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## Structural econometric approach to bidding in the main refinancing operations of the Eurosystem

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EUROPEAN CENTRAL BANK

EUROSYSTEM

**WORKING PAPER SERIES**

**NO 793 / AUGUST 2007**

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# STRUCTURAL ECONOMETRIC APPROACH TO BIDDING IN THE MAIN REFINANCING OPERATIONS OF THE EUROSYSTEM <sup>1</sup>

by Nuno Cassola <sup>2</sup>,  
Christian Ewerhart <sup>3</sup>  
and Claudio Morana <sup>4</sup>



In 2007 all ECB publications feature a motif taken from the €20 banknote.

This paper can be downloaded without charge from <http://www.ecb.int> or from the Social Science Research Network electronic library at [http://ssrn.com/abstract\\_id=1003968](http://ssrn.com/abstract_id=1003968).

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## Abstract

This paper contributes to the existing literature on central bank repo auctions. It is based on a structural econometric approach, whereby the primitives of bidding behavior (individual bid schedules and bid-shading components) are directly estimated. With the estimated parameters we calibrate a theoretical model in order to illustrate some comparative static results. Overall the results suggest that strategic and optimal behavior is prevalent in ECB tenders. We find evidence of a statistically significant bid-shading component, even though the number of bidders is very large. Bid-shading increases with liquidity uncertainty and decreases with the number of participants.

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*Keywords: repo auctions, monetary policy implementation, primary money market, multi unit auctions, discriminatory auctions, collateral, central bank, nonparametric estimation*

## Executive Summary

The European Central Bank (ECB) provides refinancing to the banking system on a weekly basis via standard tender procedures. This paper contributes to the existing literature on central bank auctions by applying a structural econometric approach to modelling bidding behaviour at these tenders. The primitives of bidding behaviour are estimated (individual bid schedules and residual supply) and a re-sampling methodology is used to retrieve the individual bid-shading components (i.e. bid submitted below the marginal valuation). This is done in three steps: first, the market clearing price for each auction is estimated; second, given the market clearing price for each auction, the probability, for each bank, that an individual bid is successful is calculated; third, using these probabilities the first order optimality conditions are used, for each bank, to retrieve the individual bid-shading components.

The data set includes the bids submitted to the 31 weekly main refinancing operations conducted by the ECB between 16 March 2004 and 11 October 2004. Estimation has been performed by considering jointly the data for all the auctions for each bank, aggregating the bids over all the auctions, and averaging the bids to obtain the final data. The aggregation is justified by the stable environment that characterized the euro area money market over the period investigated both in terms of tender volumes and prices.

Overall the econometric results suggest that strategic and optimal behaviour is prevalent in ECB tenders. In fact, and despite some heterogeneity across bidders, there is evidence of a statistically significant bid-shading component even though the number of bidders is very large. Furthermore, we found that bid-shading increases with liquidity uncertainty and decreases with the number of participants and with price uncertainty. These results are fully in line with the theoretical predictions of a multi-unit auction model with discriminatory pricing and declining marginal valuations.

## 1. Introduction

The banking system in the euro area<sup>1</sup> is in a structural deficit position vis-à-vis the Eurosystem.<sup>2</sup> In fact, according to the consolidated financial statement of the Eurosystem<sup>3</sup> on 1 July 2005, on the asset side, the refinancing of the ECB provided to the banking system via open market operations and recourse to the marginal lending facility amounted to EUR 398 billion, of which EUR 308 billion corresponded to liquidity provided through the regular (weekly) main refinancing operations. The latter are executed in the form of tender procedures.<sup>4</sup>

Central bank operations and government auctions of treasury securities look like similar means of allocating a good. In particular, both take place in the environment of a secondary market which in principle allows potential buyers to arbitrage away any potential difference in prices between the primary and the secondary markets. However, the central bank auctions like those conducted by the ECB differ from treasury auctions in several important dimensions. Firstly, central bank refinancing is provided against collateral. To the extent that low opportunity cost collateral is used first, the marginal valuation of liquidity should be declining as collateral of better quality must be increasingly provided. Second, in the euro area banks have to fulfill reserve requirements and this, rather than reselling in the secondary market, is the main motive for banks to bid in the regular open market operations of the ECB. Third, unlike T-bills, there are only imperfect substitutes to ECB refinancing. For example banks face credit limits and may not be able to borrow the full extent of their liquidity needs, or they may not be willing to extend their own credit limits. Thus, borrowing in the primary market with the objective of reselling in the secondary market is not as prevalent as in the treasury bond market. Fourth, there is little uncertainty about

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<sup>1</sup>The euro area refers to the 13 European Union (EU) Member States that share a single currency - the euro. These countries are Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Slovenia and Spain.

<sup>2</sup>The Eurosystem refers to the European Central Bank (ECB) and the 13 National Central Banks (NCBs) of the participating EU Member States.

<sup>3</sup>The consolidated balance sheet of the Eurosystem shows that, on the liabilities side, the main liquidity absorbing factor is banknotes in circulation followed by current account holdings of credit institutions with the Eurosystem, where the latter cater essentially for the minimum reserve system. The consolidated balance sheet of the Eurosystem is published regularly in the Euro Area Statistics Annex of the ECB Monthly Bulletin.

<sup>4</sup>For details on the operational framework of the Eurosystem see "The implementation of monetary policy in the euro area: general documentation on Eurosystem monetary policy instruments and procedures", ECB, September 2006, downloadable from [www.ecb.int](http://www.ecb.int).



the (common) value of the good auctioned.<sup>5</sup> In fact, refinancing is provided for very short-term (overnight in the case of the marginal lending facility or one-week in the case of the main refinancing operations of the ECB) for which there is little price risk and, besides, a very liquid derivatives (swap) market exists, allowing hedging short-term interest rate risk.<sup>6</sup>

The combined features of declining marginal valuations, low uncertainty about the market value of the good and reserve requirements should be taken into account when modelling ECB tenders. In this paper we empirically test a model of optimal bidding in variable rate tenders using data from ECB auctions. Existing empirical work on the ECB main refinancing operations has relied exclusively on panel data analysis without any underlying structural model (see Nyborg et al. (2002) and Scalia et al. (2005)). Both papers conclude that bid-shading by participants to ECB tenders decreases with interest rate uncertainty, which is against the prediction of standard single-unit, common value auction theory (winner's curse). However, in none of these papers are the individual bid-shading components estimated. For example, Nyborg et al. (2002) compute two price measures, *discount* and *underpricing*, defined as the difference between the swap rate and, respectively, the quantity-weighted average bid rate and the quantity-weighted average winning rate for each bidder. As argued in this paper these measures may be good proxies for bid-shading only if marginal valuations are constant.

This paper contributes to the existing literature on central bank auctions in so far as it is based on a structural econometric approach, whereby the primitives of bidding behavior (individual bid schedules and bid-shading components) are directly estimated. With the estimated parameters we calibrate a theoretical model of the discriminatory auction, in order to illustrate some comparative static results. The remainder of the paper is organized as follows. Section 2 sets out the theoretical model of optimal bidding and Section 3 explains the econometric methodology. The data used in the study is described in Section 4 and the results are presented in Section 5. The main conclusions are presented at the end.

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<sup>5</sup>Except on the final day of the reserve maintenance period. In the euro area the reserve maintenance period has a variable length, of approximately one month.

<sup>6</sup>The announcement of the weekly auction takes place, as a rule, on Monday at 15:00, together with the publication of the Eurosystem's forecast of the average daily liquidity needs of the banking system until the next open market operation, stemming from the so-called autonomous factors. At the same time, the ECB also publishes the benchmark allotment which corresponds, in general, to the amount of reserves that, based on past fulfilment and the projected autonomous factors, would bring the average reserve holdings one week ahead in line with the reserve requirement plus a technical, small amount for excess reserves.

## 2. Theoretical framework

As mentioned in Section 1, the Eurosystem conducts weekly tenders whereby refinancing is provided to the banking system. The liquidity is allotted via standard tender procedures, pay-your-bid and pro-rata allotment at the cut-off price (marginal tender rate).<sup>7</sup> Formally these auctions are multi-unit auctions (or share auctions) with discriminatory pricing and a reserve price. The econometric approach employed in this paper is based on the idea that individual bidders face uncertainty about residual supply, as modeled by Klemperer and Mayer (1989), Kyle (1989), Back and Zender (1993) and Viswanathan and Wang (2002), among others. Ewerhart et al. (2006) have shown that when bidders have ex-post discretion about the choice of collateral that is used in funding transactions, as is the case in the Euro area, then such a model is consistent with the existence of a perfect secondary market for short-term credit. For complete references and details on the derivations, as well as for the discussion of uniform vs. discriminatory pricing, the reader is referred to Ewerhart et al. (2006). In this paper the discussion will focus exclusively on the discriminatory pricing case.

**Model** A central bank puts up for sale a random quantity, the total allotment  $\tilde{Q} \geq 0$ , of liquidity (i.e. a perfectly divisible good). There are two alternative interpretations for uncertainty about aggregate allotment. First, the central bank may possess a superior knowledge about the aggregate liquidity shortage facing the banking system. Second, there may be a fraction of non-strategic bidders. In practice, both effects contribute to the uncertainty about the residual supply perceived by the individual bidder (bank). For reasons of tractability we assume that  $\tilde{Q}$  is uniformly distributed in  $[0, \bar{Q}]$ . There are  $i = 1, 2, \dots, n$  bidders which do not observe the total allotment prior to the submission of bids. The central bank does not exploit its information about the incoming bid schedules to affect

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<sup>7</sup>The Eurosystem has the option of conducting either fixed rate (volume) or variable rate (interest) tenders. The main refinancing operations have been conducted as variable rate tenders, with a minimum bid rate, since June 2001. In the variable rate tenders banks may submit bids for up to ten different pairs of interest rate/quantity levels. The interest rates bid must be expressed as multiples of 0.01 percentage point. The minimum bid amount is EUR 1,000,000 and bids exceeding this amount must be expressed as multiples of EUR 100,000. Counterparties are expected to cover the amounts allotted to them (not their bids) by a sufficient amount of eligible underlying assets. For further details on the tender procedures see "The implementation of monetary policy in the euro area: general documentation on Eurosystem monetary policy instruments and procedures", ECB, September 2006, downloadable from [www.ecb.int](http://www.ecb.int).

the distribution of  $\tilde{Q}$ . Marginal valuations are assumed to be linearly decreasing from a maximum valuation  $\bar{v} > 0$  that is common to all bidders. Thus, bidder  $i$ 's marginal valuations for quantities  $q_i \geq 0$  are formally given by  $v_i(q_i) = \bar{v} - q_i/B_i$ , for an exogenous parameter  $B_i > 0$ . We consider a symmetric set-up where  $B_1 = B_2 = \dots = B_n$ . The tender mechanism asks each bidder to submit a bid schedule that specifies, for any price  $p \geq 0$ , the amount  $x_i(p_i) \geq 0$  that bidder  $i$  is willing to buy at  $p$ . A schedule  $x_i(p_i)$  is admissible if it is non-increasing, left-continuous, and if  $x_i(p_i) = 0$  for a sufficiently high  $p$ . It is assumed that only admissible bid schedules are accepted by the auctioneer. Let  $x(p) = \sum_{i=1}^n x_i(p)$  denote total demand at price  $p$ , and  $P^*(\tilde{Q}) = \{p \geq 0 | x(p) \leq \tilde{Q}\}$  the set of prices at which total demand can be satisfied. The stop-out price is defined as the infimum  $p^*(\tilde{Q}) = \inf P^*(\tilde{Q})$  of such prices.

Individual allotments are determined by satisfying all bids strictly above the stop-out price, and by applying rationing at the margin, if necessary. Formally, define  $x_i^+(p^*) = \lim_{p \rightarrow p^*, p > p^*} x_i(p)$  as bidder's  $i$  demand at a price just above  $p^*$ , and let  $x^+(p^*) = \sum_{i=1}^n x_i(p^*)$ , denote the corresponding aggregate. Bidder  $i$  obtains an allotment

$$q_i^*(\tilde{Q}) = x_i^+(p^*(\tilde{Q})) + \frac{x_i(p^*(\tilde{Q})) - x_i^+(p^*(\tilde{Q}))}{x(p^*(\tilde{Q})) - x^+(p^*(\tilde{Q}))} \left\{ \tilde{Q} - x^+(p^*(\tilde{Q})) \right\}, \quad (2.1)$$

in state  $\tilde{Q}$ . Thus, when demand exceeds supply, the allotment is composed of a complete allocation of the part of the bid schedule that lies above the stop-out price, and a pro-rata allocation of any flat segment of the bid schedule that lies at the stop-out price. The tuple  $(p^*, q_1^*, q_2^*, \dots, q_n^*)$  consisting of the stop-out price and the individual allotments will be referred to as the outcome of the tender.

Bidders are risk-neutral, assumed to maximize expected profits. Define the inverse bid schedule as  $b_i(q_i) = \inf \{p \geq 0 | x_i(p) \leq q_i\}$ . Under discriminatory pricing, the bidder  $i$  pays her own bid  $b_i(q_i)$  for any marginal unit, so that the resulting profit from an outcome  $(p^*, q_1^*, q_2^*, \dots, q_n^*)$  amounts to

$$\Pi_i = \int_0^{q_i^*} \{v_i(q_i) - b_i(q_i)\} dq_i. \quad (2.2)$$

**Equilibrium** An equilibrium can be found in the discriminatory auction for  $n \geq 2$ , when bidders  $i = 1, 2, \dots, n$ , have identical marginal valuations  $v_i(q_i) =$

$\bar{v} - q_i/B$ . For simplicity, we assume also that demand is sufficiently strong, i.e.,  $\bar{Q} < n\bar{v}B$ . Then bidder  $i$  submits the piecewise linear bid schedule

$$x_i(p) = \begin{cases} 0 & \text{for } p > \bar{v}^d \\ B^d(\bar{v}^d - p) & \text{for } p_{\min} < p \leq \bar{v}^d \\ B(\bar{v} - p) & \text{for } p \leq p_{\min} \end{cases} \quad (2.3)$$

for  $i = 1, 2, \dots, n$ , where

$$\bar{v}^d = \bar{v} - \frac{\bar{Q}}{(2n-1)B} \quad (2.4)$$

$$B^d = \frac{2n-1}{n-1}B \quad (2.5)$$

$$p_{\min} = \bar{v} - \frac{\bar{Q}}{nB}. \quad (2.6)$$

are the maximum price bid, the slope of the inverse bid schedule, and the minimum stop-out price, respectively.<sup>8</sup>

The equilibrium marginal rate in the model is stochastic as it depends on the allotment. The expected stop-out rate is equal to the rate that obtains when the central bank allots half of the maximum quantity and it is given by

$$E(p^{\text{mar}}) = \bar{v} - \frac{(3n-1)\bar{Q}}{2n(2n-1)B}. \quad (2.7)$$

When  $n \rightarrow \infty$  the quantity allotted is  $\bar{Q}(n) = n \bar{Q}$ . Then, the maximum price at which a bid is placed will converge to

$$\lim_{n \rightarrow \infty} \bar{v}^d = \bar{v} - \frac{\bar{Q}}{2B}, \quad (2.8)$$

and the expected stop-out rate will converge to

$$\begin{aligned} \lim_{n \rightarrow \infty} E(p^{\text{mar}}) &= \bar{v} - \frac{3\bar{Q}}{4B} \\ &= \bar{v} - \frac{3\sqrt{3}}{2B} \text{std}(\tilde{Q}) \end{aligned} \quad (2.9)$$

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<sup>8</sup>For formal proofs see Ewerhart et. al. (2006).

with  $std(\tilde{Q}) = \bar{Q}/(2\sqrt{3})$ . From equation (2.9) three conclusions can be drawn. First, strategic behavior does not disappear when the number of participants to the auction is very large; thus some bid-shading will be observed also in this case. Second, an increase in liquidity uncertainty, measured by an increase in the standard deviation of the total allotment (or its variance) increases bid-shading and leads to a fall in the stop-out rate. Third, if less liquid collateral becomes relatively more abundant in the collateral pool (increase in  $B$ ) bid-shading is reduced and the stop-out price increases.

**Empirical predictions** The theoretical model suggests five testable predictions about individual bidding behavior and interest rate spreads:

1. The inverse bid schedule is flatter than the true demand or, equivalently, the bid schedule is steeper than the true marginal valuation curve.
2. In equilibrium there is a positive spread between the (shadow) repo rate and the marginal (stop-out) price.
3. Bid-shading decreases with the number of bidders; however, it does not disappear even when the participation in the auction ( $n$ ) is very large.
4. Bid shading increases with allotment uncertainty.

**Illustration of the model** The solution of the model is illustrated in Figure 1. The true linear demand curve (dotted line) is represented above a piecewise linear bid schedule ( $x_i(p)$ ) which was drawn for  $\bar{Q}(n) = 300$  (EUR billion). The other parameters are set as follows:  $\bar{v} = 2.06$  (the one-week EONIA swap rate level<sup>9</sup>),  $B = 18.7$ ,  $n = 300$ , i.e. calibrated to match euro area data (see Section 3 for details). Auction prices correspond to interest rates in percent.

Equilibrium is determined at the interception of the individual bid schedule with the residual supply curve, i.e. the supply diminished by the allotments made to the other bidders at a given price. The theory predicts that bids will

<sup>9</sup>EONIA (euro overnight index rate) is a weighted average of the interest rates on unsecured overnight lending transactions denominated in euro, as reported by a panel of contributing banks. The one-week EONIA swap rate is the main reference for banks when they prepare their bids, given that this segment of the swap market is very liquid and the Eurosystem's refinancing operations have one-week maturity. Given that the underlying EONIA refers to unsecured loans, bids submitted to ECB repo operations should be below that rate.



be submitted at rates between 2.007 and 2.033. An equilibrium is depicted such that the allotment ratio is 50%; the stop-out price (marginal ECB tender rate) is at 2.02, and the corresponding shadow repo rate (equal to the true marginal valuation) is at 2.033 with a bid-shading component of 1.3 basis points. Suppose the minimum bid rate was set at 2.0. Thus, in this particular case, the spread between the swap rate and the minimum bid rate would be 6 basis points; the spread between the repo rate<sup>10</sup> and the minimum bid rate would be 2.7 basis points, and the spread between the marginal tender rate (cut-off rate) and the minimum bid rate would be 2 basis points. These spreads are close to those observed in the euro money market when ECB's minimum bid rate was 2.0.

Consider next an allotment with  $\bar{Q}(n) = 375$  with the remaining parameters unchanged. This could result from an increase in liquidity uncertainty (see Figure 2). The (expected) stop-out price is at 2.01, while the shadow repo rate is 2.027 with a bid-shading component of 1.7 basis points. Thus, in this particular case, the spread between the swap rate and the minimum bid rate would still be 6 basis points; the spread between the repo rate and the minimum bid rate, 2.7 basis points, and the spread between the marginal tender rate and the minimum bid rate would be 1 basis points. This exercise illustrates the *ceteris paribus* impact of an increase in liquidity uncertainty on bid shading (increase from 1.3 to 1.7 basis points).

Finally consider again an allotment with  $\bar{Q}(n) = 300$ , however with a higher swap rate ( $\bar{v} = 2.07$ ) and a steeper bid schedule (i.e. flatter marginal valuation). This shift could be due to an increase in the relative scarcity of liquid collateral.<sup>11</sup> An equilibrium is depicted in Figure 3. The (expected) stop-out price is at 2.04, while the shadow repo rate is 2.05 with a bid-shading component of 1 basis points. Thus, in this particular case, the spread between the swap rate and the minimum bid rate would be 7 basis points; the spread between the repo rate and the minimum bid rate, 5 basis points, and the spread between the cut-off rate (marginal tender rate) and the minimum bid rate would be 4 basis points. In this case volatility in market interest rates would be correlated with a decline in bid-shading, which could be wrongly interpreted as a reversal of the winner's curse and may explain the finding in Nyborg et. al. (2002).

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<sup>10</sup>The theoretical repo rate does not correspond to the private market repo rate (the so-called GC rate). The former should lie somewhat above the latter because it is collateralized with less liquid paper.

<sup>11</sup>This situation could also be explained by an increase in  $\bar{Q}(n)$  when this shift captures an increase in demand/supply with unchanged availability of liquid collateral. This would lead to an increase in  $\bar{v}$ . For simplicity we kept  $\bar{Q}(n)$  unchanged in this simulation.



### 3. Econometric methodology

#### 3.1. Estimation of a structural model

In the econometric work we follow the structural empirical approach to auctions, which is an expanding field recently surveyed by Athey and Haile (2004). More specifically we follow the approach suggested by Hortaçsu (2002 a, b). We proceed in three steps:

1. Estimation of the equilibrium price for each auction.
2. Estimation of the bid-shading components.
3. Tests on individual bidding behavior.

Denote bidder  $i$ 's marginal utility from winning  $q$  units of the good,  $v_i(q)$ . The utility maximization problem can be written as

$$\max_{y_i(\cdot)} \int_0^\infty \left\{ \int_0^{q_i} [v_i(q) - b_i(q)] dq \right\} dH(p^c, x_i(p)), \quad (3.1)$$

where  $q_i = x_i(p)$ , and  $H(p^c, x_i(p))$  and  $dH(p^c, x_i(p))$  are the cumulative distribution and density functions of the market clearing price ( $p^c$ ), conditional on submitting a demand function  $x_i(p)$ , respectively, i.e.  $p^c$  is such that  $x_i(p^c) = \tilde{Q} - \sum_{j \neq i} x_j(p^c)$  and  $H(p^c, x_i(p)) = \Pr\{p^c \leq p | x_i(p)\}$ .

The Euler necessary condition for the maximization of the objective function is then

$$v(x_i(p)) = p + \frac{H(p^c, x_i(p))}{H_p(p^c, x_i(p))}, \quad (3.2)$$

where  $H_p(p^c, x_i(p)) = \frac{\partial H(p^c, x_i(p))}{\partial p^c}$ ;  $v(x_i(p))$  is the true marginal valuation given to quantity  $q$  by bidder  $i$ . It is equal to the price bid  $p$  plus the bid-shading component, measured by the inverse hazard ratio. The above optimality condition allows to nonparametrically identify the marginal valuations of the bidders using observed bids.

### 3.2. Estimation of the auction's equilibrium price

Estimation has been performed by considering jointly the data for all the auctions for each bank, aggregating the bids over all the auctions, and averaging the bids to obtain the final data. This has required the exclusion from the sample of all banks that bid at the same price in all auctions. The aggregate approach can be justified by the stable environment that characterized the euro area money market over the period investigated. Moreover, during the sample period there were no changes in ECB key policy rates. The assumption that auctions take place in a static environment is important for the validity of the methodology we follow in this paper.

The OLS estimator has been employed, considering both linear and log-log specifications. The clearing (equilibrium) price for each auction ( $t$ ),  $p^{c,t}$ , has been computed by equating the aggregate bidding function, obtained by horizontal summing of the inverse individual bidding functions, and total supply, and solving for the equilibrium price (interest rate). Hence, by denoting the estimated inverse aggregate bid function as  $p = \hat{\alpha} - \hat{\beta}q^d$ , the equilibrium price has been computed from the market equilibrium condition,  $q^d = q^s$  as  $p^{c,t} = \hat{\alpha} - \hat{\beta}q^s$ .

### 3.3. Nonparametric estimation of the bid-shading components

In this part we follow the methodology developed by Hortaçsu (2002b). There are  $T$  auctions in the sample and  $n_t$  bidders participate at auction  $t$ ,  $t = 1, \dots, T$ . The procedure to estimate the bid-shading components works as follows:

- i) select auction  $t$  and bidder  $i$ ;
- ii) from the sample of  $n_t - 1$  vectors, draw a random sample of  $n_t - 1$  individual intercept and slope vectors with replacement;
- iii) use the random sample to compute the residual supply function and intersect with bidder  $i$ 's bidding function to determine the market clearing price conditional on  $i$ 's submitting a bid schedule ( $p^c$ );
- iv) repeat for  $K$  times the previous steps to determine the empirical cumulative conditional distribution of the market clearing price,  $\hat{H}(p^c, x_i(p))$ , taking into account the truncation implied by the minimum bid rate;
- v) then, with reference to the estimated equilibrium price for the auction,  $p^{c,t}$ , compute the probability  $\Pr \{p^c \leq p^{c,t} | x_i(p)\} = \hat{H}(p^{c,t}, x_i(p))$  and the value of the density function at  $p^{c,t}$ , i.e.  $\frac{\partial \hat{H}(p^{c,t}, x_i(p))}{\partial p}$ , as  $\frac{\hat{H}(p^{c,t}, x_i(p)) - \hat{H}(p^0, x_i(p))}{p^{c,t} - p^0}$ , where  $p^0$  is the ordered price statistic before the equilibrium price ( $\dots < p^0 < p^{c,t} < \dots$ ).

The bid-shading component can then be computed as the ratio of the probability over the value of the density function;

- vi*) repeat the previous steps for each of the bidders participating to auction  $t$ .
- vii*) repeat the previous steps for each auction.

Kernel estimation has been employed at point  $v$ ). Given that the price distribution is truncated to the left, i.e. the bid rate cannot fall below the minimum bid rate, a Gaussian truncated kernel has been employed for the estimation of the equilibrium price density function.<sup>12</sup> Finally, standard errors for the bid-shading components have been obtained by bootstrapping the empirical distribution of the bid-shading components for each auction.

### 3.4. Tests of individual bidding behavior

On the basis of the estimated slopes and intercepts, heterogeneity across bidders can be assessed and measured by standard statistical tools. Moreover, tests on bidding behavior can be carried out as follows.

#### 3.4.1. Test 1: Is more successful bidding associated with more aggressive bidding?

The first test of bidding behavior is a general one, not directly related to the theoretical model but nonetheless interesting on its own. The following cross sectional regressions were performed

$$\begin{aligned}\bar{s}_i &= \theta_{\alpha_0} + \theta_{\alpha_1} \hat{\alpha}_i + \varepsilon_{\alpha i}, \\ \bar{s}_i &= \theta_{\beta_0} + \theta_{\beta_1} |\hat{\beta}_i| + \varepsilon_{\beta i},\end{aligned}\tag{3.3}$$

where  $\bar{s}_i$  is the average shortfall over the auctions in which bidder  $i$  has participated, and  $\hat{\alpha}_i$  and  $|\hat{\beta}_i|$  are the estimated intercept and (absolute) slope parameters of the individual (inverse) bidding functions. The shortfall in a given auction has been measured as the ratio of the quantity demanded by the bidder and the quantity actually allocated to the bidder. Thus, an increase in this measure means less success at the auction. It is expected that  $\theta_{\alpha_1} < 0$  and  $\theta_{\beta_1} < 0$ , denoting that an increase in shortfall is associated with less aggressive behavior measured by lower  $\hat{\alpha}_i$  and lower  $|\hat{\beta}_i|$ .

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<sup>12</sup>See Pagan and Ullah (1999).

### 3.4.2. Test 2: Is the strategic inverse bid schedule flatter than the true demand?

The test can be implemented by running the cross sectional regression

$$|\hat{\beta}_i| = \theta_{q_0} + \theta_q \bar{q}_i + \varepsilon_{\beta i}, \quad (3.4)$$

where  $\bar{q}_i$  is the average quantity bid by bidder  $i$  over all the auctions in which it has participated. It is expected  $\theta_q < 0$ , which can be interpreted as bid-shading decreasing in the quantity bid. This is consistent with the idea of a true valuation schedule steeper than the observed bid schedule.

### 3.4.3. Test 3: The sources of bid-shading

To assess whether a relationship between bid-shading, supply uncertainty and the number of bidders can be found, the following cross sectional regression has been estimated

$$bs_t = \gamma_{01} + \gamma_{11} \hat{\sigma}_t + \gamma_{21} \hat{\sigma}_{zt} + \gamma_{31} n_t + \varepsilon_{bst},$$

where  $bs_t$  is the average of the estimated bid shading components, considering all the bidders participating at auction  $t$ , obtained using the above described approaches,  $\hat{\sigma}_t$  is price value uncertainty, measured by the conditional standard deviation of the one-week Eonia swap rate for the week preceding auction  $t$ <sup>13</sup> or by the price intercept dispersion;<sup>14</sup>  $n_t$  is the number of participants to auction  $t$ , and  $\hat{\sigma}_{zt}$  is a proxy for liquidity supply uncertainty for auction  $t$ , measured by the conditional standard deviation of the cumulated liquidity forecast error for auction  $t$ .<sup>15</sup> It is expected that  $\gamma_{21} > 0$  and  $\gamma_{31} < 0$ . From the theoretical model no clear prediction can be made about the sign of the parameter  $\gamma_{11}$ .

## 4. The data

The data set includes all bids submitted to the 31 weekly main refinancing operations conducted by the ECB between 16 March 2004 and 11 October 2004.

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<sup>13</sup>The daily volatility of the one-week Eonia swap rate has been computed by means of a GARCH(1,1) model. The weekly volatility has been computed by summing the daily volatility over the five working days of the week.

<sup>14</sup>This variable is considered to control for the effect referred in Nyborg et. al. (2002).

<sup>15</sup>It refers to the conditional standard deviation of the cumulated liquidity forecast error made by the Eurosystem, over eight days, on the allotment day, computed by means of a GARCH (1,1) model.

During the period under analysis the maturity of the ECB repo operations was one week. The average number of bidders was 359 with an average of 515 bids, thus giving 1.44 bids per bidder. The average bid amount was EUR 300 billion, with a maximum of EUR 344 billion and a minimum of EUR 224 billion. Thus, in the calibration exercise presented in Section 2, we set as benchmark values  $Q(n) = 300$  and  $n = 300$ . The average allotted amount was EUR 239 billion, with a maximum of EUR 263 billion and a minimum of EUR 206 billion, suggesting a relatively stable supply environment. The bid-to-cover ratio moved around an average value of 1.26, which suggests relatively successful bidding. In the sample period the marginal MRO rate was 2.007 on average, the average secondary market repo rate 2.011, the weighted average MRO rate was 2.0148 on average, and the average EONIA swap rate 2.0306. Thus, the average spread between the secondary market repo rate and the marginal ECB tender rate was 0.4 basis points, indicative of a small though positive bid shading component.<sup>16</sup> In the calibration exercise we used somewhat higher market rates for the sake of clarity in the illustration.

## 5. Empirical results

Not all the data are usable for the empirical analysis. In fact, the implementation of the (averaged) parametric disaggregated approach requires the availability of at least two different bids placed during the 31 auctions in the sample, not necessarily at the same auction. After excluding from the sample the banks that placed only a single bid over the 31 auctions or always bid at the same price, 525 banks and 15753 bids (representing a value of EUR 9297.607 billion) are left, against a total of 593 banks and 15973 bids (for a total value of EUR 9327.326 billion). Although the number of excluded banks relative to the total number of banks in the sample is not negligible (12%; 68 banks), the number of excluded bids is negligible both in terms of total number (0.25%; 220 bids) and total value (0.3%; EUR 29.719 billion). Hence, the analysis carried out by means of the disaggregated parametric approach should not be affected by sample trimming, albeit subject to the caveat that the estimated bidding functions are only representative of the average behavior of each agent. Yet, in the light of the short sample employed (March 2004 - October 2004) and the relatively smooth liquidity supply and bidding environment that

<sup>16</sup>Note that the theoretical (shadow) repo rate should lie somewhat above the secondary market repo rate because the collateral pledged in the latter is more liquid than the collateral pledged in the ECB main refinancing operations.

characterized the euro area money market over the period investigated, the results drawn from the average analysis are expected to be reliable. Moreover, the period under analysis was marked by absence of short-term expectations of key ECB interest rate changes, which could have undermined the private values assumption underlying the modelling approach.

### 5.1. Bidders' heterogeneity

A first evaluation of the presence of heterogeneity across bidders can be carried out through the analysis of the estimated bidding functions for each single bidder. As discussed in the methodological section, bidding functions for each agent and auction have been estimated by means of OLS regressions using both a linear and log-log specification. Given the characteristics of the data analyzed, only average bidding functions could be estimated for each agent. Summary statistics are reported in Table 1, where figures have been normalized relative to the average allotment value, while in Figure 4 the estimated empirical distributions, after log transformation, are plotted. Only results obtained for the linear model have been reported, since the latter specification appeared to be superior to the log-log model in terms of fit (the average  $R^2$  is equal to 0.98 for the linear model and 0.95 for the log-log model). As Table 1 and Figure 4 show, there is evidence of heterogeneity across bidders, with 70% of the slopes and intercepts falling in the range  $(-0.002, -0.16)$  and  $(0.008, 0.85)$ , respectively (the estimated standard deviations are equal to 0.93 and 1.89, with mean values equal to -0.20 and 0.41, for slopes and intercepts respectively).

Evidence of heterogeneity is also provided by the estimated price (interest rate) elasticities, ranging between -203 and -33 (estimated mean and standard deviations are -94 and 34). Despite the variability found, in all cases the evidence points to highly elastic (inverse) bidding functions. Computing the price elasticities using the log-log model, rather than using the average bids values, does not modify this conclusion, with quantiles also numerically very similar to the ones obtained from the linear model.

As shown by the QQ-plots reported in Figure 4, the distribution of the estimated slopes and intercepts is very close to a lognormal one, while for the elasticities the evidence is less compelling, due to a heavier than predicted left tail. An important open question thus is whether the presence of heterogeneity is sufficient to empirically reject the theoretical results implied by an homogeneous agents framework.



## 5.2. Bid-shading analysis

In Figure 4 the empirical distribution for the estimated (log) bid-shading components are plotted, while in Table 1 quantiles for the actual values of the components (multiplied by 100) and the test for significance of the estimated components are reported. Three findings seem to be of particular interest. First, the bid-shading components seem to follow closely a log normal distribution. Second, the estimated bid-shading components tend to be small, ranging between 0.2 b.p. and 0.8 b.p., with average value of 0.5 b.p. and a standard deviation equal to 0.12 b.p. The fact that the sample average of the spread between the secondary market repo rate and the marginal ECB tender rate (0.4 b.p.) falls within this interval is further evidence of bid-shading (see footnote 11). Third, the estimated bid-shading components tend to be statistically significant. The null of zero bid-shading component, against the alternative of positive bid-shading component, can be rejected at the 1% significance level 90% of the times. Given the large number of bidders participating at each auction and across auctions, finding positive, statistically significant bid-shading components provides evidence that bid-shading does not disappear even when  $n$  is large. This is one of the key theoretical predictions, which is not rejected.

## 5.3. Tests on individual bidding behavior

Table 2 reports the results of the tests on bidding behavior described in the methodological section. The regressions have been estimated by OLS and heteroskedasticity consistent standard errors have been computed. Moreover, in order to control for the different magnitude of the variables employed the dependent and independent variables have been standardized.

**Test 1: Is more successful bidding associated with more aggressive bidding?** The key parameters to answer this question are  $\theta_{\alpha_1}$  and  $\theta_{\beta_1}$ , which are expected to be both negative as an increase in  $\bar{s}_i$  (less success) should be correlated with less aggressive bidding behavior. Indeed, both estimated parameters are negative and statistically significant (see Table 2). However, the  $R^2$  of the slope regression is virtually zero (0.01), while that of the intercept regression is non negligibly larger (0.12).

**Test 2: Is the strategic inverse bid schedule flatter than the true demand?** The key parameter for this test is  $\theta_q$ , which is expected to be negative

in the case large bid volumes are accompanied by less bid-shading. This hypothesis is weakly supported by the data (see Table 2). In fact, the linkage between slopes and the bid quantities is negative, but significant only at the 10% level. However, the  $R^2$  of the regression is virtually zero (0.01), suggesting that bidders' heterogeneity is little explained by this size variable.

**Test 3: Sources of bid shading** The key parameters for this test are  $\gamma_{1_1}$ ,  $\gamma_{2_1}$ ,  $\gamma_{3_1}$ . Theoretical results suggest that  $\gamma_{2_1} > 0$ ; and  $\gamma_{3_1} < 0$ ; No clear cut prediction can be made about  $\gamma_{1_1}$ . Empirical evidence (see Table 2) does not reject the hypothesis that bid-shading falls as value uncertainty and the number of bidders increase ( $\hat{\gamma}_{1_1}, \hat{\gamma}_{1_3} < 0$ ); and that bid-shading increases as supply uncertainty increases ( $\hat{\gamma}_{3_2} > 0$ ). The linkage of bid-shading with value uncertainty is significant only when the one-week Eonia rate volatility is employed as a measure of value uncertainty. As a general result, using the standard deviation of the estimated intercepts to proxy value uncertainty leads to less significant estimates, both in terms of estimated coefficients and  $R^2$  of the regressions, than when the volatility of the one-week Eonia rate is employed.<sup>17</sup>

The empirical evidence is in line with the theoretical predictions. The finding that the parameter  $\gamma_{1_1}$  has a negative sign confirms the previous findings in Nyborg et. al. 2002 that interest rate volatility leads to a reduction in bid-shading. This empirical finding can be explained within the theoretical framework presented in this paper, by an increase in the relative scarcity of liquid collateral. Unfortunately, until individual data on collateral is available this hypothesis cannot be tested. Nevertheless, we find that allotment uncertainty increases bid-shading and lowers tender rates, which is a result so far not considered or tested by other authors.

## 6. Conclusions

Overall the econometric results suggest that strategic and optimal behavior is prevalent in ECB tenders. Despite the documented heterogeneity across bidders, bidding behavior in ECB tenders seems consistent with optimal behavior in a multi-unit discriminatory pricing auction. There is evidence of a statistically significant bid shading component, even though the number of bidders is very large.

<sup>17</sup>The highest, average and lowest  $R^2$  for the parametric disaggregated approach are 0.73, 0.66 and 0.58, respectively.

We found that bid-shading increases with liquidity uncertainty and decreases with the number of participants and with price uncertainty.

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Table 1: Estimated parameters, quantiles.

$Q$	$\beta_L^d$	$\alpha_L^d$	$\varepsilon_L^d$	$\beta_{LL}^d$	$P_{d_k}$	$p\text{-val}_{d_k}$
0.01	-2.6004	0.0007	-203.12	-240.28	0.2161	0.0000
0.05	-0.9268	0.0016	-154.64	-178.69	0.2806	$3E-6$
0.10	-0.4288	0.0033	-135.00	-162.78	0.3186	$1E-5$
0.20	-0.1649	0.0075	-118.74	-138.98	0.3683	$4E-5$
0.30	-0.0659	0.0136	-106.39	-122.35	0.4017	$8E-5$
0.40	-0.0361	0.0232	-98.64	-112.58	0.4312	0.0002
0.50	-0.0207	0.0408	-89.46	-102.88	0.4586	0.0003
0.60	-0.0114	0.0729	-80.40	-92.36	0.4878	0.0005
0.70	-0.0067	0.1303	-73.98	-84.95	0.5202	0.0010
0.80	-0.0037	0.3322	-67.06	-75.97	0.5571	0.0019
0.90	-0.0016	0.8484	-58.83	-67.13	0.6144	0.0048
0.95	-0.0008	1.6879	-51.46	-58.35	0.6634	0.0102
0.99	-0.0004	4.6742	-33.18	-39.07	0.7914	0.0329
<i>mean</i>	-0.1996	0.4067	-94.12	-108.53	0.4653	0.0022
<i>std.dev.</i>	0.9288	1.8951	33.68	39.62	0.1185	0.0065

The table reports the quantiles for the estimated slopes ( $\beta$ ), intercepts ( $\alpha$ ) and price (bid rate) elasticities ( $\varepsilon$ ) obtained from the disaggregated ( $d$ ; single bidder) models. The linear model is denoted by  $L$ , while the log-log model by  $LL$ . Note that the slope parameter in the log-log model measures the price (bid rate) elasticity. The table also reports the quantiles for the estimated bid-shading components and for the p-values of the one-sided test for statistical significance of the estimated bid-shading components. Figures have been multiplied by 100.

Table 2: Tests on bidding behaviour

	$P_{d_k}$	$P_{d_{k_2}}$
$\theta_{\alpha_1}$	-0.342** (0.081)	
$\theta_{\beta_1}$	-0.117** (0.026)	
$\theta_q$	-0.093 (0.055)	
$\gamma_{1_1}$	-0.352* (0.169)	-0.144 (0.175)
$\gamma_{2_1}$	0.306** (0.133)	0.455** (0.136)
$\gamma_{3_1}$	-0.676** (0.085)	-0.494** (0.089)

The table reports the estimated parameters for the auxiliary test regressions. Heteroschedastic standard errors are reported in brackets. \* denotes significance at the 5% level, \*\* denotes significance at the 1% level.  $P_{d_k}$  denotes the results obtained by the disaggregated parametric approach with kernel estimation, using the conditional standard deviation of the one-week Eonia rate as proxy for value uncertainty;  $P_{d_{k_2}}$  denotes the results obtained by the disaggregated parametric approach with kernel estimation, using the standard deviation of the estimated intercepts as proxy for value uncertainty.



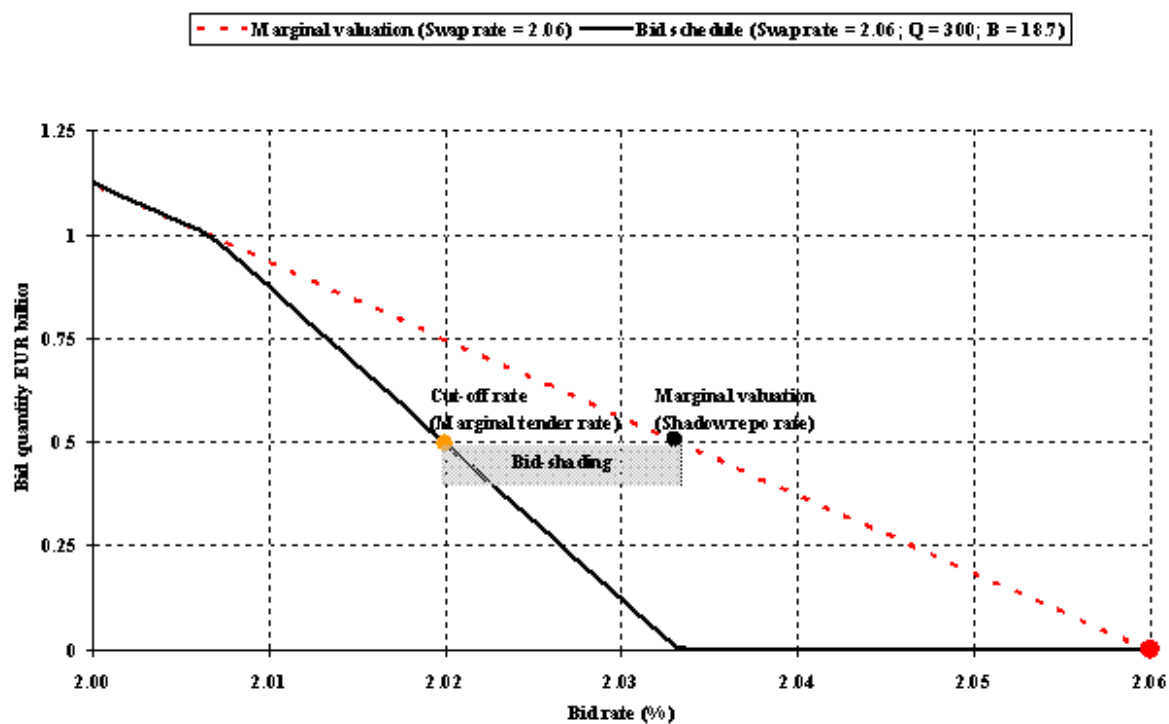


Figure 1. Equilibrium bidding

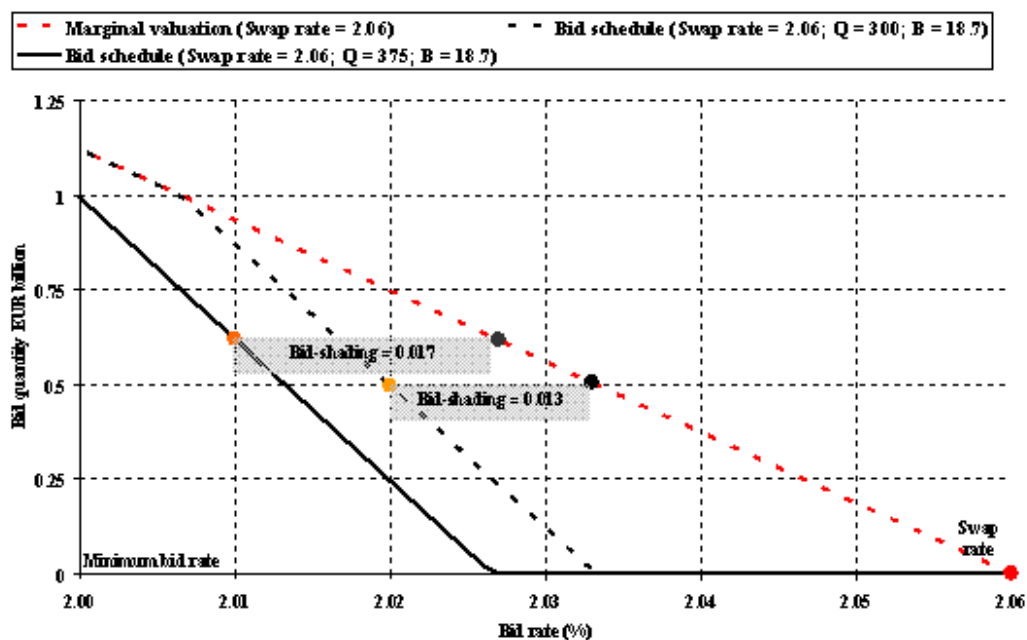


Figure 2. Increase in bid-shading

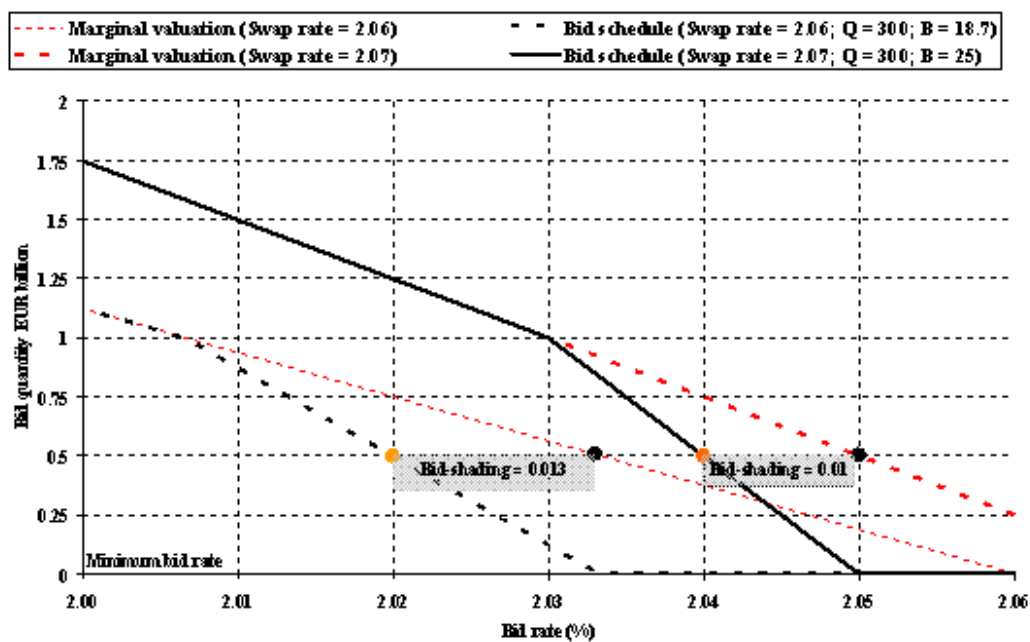


Figure 3. Decrease in bid-shading

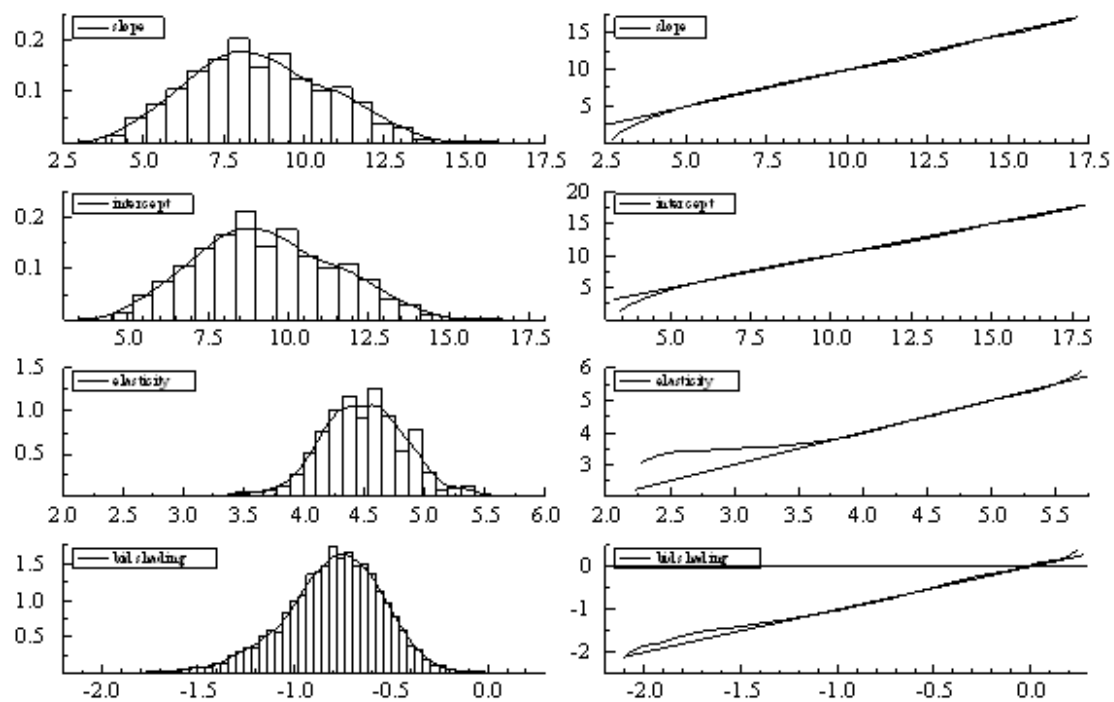


Figure 4: Empirical distributions and QQ-plots. Estimated log intercepts, log absolute slopes, log absolute elasticities, and log bid shading components.

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