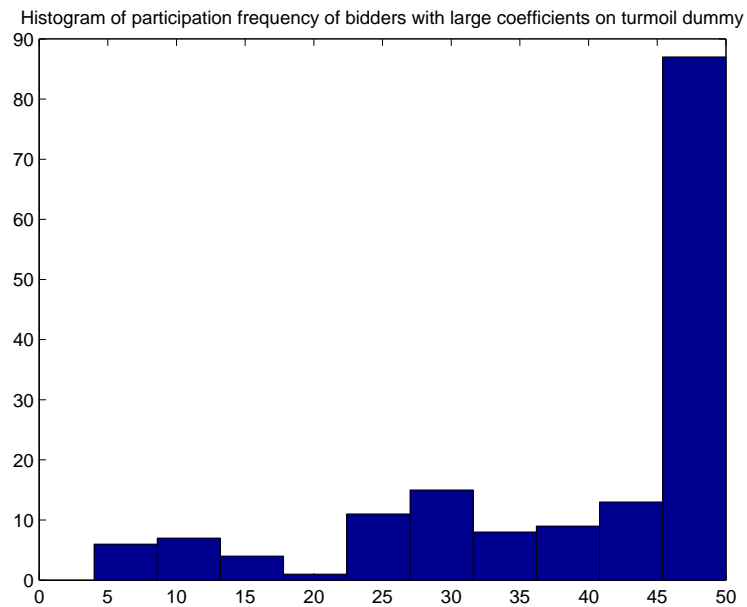


Figure 15: Histogram of Participation by Bidders with Large Turmoil Effects

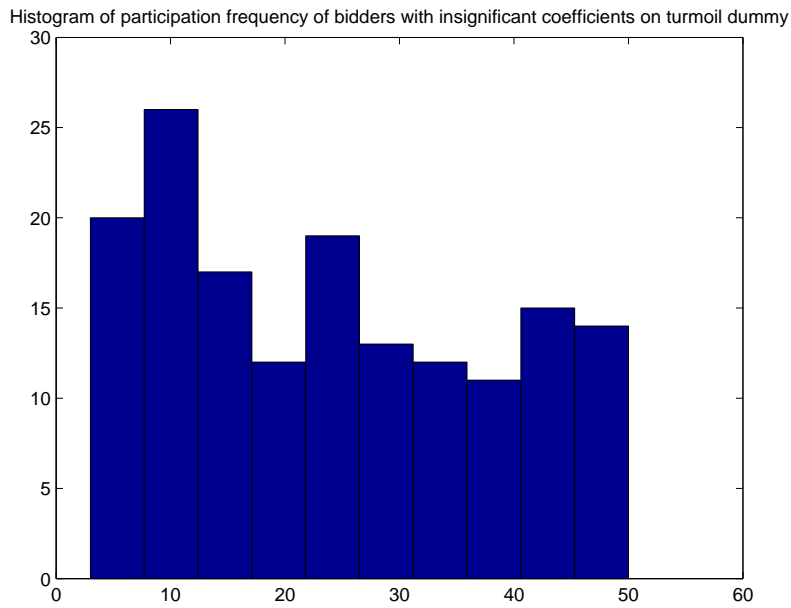


Figure 16: Histogram of Participation by Bidders with Insignificant Turmoil Effects

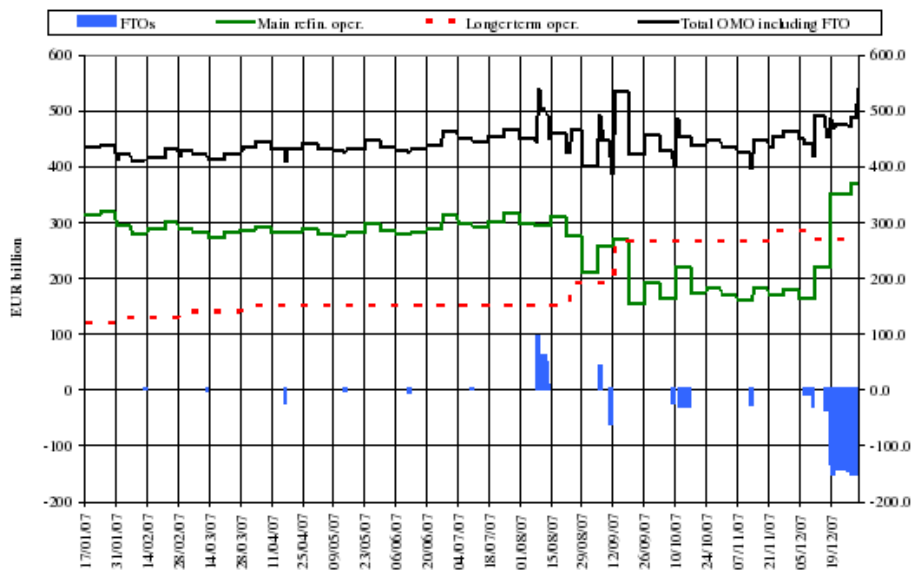


Figure 17: Liquidity Provision by the ECB in 2007

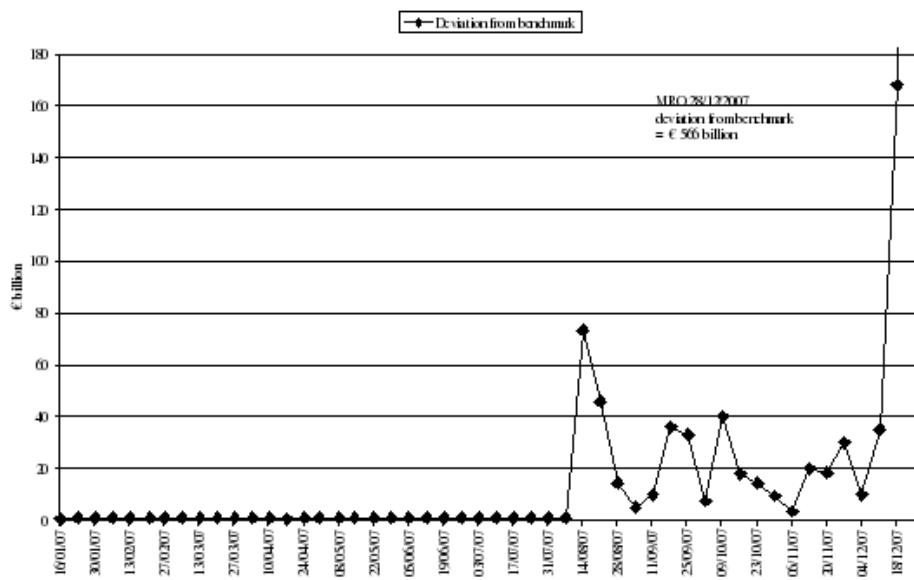


Figure 18: Deviation from Benchmark at the MROs in 2007