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An Experimental Analysis of Multiple vs. Single Bids in Sealed-Bid Auctions of Divisible Goods

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Abstract

In this paper we report on an experimental examination of the comparison between multiple and single bids in a discriminatory-price procurement auction of divisible goods. Having been inspired by energy trading, sellers with a portfolio comprising several cost-quantity pairs bid into a market with a single buyer. Depending on the treatment, they are allowed to submit either one or two bids constructed from their endowments. The allocation rule has no rationing, i.e. marginal bids are completely accepted. We specified both a low and a high competition scenario to evaluate the effects of competitive forces on both bidding regimes. We find that multiple bids have a calming effect on the market, reducing volatility substantially. However, this comes at the cost of lower profits for bidders, whereas auctioneer's revenue is maximized. At the same time, supply reduction, which is equivalent to demand reduction in demand auctions, is more pronounced in the multiple-bid setting. A reason for this might be that expensive units are driven out of the market more easily in the multi-bid setting and they can no longer be offered without causing loss of market efficiency during dispatch.

Keywords: Divisible good auction, laboratory experiment, discriminatory pricing, multiple bids

1 Introduction

An important design feature in multi-unit or divisible good auctions is the number of bids that can be submitted. While demand or supply is often associated with continuous cost or valuation functions, real world bidding systems usually impose constraints on the number of bids that can be entered. The transformation of continuous curves into discrete bids can lead to the obvious problem of not being able to map the underlying information exactly, and engaging in price/quantity trade-offs that might not be optimal. Eventually, inefficiencies and market failures can emerge. In markets with non-professional bidders such as private households, the problem becomes even more severe as these bidders lack the experience and often the capabilities of finding an appropriate bid, especially in a situation like the one described above. Anecdotal evidence for this can be found with one of the most popular online auction websites, eBay, which offered the possibility of a multi-unit auction for several years. When launching the website it was introduced under the name "Power Auction", but was renamed "Multi-Auction" in July 2005, with adjusted rules that were closer to the single-unit auctions, and that allowed bidders to enter one bid consisting of the number of items they wanted to purchase and the price they were willing to pay for each item. As the auction seems to have caused confusion among bidders and led to undesired outcomes, it is no longer available (cf. eBay archives). A similar discussion could emerge in the context of the Treasury auctions of the European Central Bank. The number of possible bids (price-quantity pairs) is limited to ten (European Central Bank, 2006, p.26) in the variable-rate tender, but most bidders submit between one and three bids maximum (Nyborg et al., 2009).

Nevertheless, the majority of studies in the field of divisible good auctions focuses on single bids or continuous bid schedules. The theoretical and practical complexity of these auctions lies in the reciprocal effects of price and quantity, i.e. price and quantity bids need to be traded off against each other, while real-world auction rules require certain minimum quantities for administrative reasons. Tenorio (1997; 1999) and Kremer and Nyborg (2004) have analyzed the impact of discrete bids theoretically, but so far its practical validity has not been examined experimentally for a divisible good auction. In multi-unit auctions, however, supply reduction has been observed. It can be described as "intra-subject collusion" with the goal of achieving higher prices (Back and Zender, 1993).

In this paper, we present an experiment on the effect of the number of permissible bids on bidding behavior, efficiency, and revenue. It is framed in an energy market context, but results are very broad and can be transferred to any other auction with similar properties. A major field hereby would be the financial sector with Treasury bond auctions or cloud financing. Bidders dispose of a portfolio with three different quantities and costs. These can be offered in a discriminatory price ("pay-as-you-bid") auction, where both price and quantity are determined by the bidder. In the multi-bid treatment, they may submit up to two price-quantity pairs, whereas they can only submit one pair in the single-bid treatment. Demand is fixed and unknown throughout the entire session. We find that in the multi-bid treatment individual profits fluctuate much less than in the single-bid treatment, while auctioneer's revenue is maximized.

We proceed as follows: Section 2 gives an overview of the relevant literature, focusing essentially on experimental and theoretical research on divisible good, single- and multi-bid auctions. Section 3 uses this input to provide some theoretical predictions of the experimental results. Section 4 explains the experimental procedure, while section 5 presents the results obtained. Section 6 concludes our findings and their implications.

2 Related research

In previous research, mainly three types of bidding regimes are used (Table 1). In theoretical studies, continuously differentiable bid functions are the most popular ones, but they are not used exclusively. Two notable exceptions are Tenorio (1997, 1999) and Kremer and Nyborg (2004), who study the effect of discreteness on the auction outcome. In empirical studies, bid schedules in several variations are very common for modeling, as they better reflect the actual bidding rules in divisible good auctions, which often allow for multiple bids to be submitted, and can therefore be better applied to the available data. In experimental studies, usually a discrete number of bids is allowed, constituting either a single bid or a bid schedule. To our knowledge, their respective effect on the auction outcome, however, has not been evaluated.

One of the first to analyze the reciprocal relationship of quantity and price bids was Smith (1966). He shows the possibility, when both decision variables are available, bidders will reduce them both in a demand auction (i.e. in case of a procurement auction they will reduce the quantity and increase the price) to increase their profit. The problem of differences in multiple bids versus single bids was only addressed much later by Scott and Wolf (1979). In their setting, multiple price-bids increase bidders' expected utility gained from the auction and thereby dominate single price-bids.

Also in experimental research, multi-unit or divisible good auction markets have played a role for quite some time. Early research has focused on the equivalence or possible differences in single- and multi-unit auctions, with the insight that revenue and efficiency results from single-unit auctions cannot simply be transferred to the respective multi-unit auction (Ausubel and Cramton, 1996; Branco, 1996), also with the single-unit auction emerging as a special case (Noussair, 1995). Later research has then accepted the evidence for non-equivalence of the two auction types and moved on to explore differences in allocation rules. Examples concern rationing and pricing mechanisms, the latter mainly encompass uniform pricing and discriminatory pricing, but also include more exotic forms such as the Spanish auction (Abbink et al., 2006).

Previous research in divisible good auctions has either focused on bids for discrete units or on continuous bid schedules. Theoretically, this has, for example, been examined by Back and Zender (1993). Experimental research on this topic, but with discrete prices and quantities, has been published in 2013 by Morales-Camargo et al. (for further examples see Table 1). The latter find that the mean number of distinct bids submitted was 3.76, which is substantially less than the possible number of bids, with more bids submitted in the uniform-price auctions than in the discriminatory-price auctions. Bids could be submitted in the form of quantity indications in a predetermined price schedule. Also, they found that most bidders bid in sum for the entire quantity available.

When analyzing data on the Norwegian Treasury bond auction, Bjonnes (2001) finds that the smaller the quantity demanded by the bidder, the fewer bids he submits. Bjonnes divides all bidders into three categories, the first being large (institutional) bidders, the second medium-sized bidders and the last small bidders. He finds that the latter only submit 2.2 bids on average, whereas larger bidders submit up to 7.5 bids on average.

Kremer and Nyborg (2004) relax the common assumption of continuous demand functions and introduce discrete bids into a model to analyze underpricing. They conclude that due to an increased price competition on marginal units, underpricing vanishes when supply is either uncertain or larger than individual demand.

Kastl (2011) has a similar approach and starts his analysis with a standard uniform-pricing model for a divisible good auction. He then introduces a model for step functions, which he applies to the Czech Treasury auction. He also establishes the close link between divisible good auctions with discrete bids and multi-unit auctions. His findings suggest that it makes a difference whether one assumes a model with discrete or continuous biddung for analyzing data, but that bidder's profits are not necessarily improved with continuous bidding.

In an energy context, Rassenti et al. (1994) conduct an experiment for gas pipeline networks, where bidders are allowed to submit two price-quantity pairs as bids. They, however, do not report how these bids may be constructed or what variance can be observed over several rounds.

Alsemgeest et al. (1998) find that sealed-bid auctions generate more revenue than open (English) auctions under both single- and multi-unit demand. They also find that the revenue generated is not significantly different between the two types of demand. Furthermore, they conclude that underrevelation of demand hardly occurs in the single-unit demand environment, but occurs more often in the two-unit demand environment. This leads to higher revenues in the single-unit demand case, at least for English clock auctions.

Sade et al. (2006) examine an auction market inspired by Treasury auctions to investigate the effects of uniform versus discriminatory pricing. In their experiment, bidders were allowed to submit four bids, each being a quantity at a predefined price. The sum of the bids was not allowed to exceed the total quantity available. While their theory they apply predicts flat bids in discriminatory auctions, the authors find that 36% of the bidders submit multiple price/quantity pairs. They also find a much smaller standard deviation in the demand schedules in the discriminatory-price auction than in the standard uniform-price auction. However, the standard deviation and the skewness are higher than predicted by theory, because bidders did not submit completely flat demands.

Tenorio (1999) shows that for divisible good auctions with "lumpy bids", i.e. bids that do not follow a continuous bid function, expected revenue is higher the bigger the chunks (in terms of quantity) are that need to be bid for. Lumpiness hereby refers to the discreteness of several units, or alternatively "pieces" of the good demanded at the same price, which is often required by the auction rules through the enforcement of minimum quantities. This implies that when only one bid for the entire quantity can be placed, expected auctioneer's revenue is highest. An explanation for this would be the perceived risk by bidders of experiencing rationing, which is obviated by more aggressive price bidding. Equivalently, when bidders bid for shares of an object rather than for the whole object, their expected payoffs are larger.

Tenorio (1997) also shows that the above-mentioned phenomena are even more severe in uniform-price auctions than in discriminatory-price auctions, supporting our choice of design. The negative effects on efficiency caused by an altered distribution of units are evident.

Bernard et al. (1998) compare the outcomes of two uniform auction designs with varying numbers of bidders. The price is either determined by the last accepted offer or the first rejected offer. Describing the second-price auction mechanism, the latter is incentive-compatible for the unit demand case. Similar to our procedure presented below, costs were increased in quantity in three discrete steps. They also used a reservation price.

Grimm et al. (2008) examine divisible good auctions experimentally, but their focus is very different from that of the aforementioned studies: They evaluate the impact of rationing on bidder behavior. The results, however, cannot be compared to ours in any way, as Grimm et al. use a mechanism where the seller announces a price and bidders can only react with a quantity bid without being able to actually impact the price. This means that the quantity is not necessarily sold completely, resulting in an inefficient market outcome. They do, however, find that a mechanism without rationing is incentive-compatible.

Another experiment on divisible good auctions was performed by Sefton and Zhang (2009). They use uniform pricing, and focus on the impact of communication, i.e. cheap talk. In their set-up, bidders could submit as many price-quantity pairs as they wished until the sum of the quantity bids hit the pre-announced boundary. They find that for the standard allocation rule with rationing, bidders most easily coordinated their actions when communication was allowed.

In the following, we introduce the auction mechanism and its application in our experiment.

Table 1: Bidding regimes in the literature

Study	Bidding regimes	Type of study
Ausubel and Cramton (2002)	Continuous bid function	theoretical
Back and Zender (1993)	Continuous bid function	theoretical
Back and Zender (2001)	Continuous bid function	theoretical
Bourjade (2009)	Continuous bid function	theoretical
Burke and Auslander (2009)	One bid with soft budget constraint	theoretical
Denton et al. (2001)	Bid schedule	experimental
Federico and Rahman (2003)	Continuous bid function	theoretical
Hortascu and McAdams (2010)	Bid schedule (step function)	empirical
Kang and Puller (2007)	Price grid / discrete and continuous bid functions	empirical
Kastl (2011)	Bid schedule (step function)	empirical
Rassenti et al. (1994)	2 discrete bids allowed	experimental
Rassenti et al. (2001)	Bid schedule (step function)	experimental
Rosen and Madlener (2013)	Continuous bid function	theoretical
Rostek et al. (2010)	Continuous bid function	theoretical
Sade et al. (2006)	4 discrete bids allowed	experimental
Scott and Wolf (1979)	Discrete bids (single vs. multiple)	empirical
Sefton and Zhang (2009)	Multiple discrete bids allowed	experimental
Smith (1966)	One bid	theoretical
Wang and Zender (2002)	Bid schedule (piece-wise differentiable)	theoretical

3 Auction rules

We consider a procurement auction with a discriminatory pricing mechanism. This means that bidders receive exactly the price that they bid in case they are allocated. Costs are private information and increase discretely for the quantity chunks. Each bid consists of a price and a quantity, which can be chosen as integer numbers within the given limits. The highest price that can be achieved is the reservation price, p_R, which is set in advance and commonly known. In total, one or two bids may be submitted, but do not have to be submitted, i.e. the quantity can always be set to zero. As the experiment runs over 20 identical auction rounds, it is a repeated game, which might set an incentive to collude, especially in the first rounds. Marginal bids are accepted completely, i.e. without rationing. The set of potential bidders I consists of n bidders. Each bidder $i \in I$ can submit up to two bids $b_{i,j}$, which are composed of a price $p_{i,j}$ and a quantity $q_{i,j}$. Each bidder knows his costs as a function of quantity $c_i(q)$. Costs follow a discrete step function and are drawn from a common distribution, as are available quantities. Let $\mathbf{p_i}$ be the vector of prices that bidder i submits, and let $\mathbf{q_i}$ be the corresponding quantity vector. From there we obtain the set of all possible bids $\mathbf{b_i}$.

$$\mathbf{p_i} = \begin{pmatrix} p_{i,1} \\ p_{i,2} \end{pmatrix} \text{ with } \quad p_{i,j} \geq 0 \tag{1}$$

$$\mathbf{q_i} = \begin{pmatrix} q_{i,1} \\ q_{i,2} \end{pmatrix} \text{ with } \quad q_{i,j} \geq 0 \tag{2}$$

$$\mathbf{b_i} = \begin{pmatrix} \{p_{i,1}, q_{i,1}\} \\ \{p_{i,2}, q_{i,2}\} \end{pmatrix} = \begin{pmatrix} b_{i,1} \\ b_{i,2} \end{pmatrix} \tag{3}$$

A bid can either be accepted or rejected. Both bids can be accepted at the same time, and are, thus, not mutually exclusive. Acceptance is a binary variable described by

$$\mathbf{x_i} = \begin{pmatrix} x_{i,1} \\ x_{i,2} \end{pmatrix} \tag{4}$$

with $x_{i,1}, x_{i,2} \in \{0,1\}$. Bidder i's revenue in one round is, therefore (we leave out the "i" for simplicity):

$$x_1 p_1 q_1 + x_2 p_2 q_2 = \sum x_j p_j q_j \tag{5}$$

The auctioneer needs to procure a fixed, predetermined quantity Q and tries to do so at the lowest possible costs. This leads us to the minimization problem, where the binary variable s denotes if the total demand can be satisfied by all offers.

$$\begin{aligned} &\min_{x_{i,j}} \left\{ \sum_i \sum_j x_{i,j} p_{i,j} q_{i,j} \right\} \\ \text{s.t.} \\ &x_{i,j} \geq 1 - s \; \forall \; i, j \\ &\sum_i \sum_j x_{i,j} q_{i,j} \geq Qs \\ \text{with} \\ &s = \begin{cases} 0 \text{ if } \sum_i \sum_j q_{i,j} < Q \\ 1 \text{ otherwise} \end{cases} \end{aligned} \tag{6}$$

Note, that in case $s = 0$ due to the first constraint all bids are accepted, and the objective function is constant in $x_{i,j}$ with value $\sum_{i,j} p_{i,j} q_{i,j}$.

3.1 Implementation in the experiment

This formulation of the optimization problem could lead to a situation where a bidder's offer is rejected even though his price is lower than the accepted price of an opponent. In that case a bidder could believe that his demanded price was too high, even if it was clearly not, and falsely adjust the price downwards during the following auction round. To avoid sending such false signals to the participants of the experiment, we altered the optimization process in such a way that those rejected bids at lower prices are additionally accepted. Alternatively, one can imagine the bids to be ranked according to price, with $(b_{i,j})_1$ being the lowest offer and $(b_{i,j})_m$ representing the highest offer. Index k with $k \in \{1, 2, ..., m\}$ hereby denotes the rank of an individual bid among all submitted bids with m being the number of all submitted bids. So, in order not to provoke undesired behavior and false signals, bids are strictly accepted according to their rank. As bidders are relatively small, this does not impose any problems or exorbitant deviations in the experiment. In a real market like the one presented in Rosen and Madlener (2013), this issue is even less pronounced as bidders are much smaller in comparison to the market size.

As mentioned above, we evaluate a low and a high competition scenario. Table 2 indicates the available quantities and costs to bidders in the three-person (low) competition case. For the six-person (high) competition case, each portfolio is assigned to two bidders. Due to the chosen allocation rule without rationing, in the single-bid treatment it is always optimal to offer the entire quantity that can be produced at costs that are at or below the stated (bid) price. In the multi-bid treatment, this cost-quantity rule can in principle be applied in the same way, but bids can be truncated such that each represents one, two or all three parts of the quantity portfolio. Another option would be to construct a safe bid, that is close to the presumed market price and has a very high chance of being allocated, and a "gambling" bid with a very high price and a lower chance of being allocated. This bid is then used for an occasional profit boost, but also and mainly to gather information about the possible set of prices which are still allocated. When constructing such bids, the "rule" of using entire lumps should, however, still be observed. Any other way of distributing the quantities over the bids leads ceteris paribus to reduced profits on some of the units. Also, a change in allocation probabilities cannot be reached by such behavior, at least not when assuming symmetric behavior of all bidders and with our particular supply and demand structure. To illustrate the optimal bidding behavior and because a mathematical derivation of an equilibrium is, if at all possible, beyond the scope of this paper, we provide two numerical examples. These solutions are not to be confused with Nash equilibria and only present a sensible outcome that clears the market. As bidders neither have information about the actual supply structure of their competitors, nor about

Table 2: Cost and quantity pairs of the three bidders considered

Bidder 1		Bidder 2		Bidder 3	
Quantity	Cost	Quantity	Cost	Quantity	Cost
10	6	12	6	14	7
16	10	14	12	16	12
23	15	18	15	17	15

the probability distribution of costs and quantities, we can assume that they are indeed quite stable, even though all bidders would have an incentive to deviate. It should also be noted that the prices can be understood as benchmarks, i.e. for the same quantity bid they can freely move in the range of their costs up to the costs of the next truncation.

From the table, the minimum market price results, namely 12 Experimental Currency Units (ECU) for a demand of 56 units in the low competition case (accounting for 40% of total supply, a percentage that was chosen because marginal bids were not partially accepted, but completely). The high competition case is analogous and produces the same theoretical market price. With this market price, all bidders would optimally offer their first and their second quantity lumps. As bidder 1 and bidder 2 cannot fulfill the demand, bidder 3 is always allocated with 30 units. The probabilities of allocation for bidders 1 and 2 result from the possible order in which the bids might be accepted. This leads to the following expected profits (solution I):

$$\begin{aligned}
\text{Bidder 1:} \quad & \frac{2}{3}(26 \cdot 12 - (10 \cdot 6 + 16 \cdot 10)) &&= 61.3\bar{3} \\
\text{Bidder 2:} \quad & \frac{2}{3}(26 \cdot 12 - (12 \cdot 6 + 14 \cdot 12)) &&= 48 \\
\text{Bidder 3:} \quad & (30 \cdot 12 - (14 \cdot 7 + 16 \cdot 12)) &&= 70
\end{aligned} \tag{7}$$

Considering the cost structure of bidder 1, we see that he should deviate from the market price of 12 ECU to 11 ECU, ensuring that he sells both quantities with a certain profit of 66. This reduces the expected profit of bidder 2 to 36, who should now reduce his quantity offer to 12 and his price to 11 ECU, giving him a certain profit of 60. Bidder 3's bid remains unchanged with a certain profit of 70, but he could safely increase his price bid up to 14 ECU without changing the allocation or the profits of the others. With these bids all bidders are allocated and the allocation is efficient.

This profit structure is stable for the single-bid case. Note, however, that in the multi-bid system the second price bid should be 12 ECU (except for bidder 1 who should bid 11 ECU, ensuring an efficient allocation), while the first bid could decrease to 7 ECU under perfect competition. Although bidding 6 ECU could ensure allocation, it should not be offered because it reduces the profit to zero, making the bidder indifferent between participating in the market or not. If bidders are able to foresee these movements and coordinate on the above-mentioned solution, the price can never drop to marginal costs.

An alternative structure could develop when bidders try to maximize the quantity they sell. This would result in the following profits (solution II):

$$\begin{array}{lrcl} \text{Bidder 1:} & \frac{2}{3}(49 \cdot 15 - (10 \cdot 6 + 16 \cdot 10 + 23 \cdot 15)) & = & 113.3\bar{3} \\ \text{Bidder 2:} & \frac{2}{3}(44 \cdot 15 - (12 \cdot 6 + 14 \cdot 12 + 18 \cdot 15)) & = & 100 \\ \text{Bidder 3:} & \frac{2}{3}(47 \cdot 15 - (14 \cdot 7 + 16 \cdot 12 + 17 \cdot 15)) & = & 106.6\bar{6} \end{array} \tag{8}$$

Comparing the expected profits when the entire portfolio is offered to the expected profits in the more price-oriented scenario, they are strictly larger, giving preference to quantity- over price-strategies. Note that the resulting allocation is not efficient anymore.

Alternatively, when following Tenorio (1999), we would expect the single-bid treatment to result in higher competition, i.e. lower prices and smaller quantities, and therefore lower auctioneer's expenditures. In principle, in the multi-bid treatment, bidders can partition their available quantity and reduce their offer in any way they like, resulting in numerous possible outcomes (see Li and Tesfatsion, 2012 for a discussion of different modes of supply reduction in an energy context) . In contrast, in the single-bid treatment, they can only determine the amount from their total supply, but with between 44 and 49 units, this induces many possibilities as well.

4 Experimental procedure

In the experiment realized, 126 test subjects participated in four different treatments (high competition multi-bid, high competition single-bid, low competition multi-bid and low competition single-bid). The experiment was programmed using z-Tree (Fischbacher, 2007), and was conducted in the AIXperiment Lab at the School of Business and Economics, RWTH Aachen University, in November and December 2012. Participants were recruited using the web-based online recruitment tool ORSEE (Online Recruitment System for Economic Experiments) developed by Greiner (2003). This online recruitment tool draws from a pool of registered participants, which is regularly expanded using announcements and university-wide marketing. Most participants were students and had either an engineering or a business studies background, or both. It was only possible for them to participate in the experiment once.

When all participants had arrived at the laboratory, they were randomly allocated to seats. Instructions were handed out and read aloud. Afterwards, there was ample time for questions. To foster the understanding of the auction mechanism, a quiz containing questions and calculation exercises had to be taken and only when all participants had completed it successfully, the actual experiment began. To prevent any anchoring effect, prices and quantities for the quiz differed from the prices and quantities of the experiment by at least a factor of 20.

For each session, there were either ten fixed bidding groups consisting of three bidders, or five groups consisting of six bidders. Bidders were seated in the same room in booths that were protected on three sides by screens. In order to prevent collusion, they were neither aware of how many competitors they had nor of who was in their group. Additionally, group IDs were randomly distributed, meaning that any two participants seated close to each other were unlikely to be competitors.

One session was composed of 20 identical one-shot auctions, which were called “rounds” during the experiment. Settings did not change from round to round, so that quantities and costs always remained the same. The individual supply capacity was in the form of a portfolio of three quantities at three different prices (see Table 2). Participants were told that they could imagine these to be different generation technologies with specific operating properties in an energy context. Bidders were allowed to sell at a maximum the sum of these three, which would then be the maximal amount they can produce. When they chose to sell less, and in the two-bid treatment, the system automatically assumed that they would sell the lowest-cost quantities first, thus maximizing their profit. The costs were calculated accordingly, beginning with the lowest costs and subsequently adding further costs proportionally. The average costs of one quantity-bid also determined the minimum price that could be offered, i.e. the price must not be lower than the costs for the chosen quantity in the quantity bid. If participants tried to bid below their costs, they faced an error message, but this hardly occurred after the test questions were successfully answered. This way, they could not make a loss during the entire session. The profit was calculated in the same way, i.e. such that the accepted bid - irrespective of it being the first or the second bid entered - was assumed to have the lowest costs. In the case of two bids, the lower bid was assumed to have the lower costs. The maximum price that could be entered was limited by a reservation price of 100 ECU, which was common knowledge. For offers that were accepted, however, this reservation price was non-binding.

Treatments differed in the number of bids that could be submitted. The goal is to examine whether and how bidders behave strategically in terms of price and quantity. In the first treatment, participants are only allowed to submit one single bid, whereas they may submit up to two bids in the second treatment. The sum of these two bids may not be more than the sum of the supply portfolio. This way, participants were given the possibility to “fine-tune” their offers, in the sense that they could better adjust their bids to their cost structure. Both treatments were conducted in a low (three bidders) and in a high (six bidders) competition scenario.

5 Results

5.1 Quantities

In general, the total amount offered was significantly higher in the multi-bid treatment than in the single-bid treatment (Figure 1), in both competitive situations. In the low competition scenario, quantities ranged from 15 to 49, with a mean of 43.7 (approximately 94 % of individual total supply) and a standard deviation of 6.9, for the multi-bid treatment, whereas the single-bid treatment only

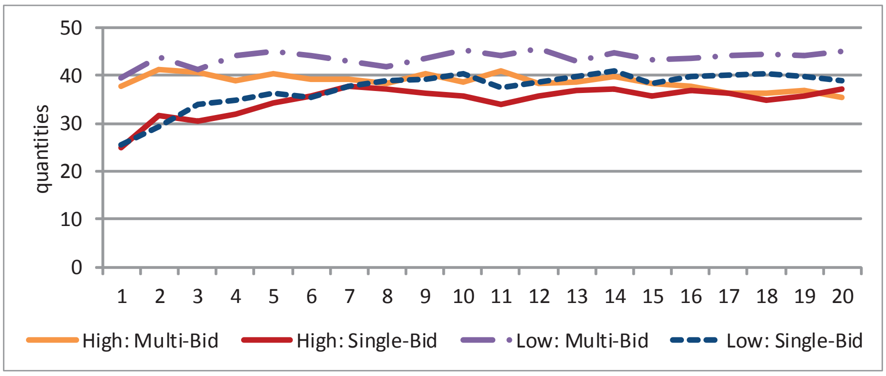

Figure 1: Development of quantities in all treatments

led to quantities from 4 to 49, with a mean of 37.3 (approximately 80 % of individual total supply) and a standard deviation of 10.6. In the high competition scenario, quantities ranged from 12 to 49, with a mean of 38.7 (84 %) and a standard deviation of 9.4 for the multi-bid treatment, whereas the single-bid treatment only led to quantities from 0 to 49, with a mean of 34.8 (74.5 %) and a standard deviation of 13.0. In each case there was excess supply at all times.

Quantities offered in the market slightly increased over time, especially in the single-bid treatments, but quantities were generally on a higher level when the format allowed multiple bids. This is evidence for a positive influence on competition triggered by the multi-bid design. Interestingly, the high competition scenario did not lead to larger amounts offered in the market. This means that stronger competition eventually leads to supply reduction. Although this is a form of collusive behavior (Back and Zender, 1993), it can also be explained with an increased efficiency in the market, meaning that high-cost supply is displaced by lower-cost supply. We have two opposing effects: If higher quantities can be translated as higher levels of competition, the multi-bid format increases competition, whereas a direct increase in the number of market participants, which is equivalent to higher competition, decreases the amount offered.

A Wilcoxon signed rank test shows that in the multi-bid high competition scenario, the bids in the first ten rounds and the bids in the last ten rounds do not come from the same distribution (hypothesis rejected at the 1%- level of significance in a two-sided test, $p = 0.001$). The same is true for the single-bid high competition scenario with $p = 0.0021$. The regression analysis supports

Table 3: Quantities in multi- vs. single-bid treatments - Kruskal-Wallis ANOVA table

	Source	SS	df	MS	χ^2	Prob > χ^2
High competition scenario	Columns	2.55256e+006	1	2552557.5	21.67	3.236e-006
	Error	1.38672e+008	1198	115752.9		
	Total	1.41225e+008	1199			
Low competition scenario	Columns	1.43083e+07	1	14308257.6	122.99	1.39805e-28
	Error	1.25174e+08	1198	104485.7		
	Total	1.39482e+08	1199			

Note: SS = sum of squares; df = degrees of freedom; MS = mean square; Prob = probability

the visual impression of a positive trend with a coefficient of 0.34, which means that the offered quantities indeed rose over the rounds. In the multi-bid treatment, the regression analysis reveals a negative trend with a coefficient of -0.20, indicating a reduction in quantity offers. In the low competition scenario, the bids do seem to come from the same distribution in both parts of the experiment, at least when tested at the 5%- significance level (though not at the 1%- level), with a p-value of 0.0354 for the multi-bid treatment. In the single-bid treatment, the hypothesis is again rejected at the 1% - significance levels with a very small p-value of 2.2159e-09. Again, the regression analysis supports this with a coefficient of 0.52, whereas the coefficient is almost zero in the multi-bid treatment. The test results are further supported by a Kruskal-Wallis-ANOVA (Table 3). From this we can conclude that with low competition, quantity bids increase only in the single-bid treatment, whereas they have a tendency to decrease in the multi-bid treatment. A reason for this might be that bidders learn over time that they achieve the highest expected profits by bidding their entire quantity in the single-bid treatment (cf. Chapter 3.1). In the multi-bid treatment, the probability of having the most expensive quantity allocated is very low, which might discourage bidders from offering that quantity.

When comparing with the predictions of Tenorio (1999), we find that they hold qualitatively and that quantities offered are indeed smaller in the single-bid treatment. This also means that supply-withholding is more pronounced in the single-bid treatments, but decreases over time.

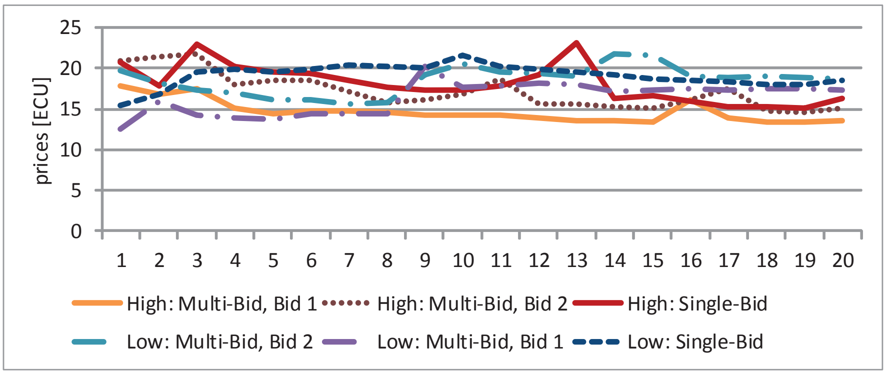

Figure 2: Development of prices in all treatments

5.2 Prices

Several distinct features influence the price development process. In a procurement auction, bidders may be uncertain as to how much they can ask, especially when just entering the market. This means that they first get to know their environment and learn possible price regions in the first couple of rounds. At the same time, competitive forces are at work that move prices down, depending on their strength. As a last issue, in a divisible good auction there is also interplay between quantity and price. In order to be able to interpret the results, we thus need to consider all three simultaneously.

When analyzing the price development it is important to keep in mind that we are looking at the prices entered into the bidding mask. The successful prices, i.e. those that were accepted, might differ from these, and are captured in the profits (cf. Section 5.4), which is why we focus our attention on the entire set of prices bid.

Figure 2 suggests that prices in the low competition single-bid treatment were much higher than prices in the low competition multi-bid treatments. This graphical impression is also supported by a Kruskal-Wallis test (Table 4, part 2). The lowest prices are, of course, those from the first bids in the multi-bid treatment. In the high competition scenario, however, the second-bid price declines very rapidly, too, and comes close to the first-bid price. Still, the difference between the single-bid and the multi-bid treatments is not statistically significant (Table 4, part 1).

Speaking in numbers, prices ranged from 6 to 100 ECU in the first bid, with a mean of 14.7 ECU

Table 4: Second price in multi- vs. price in single-bid treatments - Kruskal-Wallis ANOVA table

	Source	SS	df	MS	χ^2	Prob > χ^2
High competition scenario	Columns	0.96333	1	1	8.15287e-006	0.9977
	Error	141672325.53667	1198	118257.4		
	Total	141672326.5	1199			
Low competition scenario	Columns	1.20428e+006	1	1204283.5	10.28	0.0013
	Error	1.39283e+008	1198	116263.3		
	Total	1.40488e+008	1199			

Note: SS = sum of squares; df = degrees of freedom; MS = mean square; Prob = probability

and a standard deviation of 7.5 ECU for the high competition scenario, while the mean was 16.3 ECU and the standard deviation 12.9 ECU for the low competition scenario. The second bids ranged from 10 to 100 ECU in the high competition scenario (mean: 17.2 ECU, standard deviation of 8.7 ECU), while they ranged from 9 to 100 ECU in the low competition scenario (mean: 18.6 ECU, standard deviation of 13.0 ECU). In contrast, they spanned from 7 to 100 ECU in the single-bid treatment in the high competition scenario, with a mean of 18.1 ECU and a standard deviation of 11.6 ECU. In the low competition scenario, prices have the same range, but a mean of 19.1 ECU and a standard deviation of 10.4 ECU.

A regression analysis does not support any trend in the data for the low competition case. In the high competition case, there is a negative trend for both treatments and in the multi-bid treatment for both bids, with a stronger trend in the second bid. The reason for this is that the first bids already provide a reasonable solution (cf. Section 5.5), whereas the second bids are used for "gambling" with low chances of winning. In the resulting absence of success, bidders are inclined to reduce their prices to increase their chances. This means that bidders followed a simple algorithm, such as the learning-direction theory would propose (Erev and Roth, 1998), only to some extent, or followed a more complicated one (or none at all), which makes bidding arbitrary within the given range.

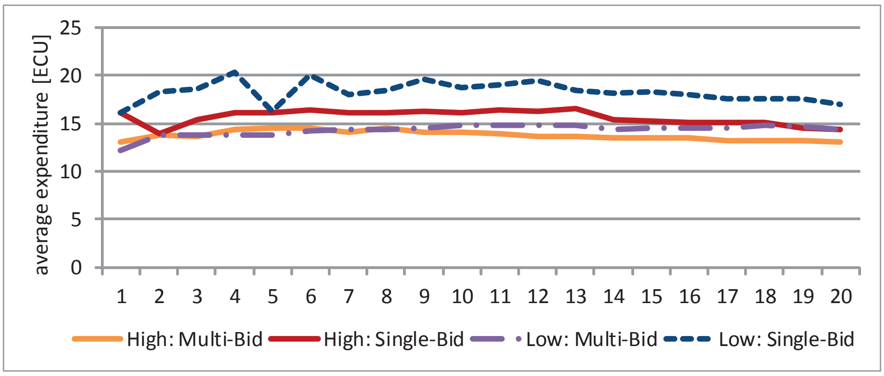

Figure 3: Average expenditures per unit of the auctioneer in all treatments

5.3 Auctioneer's expenditure

The auctioneer has the goal of minimizing his expenditure. To this end, the multi-bid format is preferable compared to a format where only one bid may be submitted. In particular, in the single-bid treatment (Figure 3) the quantity-weighted expenditures range from 9.5 to 52.3 ECU, with a mean of 18.3 ECU per unit and a standard deviation of 6.1 ECU in the low competition scenario. In the high competition scenario, the expenditures range from 12.3 to 25.8 ECU, with a mean of 15.6 ECU per unit and a standard deviation of 2.5 ECU. The lower variation in the high competition scenario is simply a result of the greater number of bidders in one group, i.e. the higher amount that needed to be procured, which averages out some of the more extreme values. It should be noted, however, that the extreme values could only be observed during the first rounds; in later rounds, some convergence took place, but full convergence could not be reached. In the multi-bid treatment (Figure 3), the weighted expenditures range from 10.9 to 19.1 ECU for the low competition scenario, with a mean of 14.3 ECU per unit and a standard deviation of 1.5 ECU. In the high competition scenario, the multi-bid treatment produced values between 11.3 and 19.5 ECU, with a mean of 13.9 ECU and a standard deviation of 1.7 ECU. This means that the multi-bid treatments exhibit considerably less variation in the results than the single-bid treatments, which might be an important criterion for companies engaged in the market. The stabilizing effect of multiple bids can also be observed in the bidders' profits (which will be discussed in the next section), supporting the notion of a reliable market environment.

Table 5: Auctioneer's revenue in multi- vs. single- bid treatments - Kruskal-Wallis ANOVA table

	Source	SS	df	MS	χ^2	Prob > χ^2
High competition scenario	Columns	168432.1	1	168432.1	50.28	1.33421e-12
	Error	498217.9	198	2516.3		
	Total	666650	199			
Low competition scenario	Columns	1.54033e+06	1	1540329.21	115.24	6.98466e-27
	Error	3.79297e+06	398	9530.08		
	Total	5.3333e+06	399			

Note: SS = sum of squares; df = degrees of freedom; MS = mean square; Prob = probability

Single-bid settings seem to be less advantageous for the auctioneer in terms of expenditures in our procurement auction. Expenditures are more than 20% higher in both (high and low competition) single-bid treatments and show more variation over time. A Kruskal-Wallis test shows that the differences in the treatments are significant (Table 5).

5.4 Bidders' profit

A more comprehensive variable for analysis might be the profits generated by bidders, because they can be more easily compared across treatments than prices and quantities.

From Figure 4 we can already see that the single-bid treatments lead to higher profits for bidders. The difference is large in the low competition case and significant at the 1%-level (Table 6, part 2). For the high competition case it is somewhat smaller, but still significant at the 10%-level (Table 6, part 1).

Profits ranged from 0 to 4155 ECU per person in the single-bid low competition case. The mean was 209.8 ECU and the standard deviation was 365.8 ECU. As bidders could not make a loss, this relatively high standard deviation is mainly a result from high profits above the mean, which can also be seen from the range of obtained profits. This range was much lower in the multi-bid case, with 0 to 340 ECU per person, and also the mean was only 102.9 ECU with a standard deviation of 74.0 ECU. In the high competition scenario, the range was much smaller with 0 to 1744 ECU in the

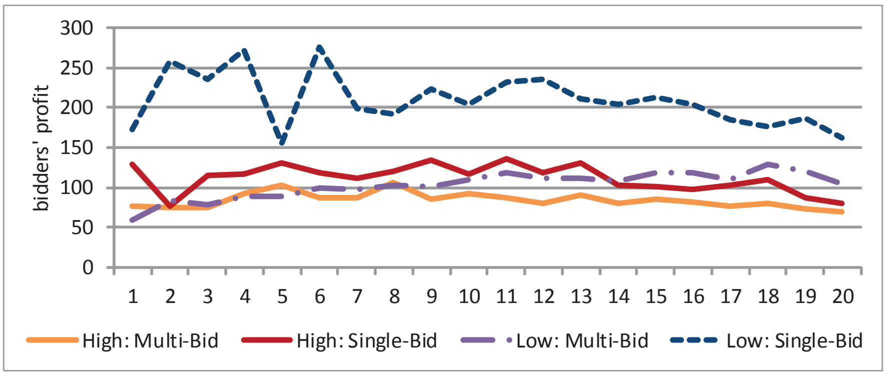

Figure 4: Mean bidders' profits per round and person in all treatments

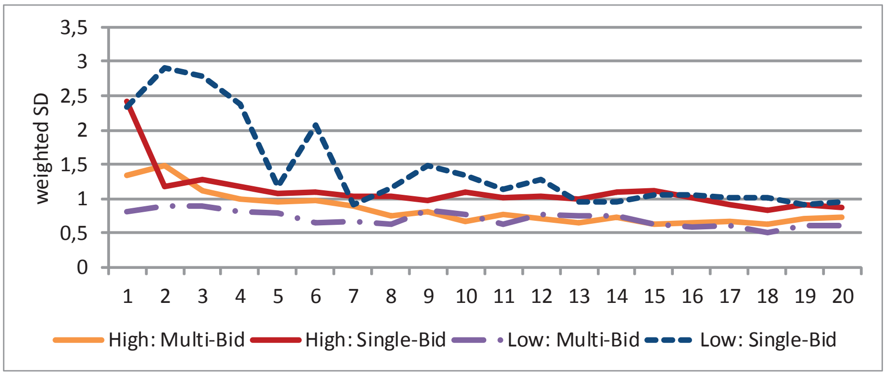

Figure 5: Weighted standard deviations of profits in all treatments

single-bid treatment (mean: 111.7 ECU, standard deviation: 135.1 ECU), but larger in the multi-bid treatment with 0 to 590 ECU (mean: 84.3 ECU, standard deviation: 72.6 ECU). This hints again at two forces being present: The high competition scenario reveals a competition effect which only allows low profits, and the multi-bid treatment induces a balancing effect.

To further investigate the latter effect, which is shown to be significant, we decided to look at the standard deviation in each case. Note that the standard deviation needs to be constructed in a way that rules out the leverage effects imposed by the mere size of the profits. The data have therefore first been normalized for each round and only then used for calculations (Figure 5).

We find that single-bid treatments exhibit a significantly larger standard deviation with a lot more variance over time than the multi-bid treatments. This means that the possibility of submitting

Table 6: Profits in multi- vs. single- bid treatments - Kruskal-Wallis ANOVA table

	Source	SS	df	MS	χ^2	Prob > χ^2
High competition scenario	Columns	440603.4	1	440603.4	3.76	0.0525
	Error	140014236.1	1198	116873.3		
	Total	140454839.5	1199			
Low competition scenario	Columns	4.23427e+006	1	4234269.6	35.68	2.32094e-009
	Error	1.3804e+008	1198	115225.7		
	Total	1.42275e+008	1199			

Note: SS = sum of squares; df = degrees of freedom; MS = mean square; Prob = probability

more than one bid levels out the market. This leads to a more reliable market both for bidders and the auctioneer, as both can count on stable prices and plan accordingly.

5.5 Optimal quantity bids

As we have shown in section 3.1, the optimal bidding behavior resulting from non-rationing is to always bid the entire quantity that can be produced at costs lower than the price bid. This means that bidders should bid the first quantity, the first and the second quantity or their entire available quantity, depending on the price chosen, but never only a part of the respective stack. Taking the inexperience and possible insecurity of the bidders into account, we allow a small deviation from the actually optimal bidding behavior when testing it. In terms of quantity, bids with a reduction of up to 10% of the predicted values are still counted as conforming to the optimal bids, while the price bids for each chunk need to be strictly less than the costs for the following chunk and for the last chunk strictly higher than the costs. It should be noted that the quantity deviation could hardly be observed.

For the analysis, we only consider the last round of each treatment to evaluate the structure resulting from market movements. In the low competition multi-bid treatment, 53% of the bidders bid according to solution I (equation 7), i.e. they bid their first and second stack in the first bid and the rest in the second bid. In the high competition multi-bid treatment, only 40% of the bidders

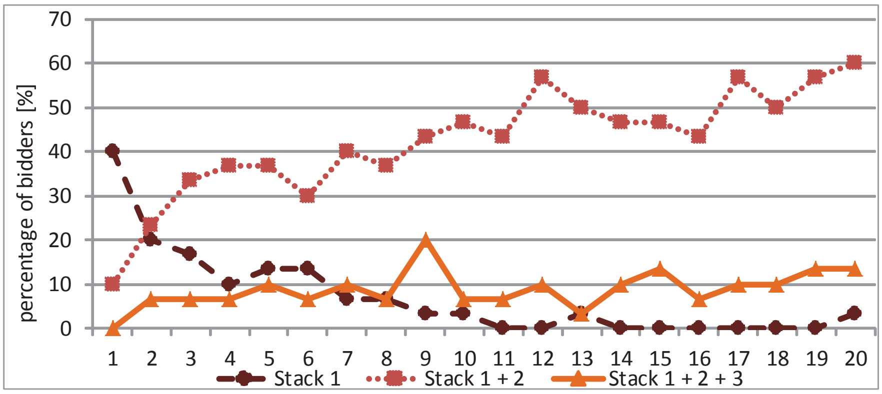

Figure 6: Strategies applied for the first bids in the multi-bid/low competition treatment

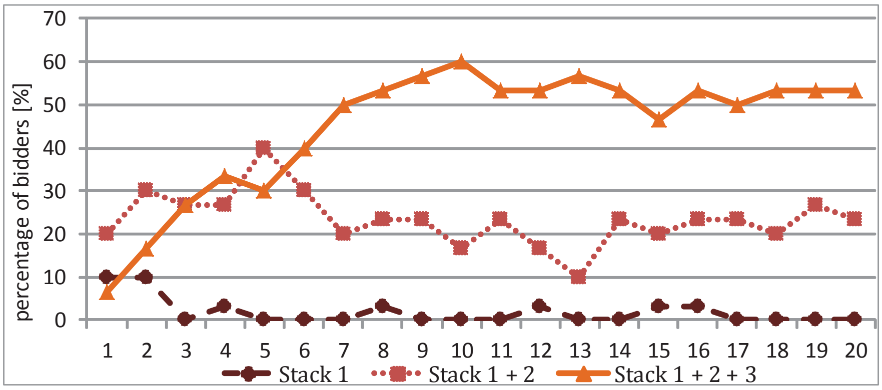

Figure 7: Strategies applied in the single bid/low competition treatment

followed that strategy. In both treatments, no other obvious strategy was followed with the two bids in the last round, i.e. no bidder offered the first stack in the first bid and the second or both remaining stacks in the second bid. When only considering the first bids in the multi-bid treatment, we find that 60% of the bidders follow the optimal strategy with their first bid in the low competition treatment, while 13% of the bidders offer their entire quantity (Figure 6). Only 3% of the bidders offer only their first stack. In the high competition treatment, 53% of the bidders bid according to solution I with their first bids, while 3% of the bidders only offer their first stack and no bidder offers the entire quantity available. It is important to note that the percentage of bidders bidding according to the optimal strategy increases over the rounds.

In the low competition case, bidding in the last round of the single-bid treatment results in 53% of the bidders offering their entire quantity, 23% of the bidders offering their first and second stacks, and no bidder offering his first stack (Figure 7). In the high competition case, a very different picture results with 50% of the bidders following the solution I strategy and 37% of the bidders following the solution II (equation 8) strategy.

Comparing the treatments, it becomes clear that the single-bid treatments are ex-post less efficient than the multi-bid treatments, especially in the low competition case. For the high competition case, the difference is significantly less obvious. When looking at solutions I and II from section 3.1, one sees that solution II has strictly higher expected profits. An important characteristic of solution II is that the entire quantity bidders are able to produce is offered. In the multi-bid setting it is possible to divide the total quantity into two bids, and as soon as the first bids accumulate sufficient supply, the second bids are not allocated anymore. As the latter include the more expensive units, this means that only the cheaper units are allocated. In the single-bid treatments, such subdivision of supply quantities is not possible. Therefore, when trying to maximize the quantity offered by bidding the total quantity available, less efficient units are automatically included. However, competition seems to be able to cure this loss in efficiency to a great extent.

6 Conclusion

In this paper we have presented an experiment on the impact of different formats when submitting bids in a divisible good auction. We investigated a multi- and a single-bid treatment in both a high and a low competition scenario.

It has been shown that a format where multiple bids may be submitted is, in terms of auctioneer's revenues, much more favorable than a format where only one bid may be submitted. The multi-bid format also leads to higher quantities being offered, which could be evidence for a reduction in the theoretically predicted supply-withholding effect. In our case, however, this was not found to have an impact on prices, as competition seems to be strong enough to compensate possible strategic behavior. In all cases, we observe (slow) convergence to the cost level. Bidders' profits were diminished by competition and by the multi-bid format, although the latter also led to smaller fluctuations and thereby more reliable income streams. Furthermore, in the multi-bid treatments bidders coordinated on a more efficient solution than in the single-bid treatments, at least in the low competition case. In the high competition case, multi- and single-bid treatments show some convergence to the same (efficient) solution.

Resorting to the most simple way of testing the model of Tenorio (1999), namely comparing a situation with one bid to a situation with two bids, our laboratory experiment is also suitable for validating his finding. However, we can only confirm his results in terms of quantities, not in terms of prices. There might be two reasons for these diverging outcomes: First of all, he assumes rationing, which does not occur in our experiment and this fact is explicitly communicated to bidders in the instructions. They can therefore not be afraid of being rationed with behavioral consequences. Tenorio interpreted competitive price bidding as a result of the fear of rationing, which cannot be found in our set-up. Secondly, he assumes a specific marginal valuation function. Being a theoretical model without empirical foundation, it might not mirror the reality as we encountered it exactly and might also look very different with our particular set of bidders.

Our findings suggest that in divisible good auctions, wherever possible, multiple bids should be preferred to single bids. They support efficiency, a reliable market environment and auctioneer's revenue. Further research is needed to validate this with different auction formats, especially with uniform pricing, and to further examine the optimal number of bids, which might be more than two. Another aspect is the cost or valuation schedule, which should be altered or resolved to study the robustness of our findings in different settings. Lastly, it might be worthwhile to implement different rationing rules and analyze their effect on the outcome.

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