Prices as indicators of scarcity - an experimental study of a multistage auction*

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Abstract

The price mecanism is the primary means of information transfer in decentralized economic systems. High prices indicate high demand, whereas low prices indicate low demand. Thus prices are the signals for accelerating or slowing production. However, using sequential, multi-unit auctions, we show that the price mechanism fails to be beneficial for producers in every case. As an example we discuss auctions for future access rights to a network. We use experiments to show that the incentives for free-riding inherent in auctions for future access provide inaccurate signals for investment.

Keywords: auctions, capacity, experiments, investment, multi-unit, networks, sequential

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1 Introduction

In decentralized economies the price system transfers the relative importance of a particular thing by attaching a numerical index which reflects its significance within the whole system (von Hayek, 1945). Thus, price is the medium of decentralized information exchange, transferring the information of increasing or decreasing use of an item from buyers to sellers. To evaluate the efficiency of prices, the actual price setting mechanism has to be considered. One currently prominent type of mechanism is an auction. Auctions have a long history as a method for rationing scarce resources and are regarded as highly efficient. In some cases, however, (e.g., highly inelastic supply or demand, economies of scale, capacity constraints) customer or producers' strategic incentives lead to a distorted picture of the commodity's importance in the system. In those cases, prices fail to properly indicate scarcity.

Indeed, this problem is important for network owners who offer network capacity with uncertain information about the size of demand. We model a situation in which the results of an auction are used to determined if a constrained resource will be expanded. As an example of our model's practicality consider the market for access rights to utility networks. Auctions have become a popular method of allocating rights to gas networks and electricity interconnectors. For example, on the National Transmission System in Britain the transmission network provider sells rights to enter gas into the network using a multi-stage, multi-unit auction. A more recent goal of utility regulators such as Ofgem in Great Britain is to require the network owner to use the auction prices as a signal for further network extensions in order to provide a reasonable capacity in later periods.[1] In this paper we investigate a context in which over- or under-supply may result within the framework of an efficient allocation mechanism. There is some evidence on multistage auctions (e.g., Weber, 1983, McAfee & Vincent, 1997 and Neugebauer & Pezanis-Christou, 2003), as well as empirical findings on the capacity extension problem (e.g., McDaniel & Neuhoff, 2002), but to the best of our knowledge, the combination of those problems has not yet been addressed.

The idea of using auctions in this way is appealing on the surface, but highly problematic. Defining property rights over short periods to an existing network is straightforward and has been accomplished in the short-term entry capacity auctions on the gas network in Great Britain and on electricity interconnectors between Germany-Netherlands and England-France.[2] In network industries, significant investments can take

[1] For more details McDaniel & Neuhoff, 2004

[2] See Newbery & McDaniel (2003) for an empirical evaluation of these auctions.

approximately three years to complete; auctions for longer periods can create great uncertainty about what is being bought if investments might be made in the meantime. A primary purpose for having a long-term auction is to collect information from producers about their expected future use of the network (since producers have better information about their future demands than does the network owner). Yet, this scenario provides incentives for strategic behavior which offsets the auction objectives. High prices signal high future demand for network capacity, and, thus, lead to capacity extension. Due to the capacity extension, prices drop in future. In this sense, network users who acquire early network capacity, create an externality for those network user who buy later.

In this paper we derive a theoretical model which we test experimentally to ask whether price is a sufficient and reliable indicator for future investments. That is, knowing the results of the auction influence (directly) the level of future capacity, will bidders reveal their true preference for capacity extension in the auction? If not, will the outcome represent over- or under-investment relative to a scenario in which the network is expanded until the value of additional expansion does not cover the cost? Our purpose is not to replicate any particular real world auction design. Yet, our model and experimental design address two of the main problems we imagine with these "long-term" auctions in network industries: namely, the uncertainty about the future market size (e.g., network size and future competition) and the potential for free-riding.

2 The experiment

Our experiment tests whether prices in multistage auctions are useful indicators for capacity expansion. We construct a two stage auction with either a stochastic or known number of bidders, where the first stage is a sealed-bid auction for a single unit. Each participant has a demand for one unit in total. All participants have a different valuation (v_i) for the units (private information), but all know that the v_i's are drawn independently from a standard uniform distribution. Prior to the auction the probability for the group sizes N (group size is 4 with probability λ and 3 with probability $(1-\lambda)$) and the critical price for capacity extension p_c are known. In the first stage one unit is auctioned ($m = 1$). The highest bidder gets the unit, pays his bid and leaves the auction. The other bidders are informed about the price paid and the actual number of participants in their group and receive a new private valuation v_j (which is again standard uniformly distributed) prior to the second stage. One can think of v_i as the price for the access right to the network on the spot market and of v_j as the (uncertain) future price. If the price for the unit on the first stage was above p_c, 2 units are sold on the 2nd stage ($m = 2$); otherwise 1 unit is sold ($m = 1$) on stage 2. Thus, we have on the second stage a sealed-bid auction for 1 or 2 units and 2 or 3 bidders. Winning bidders receive one unit each and pay their bid. If the total supply is equal to demand, all units on the second stage are sold for a minimum price ($\underline{b}$). This is the case when there are 3 players in the first stage and the price is above p_c (so that there are two units and two bidders in stage 2). Figure 1 illustrates the experiment schematically.

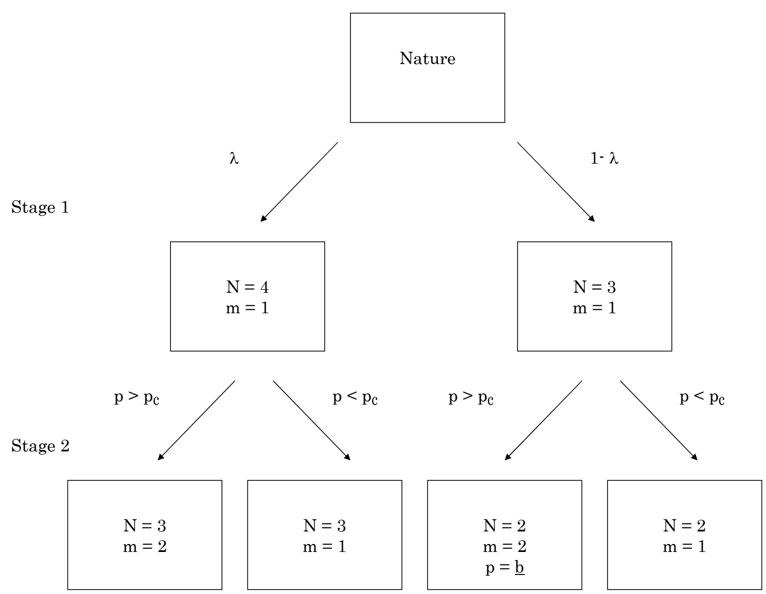

Figure 1: Schematic representation of the game

With this model we want to investigate three questions. First, does an auction with a capacity extension mechanism allocate units efficiently on the first stage so that the high-valued bidder receives capacity? Second, do bidders behave optimally by submitting bids which lead to equilibria on the first and second stages? Third, and for the topic of our investigations even more importantly, are a clear capacity extension mechanism and the information of just the price obtained on the first stage of the auction sufficient information for optimal supply on stage two of the auction. With these questions in mind, we introduce two treatments. In treatment one, participants know the group size ($\lambda = 1$ or $\lambda = 0$) prior to the auction. Equilibrium bidding leads to capacity expansion with high probability if $\lambda = 1$ and no capacity extension if $\lambda = 0$.

In contrast, in the second treatment, participants only have a probabilistic knowledge on the group size (details are discussed below), and the equilibrium frequency of capacity extension should be in a medium range. However, one can assume that due to the possibility of a free lunch (i.e., a unit for the minimum price) the "mechanic" capacity extension will fail to provide the optimal number of units for the auction on stage two and the mechanic capacity extension will lead to under-investment in equilibrium. On the other hand, a common phenomenon in first price auction is over-bidding relative to the equilibrium prediction. Over-bidding in our experiment could result in over-investment relative to the subgame-perfect Nash equilibrium but over or under investment relative to a social optimum.

3 Equilibria

In order to derive a subgame-perfect equilibrium of the complete two-stage auction, the optimal bidding behavior must be separated for the two stages of the auction. Our definition of the equilibrium on stage one depends on the predetermined critical value p_c. We maintain the standard assumption that bidders are risk neutral and that a bidder expects each of his rivals to bid according to the bid function $b_g = b(v_k)$ for $k \in \{i, j\}$ and $g \in \{1, 2\}$ denoting the values and bids on the first and the second stage of the auction. We assume that $b(.)$ is invertible and differentiable.

One unit is sold in stage one, but the number of units to be offered on the second stage is determined by the outcome of stage one. Thus one has to distinguish four different cases on the second stage before identifying the equilibrium behavior on stage one. In case 2_{a1}, the highest bid on the first stage was above the critical value p_c, and three bidders remain in the second stage of the auction. Therefore, the number of offered units in the second stage is two. In the case 2_{a2}, the highest bid on the first stage was above the critical value p_c but there are only two bidders left on the second stage. In this case, the second stage consists of two units and two bidders so each bidder receives a unit for the minimum price[3]. In the cases 2_{b1} and 2_{b2}, the highest bid on stage one was below p_c which results in an auction of only one unit in stage two. In the case 2_{b1} there are three bidders, and in 2_{b2} there are two remaining bidders on the second stage.

Let $F_1^N(x)$, $F_2^N(x)$ be the distribution of the highest and second highest, respectively, of the N values. The corresponding densities are

[3]When there is no scarcity or no competition auction prices are very low. One would expect price to be zero in such cases unless there is a reserve price.

$f_1^N(x)$ and $f_2^N(x)$. To determine the optimal bidding strategy for any bidder m suppose that all other bidders follow the equilibrium strategy $b_2(v_j)$ and bidder m bids $b_2(x)$. Since $b_2(v_j)$ is invertible and all v_j's are distributed uniformly on [0,1], the expected pay-off ($E(\Pi)$) in case 2_{a1} is:

$$E(\Pi_{2a1}) = (v_{j,m} - b_{2a1}(x))F_2^3(x) \tag{1}$$

where $v_{j,m}$ indicates the private value v_j for bidder m on the second stage of the auction.[4] Differentiating equation (1) with respect to x leads to:

$$F_2^3(x)b'_{2a1} + f_2^3(x)b_{2a1}(x) = \frac{d}{dx}(F_2^3(x)b_{2a1}(x)) = v_{j,m}f_2^3(x) \tag{2}$$

with b'_{2a1} denoting $\frac{\partial b_{2a1}(x)}{\partial x}$. $F_2^3(x)$ indicates the event that bidder i does not submit the smallest among three bids, which is in this case:

$$F_2^3(x) = 1 - (1 - F_1^2(x))(1 - F_1^2(x)) = 2x - x^2 \tag{3}$$

In equilibrium x equals $v_{j,m}$. Thus, the optimal bid b^*_{2a1} as the solution of equation (2) is then

$$b^*_{2a1}(v_{j,m}) = \frac{v_{j,m} - \frac{2}{3}v_{j,m}^2}{2 - v_{j,m}}. \tag{4}$$

Since the bidders get the units in the case 2_{a2} for the minimum price $\underline{b}$ the certain profit in this case is:

$$\Pi_{2a2} = v_{j,m} - \underline{b} \tag{5}$$

In case 2_{b1} bidder m faces a single unit auction with 3 bidders, while in case 2_{b2} she faces a single unit auction with 2 bidders. Thus bidder m's expected payoffs are:

$$E(\Pi_{2b1}) = (v_{j,m} - b_{2b1}(x))F_1^3(x) \tag{6}$$

and

$$E(\Pi_{2b2}) = (v_{j,m} - b_{2b2}(x))F_1^2(x). \tag{7}$$

Maximizing equation (6) with respect to x yields in equilibrium ($x = v_{j,m}$) the standard solution for case 2_{b1} :

$$b^*_{2b1}(v_{j,m}) = \frac{2}{3}v_{j,m} \tag{8}$$

[4] We introduce additional notation here to distinguish from the expectation of v_j when we solve for the equilibrium.

and for equation (7) in the case 2_{b2} :

$$b^*_{2b2}(v_{j,m}) = \frac{1}{2}v_{j,m}. \tag{9}$$

In the first stage of the auction the bidders have to consider that there is a trade-off between buying now and in the second stage. Using backward induction, we replace the second stage of the auction with the expected payoffs of the equilibrium bids. However, the private valuations on the second stage of the auction (v_j) are unknown at that point. Since v_j is standard uniformly distributed, the expected value for v_j is 0.5. Hence, there is an incentive for bidders with low v_i's to submit bids of zero (or very low bids) in the first stage of the auction while bidders with a high valuation in the first stage have an incentive to submit positive bids. For further discussion we use the uncertainty treatment since the corresponding certainty outcomes are special cases using the parameterizations $\lambda = 0$ and $\lambda = 1$. In the uncertainty treatment the number of bidders is unknown in stage 1, although the probability of being in a group of size N is known. Thus, we cannot distinguish ex-ante between two disparate expected payoffs in the first stage since players do not know their group size. In case 2_a a capacity extension occurs, and the expected payoff is:

$$E(\Pi_{2a}) = \lambda(v_j - b^*_{2a1}(v_j))F^3_2(v_j) + (1-\lambda)(v_j - \underline{b}). \tag{10}$$

In case 2_b there is no capacity extension, and the expected payoff is given by:

$$E(\Pi_{2b}) = \lambda(v_j - b^*_{2b1}(v_j))F^3_1(v_j) + (1-\lambda)(v_j - b^*_{2b2}(v_j))F^2_1(v_j). \tag{11}$$

The equilibrium bid in stage one has to maximize the weighted sum of both the expected pay-off in the first and the conditional expected pay-off in stage two assuming that the bid in stage one was not the highest. Therefore, bidder m's bid in the first stage (b_1) is the solution to the equation:

$$b_1(x) = \arg\max[E(\Pi_1) + E(\Pi_2)] \tag{12}$$

where $E(\Pi_1)$ is simply a single-unit auction with either 4 or 3 bidders:

$$E(\Pi_1) = \lambda(v_{i,m} - b_1(x))F^4_1(x) + (1-\lambda)(v_{i,m} - b_1(x))F^3_1(x) \tag{13}$$

where $v_{i,m}$ denotes m's private value for the first stage of the auction. $E(\Pi_2)$ is determined as

$$E(\Pi_2) = \begin{cases} E(\Pi_{2a})prob(b_{m,1} \neq b_{1,1}) & if\ b_{1,1} > p_c, \\ E(\Pi_{2b})prob(b_{m,1} \neq b_{1,1}) & if\ b_{1,1} \leq p_c. \end{cases} \tag{14}$$

where $b_{m,1}$ indicates bidder m's bid in the first stage, and $b_{1,1}$ characterizes the highest bid in this stage (and, therefore, the price paid in the first stage).[5] The probabilities of equation (14) assume that bidder m did not submit the highest bid, and the first bid is above or below the critical price p_c, and those events are not independent. We derive this joint probability in the appendix and refine our calculation of $E(\Pi_2)$ later in this section. The probability $prob(b_{m,1} \neq b_{1,1})$ indicates all those events where (at least) one bid is above $b_{m,1}$. Thus, $prob(b_{m,1} \neq b_{1,1})$ equals $\lambda(1 - F_1^4(x)) + (1 - \lambda)(1 - F_1^3(x))$. Let us assume there is a capacity extension on the second stage. Then

$$E(\Pi_2) = [\lambda(1 - F_1^4(x)) + (1 - \lambda)(1 - F_1^3(x))]E(\Pi_{2a}) \tag{15}$$

since for second stage of the auction the case (2_a) is relevant. Using equations (13) and (15), the maximization of (12) with respect to x leads to

$$\begin{aligned} \lambda b_1' F_1^4(x) + (1 - \lambda) b_1' F_1^3(x) = {} & \lambda(v_{i,m} - b_1(x) - E(\Pi_{2a})) f_1^4(x) \\ & + (1 - \lambda)(v_{i,m} - b_1(x) - E(\Pi_{2a})) f_1^3(x) \end{aligned} \tag{16}$$

The general solution of (16) is

$$b_1(x) = \frac{1}{\lambda F_1^4(x) + (1 - \lambda) F_1^3(x)} \int_0^{v_{i,m}} (\lambda f_1^4(x) + (1 - \lambda) f_1^3(x))(x - E(\Pi_{2a}))dx \tag{17}$$

or, more specifically,

$$b_1(v_{i,m}) = \frac{\frac{3}{4}\lambda v_{i,m}^2 + \frac{2}{3}(1 - \lambda)v_{i,m} - \lambda v_{i,m} E(\Pi_{2a}) - (1 - \lambda)E(\Pi_{2a})}{\lambda v_{i,m} + 1 - \lambda} \tag{18}$$

For further discussion we substitute parameter values for set a minimum price $\underline{b} = 0$ and the probability to be in the three subjects group of $\lambda = 0.5$. $E(\Pi_{2a})$ is calculated using $E(v_j) = 0.5$. Hence equation (18) changes to

$$b_1(v_{i,m}) = \frac{\frac{3}{8}v_{i,m}^2 + \frac{1}{3}v_{i,m} - \frac{1}{2}v_{i,m}E(\Pi_{2a}) - \frac{1}{2}E(\Pi_{2a})}{\frac{1}{2}v_{i,m} + \frac{1}{2}} \tag{19}$$

In what follows we first assume p_c is above the local maximum of equation (19) (which is $b_1(1) = 0.354$). Figure 2 shows $p_c = 0.4$ as the dashed diagonal line and equation (19) as the dotted line. Thus bidder m knows that, in equilibrium, there will be no capacity extension as there are no

[5] Of course, we assume for the critical price $p_c \leq 1$; otherwise the problem becomes trivial.

bids above p_c. Therefore, the expected payoff on the second stage is $E(\Pi_{2b})$ instead of $E(\Pi_{2a})$ and the solution becomes

$$b_1(v_{i,m}) = \frac{\frac{3}{8}v_{i,m}^2 + \frac{1}{3}v_{i,m} - \frac{1}{2}v_{i,m}E(\Pi_{2b}) - \frac{1}{2}E(\Pi_{2b})}{\frac{1}{2}v_{i,m} + \frac{1}{2}} \tag{20}$$

Figure 2 shows equation (20) as the solid line[6]. To determine optimal

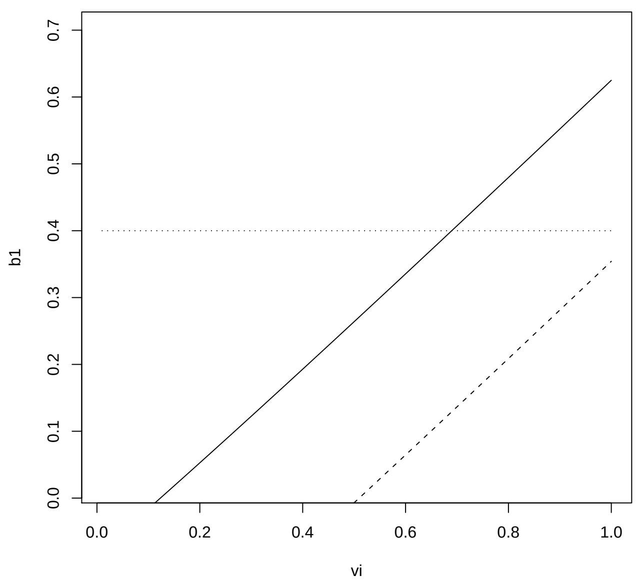

Figure 2: Bidding curves assuming $p_c = 0.4$

bidding when the value of p_c is above the local maximum of equation (19) but intersects the bid curve in (20) we have to differentiate between values to the left and to the right of the intersection. In this situation equation (20) shows the optimal bids only for values to the left of the intersection. To understand why that must be the case, suppose a bidder with a valuation to the right of the intersection submits a bid following equation (20). This would raise the price obtained in the first stage above p_c and would 'create' a world of certain capacity extension. Since we assume here that p_c is above the local maximum of equation (19) this bidding strategy cannot be optimal. Thus, the best thing bidders with values to the right of the intersection can do, is to bid p_c. Therefore, capacity extension does not occur, and the optimal bidding behavior for

[6]For all non-positive optimal bids following equation (20), we assume a bid of 0.

all p_c above the local maximum of equation (19) is

$$b_1^*(v_{i,m}) = \begin{cases} b_1(v_{i,m}|E(\Pi_2) = E(\Pi_{2b})) & if\ b_1(v_{i,m}|E(\Pi_2) = E(\Pi_{2b})) \leq p_c, \\ p_c & else. \end{cases} \tag{21}$$

Now let us assume p_c is below the local maximum of equation (19), which is shown again in Figure 3 as the dotted line. The dashed horizontal line now defines $p_c = 0.2$. As one can see there is an intersection

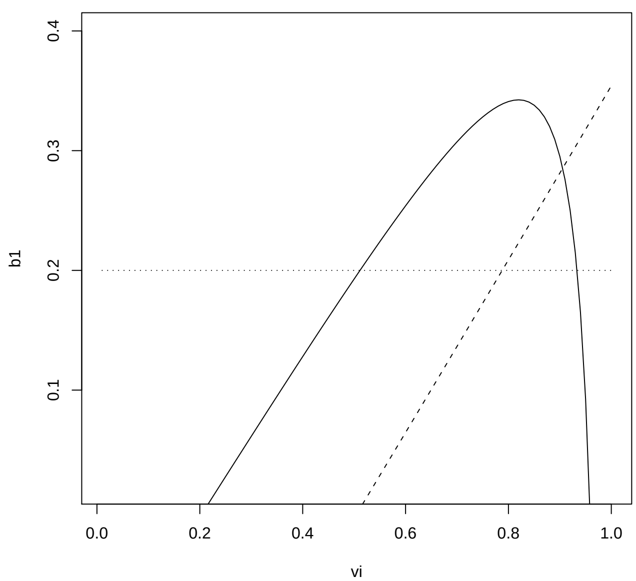

Figure 3: Bidding curves assuming $p_c = 0.2$

between the p_c line and equation (19). Suppose χ determines the value of the corresponding v_i of that intersection (which, in the case of $\lambda = 0.5$, is a value of 0.787). Then all bidders with values $v_i \geq \chi$ will bid according to equation (19) although expansion will result; the potential loss of the high present value in the first stage is too high compared with the expected profit (with an expected $v_j = 0.5$) on the second stage auction. Bidders with values $v_i < \chi$ will anticipate this and adjust their expected value in the second stage. Their bid is no longer determined as if there is no capacity expansion (equation (20)), but is instead the weighted expectation that there is a capacity extension on the second stage. The ex-ante expected payoff on the second stage for all $v_i < \chi$ is in this case:

$$\begin{aligned} E(\Pi_2) = &\, prob(b_{1,1} > p_c | b_{i,1} \neq b_{1,1}) E(\Pi_{2a}) + \\ &prob(b_{1,1} \leq p_c | b_{i,1} \neq b_{1,1}) E(\Pi_{2b}) := E(\Pi_{2\chi}) \end{aligned} \tag{22}$$

As shown in the appendix, the probabilities in equation (22) equal

$$prob(b_{1,1} > p_c | b_{i,1} \neq b_{1,1}) = \lambda \frac{1-\chi}{1-v_{i,m}^3} + (1-\lambda)\frac{1-\chi}{1-v_{i,m}^2} \tag{23}$$

and

$$prob(b_{1,1} \leq p_c | b_{i,1} \neq b_{1,1}) = \lambda \frac{\chi - v_{i,m}^3}{1-v_{i,m}^3} + (1-\lambda)\frac{\chi - v_{i,m}^2}{1-v_{i,m}^2} \tag{24}$$

respectively. Therefore, the optimal bidding behavior of bidder m with value $v_{i,m} < \chi$ becomes

$$b_1(v_{i,m}) = \frac{\frac{3}{8}v_{i,m}^2 + \frac{1}{3}v_{i,m} - \frac{1}{2}v_{i,m}E(\Pi_{2\chi}) - \frac{1}{2}E(\Pi_{2\chi})}{\frac{1}{2}v_{i,m} + \frac{1}{2}} \tag{25}$$

Equation (25) is shown as the solid curve in Figure 3.[7] To summarize, the optimal bid in the first stage of the auction assuming p_c is below the local maximum of equation (19) has three different parts. First, consider bidders with valuations to the right of the intersection between equation (25) and the p_c line. This point indicates where the corresponding bid rises above the capacity extension price. Up to this point bidder m will determine $b_1(v_{i,m}|E(\Pi_2) = E(\Pi_{2\chi}))$ as their optimal bid[8]. Following the earlier arguments bidders with higher values (but smaller than χ) on the first stage will only bid p_c. Finally bidders with values greater than χ optimize their bids with respect to (19). Thus

$$b_1^*(v_{i,m}) = \begin{cases} b_1(v_{i,m}|E(\Pi_2) = E(\Pi_{2\chi})) & if\ b_1(v_{i,m}|E(\Pi_2) = E(\Pi_{2\chi})) \leq p_c, \\ b_1(v_{i,m}|E(\Pi_2) = E(\Pi_{2a})) & if\ \chi < v_{i,m}, \\ p_c & else. \end{cases} \tag{26}$$

From our theoretical analysis, only bidders with a very high valuation on the first stage will create the 'externality' of capacity expansion, while others await the second stage.

[7] We stress that while the complete function (25) is not monotone, the equilibrium bid function is. That is, if subjects bid according to the equilibrium prediction, then bids will be monotonically increasing.

[8] As mentioned before we assume for all non-positive bids 0 as the optimal bid.

4 Experimental Setting and Results

Our experiments were conducted at the Max Planck Institute computer lab in Jena in 2003 using zTree software (Fischbacher, 1999). A total of 112 subjects participated in two treatments. Each treatment consisted of eight groups of seven subjects. There were 25 periods in each treatment. In both treatments, the probability of being in a group of size N was 0.5. Within each matching group of seven participants, subjects were randomly and anonymously divided into groups of three or four players for each period. However, in the first treatment, the group size was announced previous to the first stage of each auction (hereafter the C treatment), while in the second treatment the actual group size was announced after the first stage (hereafter UC treatment). Average payoffs for the C treatment were 9.86 euros (including a 2.50 show-up fee) with a range [5.30-13.70]. Payoffs for the UC treatment did not differ much with an average of 10.33 euros and a range [5.80-13.50]. Values were drawn independently for each subject each period using a uniform distribution with support [0,100]. The 'threshold' value, p_c, was 20. In the C treatment, the additional information prior to the first stage enabled subjects to calculate first stage bids for certain group sizes ($\lambda = 0$ or $\lambda = 1$), while participants in the UC treatment had to use $\lambda = 0.5$. Consequently, the critical individual value χ differs from 54.4 for the certain group size of four to 78.7 for the uncertain group size to 105 for the certain group size of three. Note, that the last χ does not belong to the feasible range of v_i, so that participants should bid with respect to equation (21) resulting in no capacity extension[9]. In contrast, in certain groups of four and the UC treatment, bidders should refer to equation (26). Consequently, bidders with high values (above 54.4 and above 78.7 in the C treatment with four group members and in the UC treatment, respectively) should 'create' a capacity extension on the second stage. As the private values are independently drawn, one can easily calculate the expected frequency of capacity extension as $1 - (0.544)^4 = 0.91$ in the former and $1 - [0.5(0.787)^4 + 0.5(0.787)^3] = 0.56$ in the latter case.

There are three aspects of the data we want to test. First, is this auction mechanism on the first stage efficient so that it allocates the unit to the bidder with the highest valuation. Second, what level of investment is achieved; third, is bidding optimal in the first and second stages of the auction?

Efficiency

Efficiency implies that the bidder with the highest value receives a unit.

[9]Another interpretation is that only a subject with the highest possible value would consider bidding seriously in stage 1.

Lower efficiency would result if subjects attempt to free ride. We expect this type of behavior to be stronger in the certainty treatment since subjects know the number of others they are bidding against. Table 1 shows the percentage of efficient outcomes in stage 1.

Treatment	UC	C	Wilcoxon z value
N = 3	83	70	2.18
N = 4	79	67	2.44
overall	81	69	2.53

Table 1: Efficient first stage allocations, percentages

As expected, efficiency is lower in the certainty treatment. The treatment differences are all significant at the 5% level using a Wilcoxon sign rank test. Within treatments the efficiency difference between subgroups is not significant. If efficiency is a high priority, the static capacity extension is an inadequate rationing mechanism since strategic incentives hinder efficient allocation.

Investment Levels

In equilibrium, we expect a clear ranking in the frequency of capacity extension across treatments. While there should be capacity extension in almost all rounds for the C treatment in bidder groups of four, the UC treatment should lead to moderate frequencies of capacity extension, and no extension for groups of three bidders in the C treatment. In total, capacity extension occurs in 88.8% of the auctions in the C treatment, and in 87% of the auctions in the UC treatment. We define over-investment (hereafter OI) as those first stages of auctions where the winner has a value $v_i < \chi$ and $b_1(v_i) > p_c$, and under-investment (UI) as the first stages of auctions where the winner has a value $v_i > \chi$ and $b_1(v_i) < p_c$. Analyzing the data in more detail, Table 2 provides the following picture of investment across treatments.

UC				
	Predicted	Experimental	OI	UI
N=3	106	168	75	3
N=4	129	180	60	1
C				
N=3	0	167	167	0
N=4	185	188	14	3

Table 2: Absolute number of investment (maximum = 200)

Across all variations of χ we observe over-investment relative to the equilibrium prediction. Table 3 shows, quite surprisingly, no significant difference in the investment frequencies for the two treatments; however we find significant differences comparing experimental (*exp*) data with predicted frequencies (*pre*).[10]

	UC	C	UC v. C
	pre v. exp	pre v. exp	exp
$N = 3$	-2.527^*	-2.527^*	-0.0632
$N = 4$	-2.527^*	-2.527^*	-0.707

Table 3: Wilcoxon Signed-rank Test Statistics

Because subjects overbid in the UC treatment and in three person groups of the C treatment the frequencies of expansion do not differ significantly from the frequency in four person groups in the C treatment. However, there is only one person per group necessary to trigger capacity expansion. Therefore, we will analyze bids more carefully on an individual basis in the next section.

In addition to equilibrium and actual levels of investment, one would also like to know if investments are socially optimal. Optimality occurs when the value of investment exceeds the cost. If subjects retained the same value in stage 2 of the auction, investments would be socially optimal when the third highest value exceeded the cost. This is because investment makes three units available in total. Subjects in our experiment receive new values in stage 2, so fewer investments will be socially optimal.[11] The ex-ante expected frequency of socially optimal investment is the joint probability that at least one of N bidders has a value above p_c in stage 1 and that two bidders will have values above p_c in stage 2. These probabilities are independent and equal to: $[1 - 0.2^4][1 - 0.2]^2 = 0.64$ when N = 4 and $[1 - 0.2^3][1 - 0.2]^2 = 0.63$ when N = 3. However, the frequencies of capacity extension reported from the experiment by far exceed those numbers. Table 4 shows the number of times it would be socially optimal to invest given subjects' values.

[10] * Significant at 5%. The percentage of actual investment instances looks very similar to the equilibrium number when N = 4 in the certainty treatment. However, our level of observation is the group, and at that level we find significant over investment relative to the equilibrium level.

[11] Investment can only be created on stage 1. It is optimal to have another unit if three bidders have values above cost, but those requisite three bidders are separated in time.

	UC	C
N = 3	125	132
N=4	177	178

Table 4: Number of socially optimal investments

Given the realizations of subject's values in stage 1 and stage 2 of the auction, it would be socially optimal to have investment approximately 64% of the time when N = 3 and approximately 88.8% when N = 4. Subjects in fact invest significantly more than the social optimum, while the equilibrium prediction is below the social optimum.[12] Thus, while our theory predicts under-investment, over-bidding leads to over-investment.

Bidding behavior

Investment levels relate critically to the individual bidding behavior. The complex mechanism of capacity extension is not intuitive. However, more experience should lead to *improved* bidding, so our results on bidding refer to rounds 15-25. Values in Table 4 represent mean values for actual and equilibrium bids on stage 1 and stage 2 in each treatment and for each subgroup.

The level of observation for our data is the group since a given subject always interacts with the same 6 people in the experiment. The values in Table 5 are actual and equilibria bids averaged over periods within each group, by subgroup. We present the data by subgroup for comparisons even though disaggregation to the subgroup level is not informative for treatment 1. The first two rows of Table 5(A) show group level data for both treatments, and while our Mann-Whitney test statistics are shown across subgroups, the same story emerges if one makes the more precise comparison using subgroup averages from treatment 2 and group averages from treatment 1.[13]

[12] Differences are all significant at the 5% level using a Wilcoxon Signed-Rank test (except for the comparison between optimal and equilibrium when N = 3 in treatment UC which is only significant at 8%).

[13] The Mann-Whitney test is the Wilcoxon Signed Ranked test for two independent samples. This test is needed to make comparisons across our two treatments. All data analysis was conducted using Stata version 8.0.

A			
	UC	C	$MannWhitney$
b_1 (all)	20.7	22.9	-9.4*
b_1^* (all)	15.2	19.6	-23.1*
$Wilcoxon$	21.6*	15.4*	
b_1 (N=4)	20.1	25.3	-18.0*
b_1^* (N=4)	14.7	21.9	-23.0*
$Wilcoxon$	16.3*	12.7*	
b_1 (N=3)	21.5	19.6	4.99*
b_1^* (N=3)	15.9	16.6	-3.7*
$Wilcoxon$	14.2*	8.4*	
B			
with investment	UC	C	$MannWhitney$
b_2 (N=4)	27.62	27.60	-0.13
b_2^* (N=4)	19.8	20.8	-7.2*
$Wilcoxon$	15.4*	16.1*	
b_2 (N=3)	9.8	10.3	-0.11
b_2^* (N=3)	0.0	0.0	no variation
$Wilcoxon$	12.9*	12.9*	
C			
without investment	UC	C	$MannWhitney$
b_2 (N=4)	22.7	26.7	-1.7
b_2^* (N=4)	33.2	24.4	4.6*
$Wilcoxon$	-2.0*	-1.1	
b_2 (N=3)	29.1	27.3	1.2
b_2^* (N=3)	30.3	27.9	1.4
$Wilcoxon$	1.4	-1.5	

Table 5 (A-C): Optimal versus actual bidding (* significant at 5% or less).

From Table 5(A) we observe overbidding in both treatments and for both subgroups. Across treatments subjects bid significantly lower in the certainty treatment when N = 3 and higher when N = 4. This observation is in line with the equilibrium prediction for N = 4, but not for N =3 . The equilibrium bids in the C treatment are significantly higher than the UC treatment for both subgroups– but for different reasons. When N = 4 higher bids are the result of the lower χ value. When N = 3 the values for χ are high in both treatments. In the C treatment subjects should never bid above p_c whatever their value. Thus, there should a large range of equilibrium bids equal to p_c. The relative size of equilibrium bids in the two treatments will depend on: (a) the number values above χ in treatment UC and, (b) the number of bidders who should bid below p_c in equilibrium; in the UC treatment this number is substantially higher.[14]

In Table 5 (B and C) we describe equilibrium and actual stage 2 bids for the investment and no investment scenarios. Here we again see over-bidding conditional on investment, some underbidding when investment has not occurred. Across treatments there are no significant differences in actual behavior under either scenario.

Two observations lend support to the free riding conjecture. First, although b_1^* is significantly higher in the C treatment when N = 3, actual bidding is significantly lower. When N = 4 subjects bid in the predicted direction. Second, there are more instances of inefficiency in the C treatments. This would be expected if high value bidders were attempting to low ball in order to get unit a stage 2. In such a case, a lower valued bidder could displace the high value bidder. Such behavior is expected when N = 3 where there is a clear opportunity for free riding, but is not expected to the extent that it is observed for N = 4.

The data also suggest that subjects tend to overbid in stage 2 conditional on investment, but are more likely to underbid if there was no investment. Overbidding on stage 2 might be expected if displacement occurred on stage 1. That is, if the high valued bidder does not win on stage 1, then values will be higher on stage 2.

For the analysis of the bidding development over the entire 25 periods we define the deviation $\Delta_{m,t}$ of the experimental bidding (exp) from predicted bidding (pre) of bidder m at period t as $\Delta_{m,t} = exp_{m,t} - pre(v_{m,t})$. Using panel regressions[15] a simple linear square estimation for $\Delta_{m,t}$ provides the following results (Table 5):

Variables	UC	C
Constant	0.08	0.115
p-value	0.000	0.000
Period	-0.0082	-0.0038
p-value	0.009	0.266
d_3	-0.0065	-0.051
p-value	0.889	0.000
R-square	0.332	0.353

Table 5: Linear estimation of deviation of actual and predicted bids $\Delta_{m,t}$

[14] There is a 'cut-off' point in addition to χ equal to the value at which bidders should switch between bidding according to equation (20) and bidding p_c. When N = 3 this value is 0.31 and 0.51 in treatments C and UC, respectively.

[15] Random Error Model

The dummy variable d_3 equals 1 if there were three bidders in the first stage of the auction and 0 otherwise. This dummy variable is insignificant for the UC treatment since subjects could not determine in stage 1 whether their group size was 3 or 4. As predicted, in the C treatment we find a significant, positive effect of the group size on overbidding (increasing the number of bidders increases aggressiveness). However, there is no significant decrease of $\Delta_{m,t}$ over rounds for the C treatment. Conversely, bidders move their bids in the UC treatment significantly towards the optimal solution. We find that the certain opportunity for a *free lunch* (free capacity units) in the C treatment hinders coordination on optimal bids.

5 Conclusions

Auctions can efficiently allocate existing scarce resources such as constrained capacity on a network. One advantage of auctions over alternative allocation mechanisms is that auction prices reveal bidders' willingness to pay. This information is essential to a network owner trying to optimize the size of the network. The incentive to reveal preferences for network capacity change, however, when bidding is for network expansion. In that case, bidders must trade off buying now (to ensure adequate capacity for the future) and buying later, possibly at a lower price though at the risk of too little capacity being available. Because of the strategic incentives bidders face, auctions for future capacity may result in under or over investment depending on the difference between the highest value and the cost of expanding the network. A difficulty of experimentally testing the type of model we present is that subjects in first price auctions consistently overbid. Thus, our experimental results indicate one should expect over-investment from such auctions even though the theoretical prediction is under-investment relative to a social optimum. We comment on this by noting that subjects attempt to take advantage of free riding opportunities by bidding lower when the opportunity for free riding is highest. In these situations, even if investment does occur, it is often inefficient since low value bidders displace higher valued bidders. Furthermore, this effect is more prominent in the certainty treatment, which leads to only moderate efficiency. Uncertainty improves efficiency, and while this result appears counter-intuitive initially, it is consistent since uncertainty makes free-riding opportunities less obvious.

Summarizing the findings we have to claim that the auction with the static capacity extension mechanism fails with respect to two important criteria: first, the auction is not able to provide an efficient allocation of the network capacities as, theoretically, the optimal bid function is non strictly increasing in values and, experimentally, there is consistent overbidding in the first price auction design, and second, the static capacity extension mechanism creates strategic incentives for bidders to free-ride, so that sufficient adaptation of bidding behavior does not occur, and information of further network expansion is not collected.

Network auctions in utility industries are not static events, and long term auctions are augmented with interim monthly and yearly auctions. Such dynamics change the magnitude of the problems we discuss but may not eliminate them. In particular, free-riding can increase over time as the number of future competitors becomes more certain. Understanding the static game is an essential first step to understanding the dynamics of long-term auctions specially and auctions involving investment more generally.

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6 Appendix: Proofs

We have to proof the assumption in section four that

$$prob(b_{1,1} > p_c | b_{i,1} \neq b_{1,1}) = \lambda \frac{1-\chi}{1-v_{i,m}^3} + (1-\lambda)\frac{1-\chi}{1-v_{i,m}^2}$$

and

$$prob(b_{1,1} \leq p_c | b_{i,1} \neq b_{1,1}) = \lambda \frac{\chi - v_{i,m}^3}{1-v_{i,m}^3} + (1-\lambda)\frac{\chi - v_{i,m}^2}{1-v_{i,m}^2}$$

Proof. Let us assume there is bidder m with value $v_{i,m}$ on the first stage of the auction. The bidder knows that

$$b_{1,1}(\chi) = p_c$$

Thus,

$$prob(b_{1,1} > p_c) = prob(v_1 > \chi)$$

where v_1 indicates the corresponding value of the highest bid on the first stage. Therefore,

$$\begin{aligned} prob(b_{1,1} > p_c | b_{i,1} \neq b_{1,1}) &= prob(v_1 > \chi | b_{i,1} \neq b_{1,1}) \\ &= \frac{prob(v_1 > \chi | b_{i,1} \neq b_{1,1}) prob(v_1 > \chi)}{prob(v_1 > \chi)} \\ &= \frac{prob(b_{i,1} \neq b_{1,1} | v_1 > \chi) prob(v_1 > \chi)}{prob(b_{i,1} \neq b_{1,1})} \end{aligned}$$

The probability $prob(v_1 > \chi)$ equals $1 - \chi$. Also,

$$prob(b_{i,1} \neq b_{1,1}) = 1 - prob(b_{i,1} = b_{1,1})$$

and

$$prob(b_{i,1} = b_{1,1}) = v_{i,m}^{n-1}$$

for $n-1$ other bidders. For the conditional probability, it follows

$$prob(b_{i,1} \neq b_{1,1} | v_1 > \chi) = 1 - prob(b_{i,1} = b_{1,1} | v_1 > \chi)$$

However,

$$prob(b_{i,1} = b_{1,1} | v_1 > \chi) = 0 \quad \forall \;\; v_{i,m} < \chi$$

Since we calculate those probabilities only for $v_{i,m} < \chi$ it follows summarizing the findings

$$prob(b_{1,1} > p_c | b_{i,1} \neq b_{1,1}) = \frac{1-\chi}{1-v_{i,m}^{n-1}}$$

Since $prob(b_{1,1} \leq p_c | b_{i,1} \neq b_{1,1})$ is the counter event for $prob(b_{1,1} > p_c | b_{i,1} \neq b_{1,1})$ it follows

$$prob(b_{1,1} \leq p_c | b_{i,1} \neq b_{1,1}) = 1 - prob(b_{1,1} > p_c | b_{i,1} \neq b_{1,1}) = \frac{\chi - v_{i,m}^{n-1}}{1 - v_{i,m}^{n-1}}$$

■

7 Appendix: Instructions [16]

Thank you for participating in our experiment. We kindly ask you to refrain from any public announcements and attempts to communicate directly with other participants. In case you violate this rule we have to exclude you from this experiment. If you do have any questions, please rise your hand and one of the persons who run the experiment, will come to your place and clarify your questions.

In the experiment you will be asked repeatedly, namely in rounds *t=1* to *t=25*, to participate in an auction. In this auction containers of coffee are sold (we assume that the coffee quality is always the same). You act as an intermediator and sell the coffee at the end of each round to a firm of coffee roasters. Before each round you therefore get an offer from the coffee roasters (A_t), at which price the coffee roasters are willing to buy the container of coffee from you. Mind, you can only sell one container per round. If you get one container, you can keep the difference between the price offered by the coffee roasters and the price, for which you got the container in the auction (B_t) as your profit (G_t). If you were not able to buy a container in a round you won't make any profit in that round. If there are more than one identical highest bids the winner will be randomly determined.

All participants in the auction are submitted an offer for between 0 and 100 ECU, each ECU number being represented with equal frequency in terms of bandwidth. Thus it is equally likely to get an offer of 1 ECU, 50 ECU or 99 ECU. The number of bidders in each round varies between 3 and 4 in each group. Before a new round starts you will be assigned anonymously and randomly to a 3 or 4 person group, where it is equally likely to be either in the 3 or in the 4 person group.

Each of the 25 auction rounds consists of 2 phases. Before the first phase starts each participant gets an offer from the coffee roasters.[17] In the first phase one container of coffee is sold. Each of the 3 or 4 bidders has to submit his binding bid for this first container. The highest

[16] Own translation of the German instructions for the UC treatment. Changes in the C treatment are marked by footnotes.

[17] Additionally in the C treatment 'and is informed on his actual group size.'

bid wins the auction. The winner gets the difference between the price offered by the coffee roasters and the own bid as his profit. The remaining bidders from phase one will take part in the second phase of the auction (e.g. 3 bidders, when they started with 4 bidders in the first phase, resp. 2 bidders when they started with 3 bidders). To make a new bid, the winner of the first phase has to wait for the next round of the auction since he already got a container. If the price obtained in the first phase was above 20 ECU 2 containers will be sold in the second phase, otherwise only 1 container. Before you submit your bid for the second phase we will inform you about the actual number of bidders in phase two[18] and about the price, for which the container in phase one was sold (and thus whether 1 or 2 containers will be offered). In addition, all participants of the second phase get a new offer from the coffee roasters for the containers which will be put up for auction in phase two. Again the offers range between 0 and 100 ECU, each number being represented with equal frequency. If only one container is sold in phase two the highest bidder gets the difference between the offer of the coffee roasters and the bid from phase two as his profit. If there are two containers put up for auction, the two participants with the highest bids get one each and receive the difference between the offer and the bid from phase two as profit. If there are only two bidders for two containers (e.g. the highest bid in phase one was above 20 ECU), each bidder will get one container for free. At the end of the auction round we will inform you about all results of phase two and a new round starts. At the end of the experiment we will exchange all ECUs ($\sum_{t=1}^{25} G_t$) earned within the 25 rounds at a rate of 1 ECU =0,01 Euro and pay off the participants.

Summary: We will start now an auction with 25 rounds where you will receive an offer A_t (between 0 ECU and 100 ECU for all participants) which will be valid for the first phase. If you win the auction, your profit is $G_t = A_t - B_t$. In phase one there are either 3 or 4 bidders (both is equally likely). The price B_t to be paid by the winner equals his bid. Before the second phase starts the winner of phase one leaves and the remaining bidders get a new offer from the coffee roasters. In phase two one or two containers are offered. There will be two containers if the price of the first phase was above 20 ECU. If there are only 2 bidders left in phase two, both of them get one container each for free. Otherwise the two highest bids from phase two get the container. If the price obtained in phase one was below or equal to 20 ECU only one container is offered. The highest bid (regardless whether 2 or 3 bidders submit a bid) gets the container and receives the difference between the offer and the bid from phase two.

[18]The last phrase is missing in the C treatment.