An Experiment on Supply Function Competition

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Abstract

We experimentally investigate key predictions of supply function equilibrium. While, overall, equilibrium organizes bidding behavior well, we observe three important deviations. First, bidding is sensitive to theoretically irrelevant changes of the demand distribution. Second, in a market with symmetric firms we observe tacit collusion in that firms provide less than the predicted quantities. Third, in a market with asymmetric capacities, the larger firm bids more competitively than predicted, while the smaller firms still provide less than equilibrium quantities.

Keywords: Supply function competition, experiment, demand uncertainty, asymmetric firms

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1 Introduction

We experimentally investigate behavior in supply function competition that has first been modeled by Klemperer and Meyer (1989). Firms face an uncertain demand and submit supply functions. The market clearing price is determined by the intersection of aggregate supply and (realized) demand. In its original formulation, the model has multiple equilibria with prices — roughly speaking — between the Cournot and the competitive price.

The most notable application of supply function equilibrium (SFE) analysis is spot market bidding in electricity markets, starting with Bolle (1992), Green and Newbery (1992) and Green (1996). In line with standard SFE models, rules of electricity spot markets typically require suppliers to offer a price schedule, with demand being uncertain. A variety of papers considered extensions of the original framework in order to capture more complexities inherent to many electricity market platforms, such as pivotal firms (Genc and Reynolds (2010)), cost asymmetries (Baldick, Grant, and Kahn (2004), Baldick and Hogan (2002)), entry (Green and Newbery (1992), Newbery (1998)), capacity constraints (Baldick, Grant, and Kahn (2004), Holmberg (2007, 2008)), forward contracting (Newbery (1998)), and price caps (Baldick and Hogan (2002), Holmberg (2007, 2008)).

Parallel to the theoretical progress, field studies on the performance of SFE accumulated. The evidence is, however, mixed. While some authors emphasize that SFE organizes actual electricity market experiences well – and better than Cournot models – (see Baldick, Grant, and Kahn (2004) and the references cited therein), others come to more sceptical conclusions with respect to behavioral assumptions and predictions (e.g., Sioshansi and Oren (2007), and the references cited therein). Wolfram (1999), for instance, finds that actual prices in the British electricity industry, while higher than marginal costs, have been much lower than what is suggested by SFE analyses. She thus considers a number of additional constraints to explain her data, including contracts between the suppliers and their customers and the threat of regulatory intervention. Yet there are more constraints that complicate the direct applicability of the SFE approach to the field data, such as non-convex costs, uncertainties on the supply side, transmission constraints, arbitrage through intra-day, reserve energy and forward markets, etc. Moreover, almost all of the theoretical and empirical papers assume, at least implicitly, that human bidders can somehow handle the relatively large computational complexities in finding
rational SFE strategies. However, while there is a large literature on the behavioral robustness of simple equilibria in quantities or prices (e.g., Holt (1995), and more recently Hinloopen and Normann (2009)), little is known about the potential role of (boundedly rational) behavior in supply function competition. Our laboratory study seeks to fill this gap. We abstract away from the institutional and technical complexities mentioned above, that make it difficult to isolate behavioral phenomena in the field. We also choose a set-up (with inelastic demand and a price cap) that yields unique equilibrium predictions in order to avoid non-equilibrium play due to coordination failure.

To our knowledge, only one experiment on supply function bidding has been previously conducted. Interested in the role of forward markets, Brandts, Pezanis-Christou, and Schram (2008) studied both quantity and supply function competition with and without forward contracting. The introduction of a forward market increased total quantity produced and lowered prices paid by consumers. However, because there is a continuum of supply function equilibria in their set-up, supply functions, production levels and prices, as well as their shifts, could not be unambiguously derived from the SFE analysis. This reflects that identifying the predictive value of SFE bidding strategies was not the focus of their study.

Our behavioral robustness checks include testing two key predictions of SFE. First, we test the hypothesis that equilibrium supply functions are invariant to certain demand distribution parameters (which cannot be systematically varied in field studies). Second, we investigate how asymmetry of capacities affects the outcome of supply function competition. While some basic predictions of SFE are reflected in the data, we also find significant and systematic deviations from SFE. With symmetric competitors we find that bidding is on average less competitive than predicted by SFE. With one large and three small firms only the small firms bid less than equilibrium quantities; the large firm provides higher than equilibrium quantities. We also find that firms react to theoretically irrelevant changes in the demand distribution; they bid less competitively in a treatment where only a relatively small range of high demand realizations are possible.

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1 van Koten and Ortmann (2010) also studied the effect of forward contracting in laboratory electricity markets, yet only in a standard price competition setting.
Section 2 introduces the theoretical model underlying our analysis. In Section 3 we describe our experimental design and derive the central hypotheses. The results are reported in Section 4, and Section 5 concludes.

2 Theory and Predictions

The theoretical framework of our experiment is a simplified version of a model by Holmberg (2007, 2008). The model deviates from more standard models of supply function competition by postulating inelastic demand and introducing a price cap and capacity constraints. This ensures existence and uniqueness of equilibrium without sacrificing some key characteristics of the SFE introduced by Klemperer and Meyer (1989), as we will explain below. Moreover, both the uniqueness of equilibria and the simplicity of the set-up make the model particularly suitable for experimental testing. Finally, inelastic demand, price caps and capacity constraints are characteristic features of many electricity exchanges, as e.g. discussed by Stoft (2002).

In the model, \( n \) firms with constant marginal cost \( c \) compete in supply functions on a market with inelastic and uncertain demand \( \varepsilon \) and a price cap \( \bar{p} \). Demand \( \varepsilon \) is distributed in \([\varepsilon, \bar{\varepsilon}]\) with distribution \( F(\varepsilon) \). We assume that the firms are capacity constrained and denote firm \( i \)'s capacity by \( K_i \). We assume that with positive probability the capacity constraints of all firms are binding, i.e. \( \sum_{i=1}^{n} K_i \leq \bar{\varepsilon} \). The firms’ bids consist of individual supply functions \( S_i(p) \) that, for any given price, determine a quantity the firm is willing to offer.

In case the firms are symmetric (i.e. equal capacities), it follows from Holmberg (2008) that the unique SFE yields the following aggregate inverse supply (see Appendix A),

\[
p(\varepsilon) = c + \frac{\varepsilon^{n-1}}{\bar{\varepsilon}^{n-1}}(\bar{p} - c)
\]

(1)

The first unit, at \( \varepsilon = 0 \), is offered at marginal cost. From there on the markup is increasing in the quantity. For the last unit a firm can supply, the highest possible price, \( \bar{p} \), is posted,\(^2\) so

\(^2\) This prediction is due to the capacity constraint in Holmberg’s model. Without that constraint, we obtain multiple equilibria, where the highest posted price is in between marginal cost (most competitive equilibrium) and the price cap; see Rudkevich, Duckworth, and Rosen (1998) and Genc and Reynolds (2010).
that the equilibrium price ultimately reaches the price cap at quantity $\bar{\varepsilon}$. One particularly interesting implication of equilibrium behavior is that bidding is independent of the distribution of demand, as long as the upper limit of the support remains unchanged — this is also a central feature of the Klemperer and Meyer (1989) model.\(^3\)

Using the parameterization employed in our experimental treatment with symmetric firms (i.e., $n = 4$, $c = 0$, $\bar{p} = 50$, and $K_i = 30 \forall i$), the equilibrium bid function for ordinary firms (as opposed to large firms, whose behavior is analyzed next) is illustrated in Figure 1.

Now suppose that there is one large firm which has more capacity than the remaining $n - 1$ firms (which have the same capacity). Denote an ordinary firm’s capacity bound by $K_i$, and the large firm’s capacity bound by $K_h$. Holmberg (2007) shows that in the unique SFE all firms’ supply functions are identical in the range where none of them are capacity constrained (i.e. for quantities $\varepsilon \in [0, nK_i]$), and that the large firm posts the price cap for all units it can supply in excess of the other firms. Consequently, the unique SFE yields the following aggregate inverse supply (see Appendix A),

$$p(\varepsilon) = \begin{cases} 
    c + \frac{\varepsilon^{n-1}}{\bar{\varepsilon}^{n-1}} (\bar{p} - c) & \varepsilon \in [0, nK_i] \\
    \frac{\bar{p}}{\bar{\varepsilon}} & \varepsilon \in (nK_i, \bar{\varepsilon}] 
\end{cases}$$

Most predictions from the symmetric model also apply here, because for all quantities below $K_i$, the individual supply functions of all firms (ordinary and large) coincide. For instance, the first unit is offered at marginal cost, and prices rise in the demanded quantity until they reach the price cap $\bar{p}$ at $nK_i$, and stay there up to the industry capacity bound $\bar{\varepsilon}$. The additional insight of the asymmetric model is that, in equilibrium, the large firm does not undercut the ordinary firms’ supply functions but rather drives prices to the maximum level in case demand turns out to be very high. We illustrate the equilibrium supply functions of large firms in Figure 2 (for the parameterization we used in our experimental setting with asymmetric firms, i.e. $n = 4$, $K_i = 30$, $K_h = 90$, $c = 0$, and $\bar{p} = 50$; the supply functions of ordinary firms are as in Figure 1 in this case).

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\(^3\) Other predictions include that equilibrium prices at each quantity decrease in the number of firms in the market (which is also predicted by Klemperer and Meyer (1989), and most other model of supply function competition), that equilibrium bids increase in the price cap, and that bids decrease if all firms’ capacities increase.
3 Experimental Design

The theoretical framework and analysis in Section 2 guided our experimental design described in this section. We run three treatments, T1 - T3. In each treatment, an experimental market consists of four firms that face inelastic but uncertain demand. The price cap is set at 50 and marginal cost of all firms is zero. We compare a symmetric baseline market (T1) with a market that exhibits a
different demand distribution (T2), and with another market that exhibits asymmetric (three ordinary and one large) firms (T3). More specifically:

(T1) *Baseline treatment*: demand is distributed in the interval [1, 120], where each integer in this interval has the same probability. Each of the four firms has a capacity of 30 units.

(T2) *Variation of the distribution*: keeping everything else constant we change the distribution to a uniform distribution on the interval [80, 120].

(T3) *Asymmetric firms*: keeping everything else as in the baseline treatment we increase one firm’s capacity from 30 to 90, and demand is distributed uniformly in the interval [1, 180].

Our null-hypotheses follow directly from the analysis in Section 2: ordinary firms in T1 and T3 bid as summarized in Figure 1, and the large firm bids as summarized in Figure 2. Moreover, equation (1) implies that bidding does not respond to the change in the distribution of demand in T2; that is, bidders are predicted to submit the same supply function in treatments T1 and T2.  

The experiment was conducted at the Cologne Laboratory for Experimental Research (CLER) in October 2006. A total of 128 undergraduate students in economics or business administration were recruited using ORSEE (Greiner (2004)) among the student population of the University of Cologne.

Subjects were randomly matched into groups of four, and each group formed one market in one of the three treatments. Anonymity was preserved in the sense that subjects never got to know the identity of the other subjects in their group. Each group remained together for 60 rounds. In each round, each subject submitted a supply function via a computer interface. Then demand was generated, each market was cleared, and feedback about the market outcome was distributed as described below.

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4 In any empirical application of auction or oligopoly theory, demand is ultimately discrete, which is also true in our case. It is known that in such cases pure strategy equilibria may not exist. However, since the price and quantity grid is rather fine in our setting, we see the continuous model as an approximation, as it seems generally the case in the theoretical and empirical literature. In support of this, Holmberg, Newbery, and Ralph (2008) show that “if prices must be selected from a finite set the resulting step function converges to the continuous supply function as the number of steps increases”. One implication of the discreteness is, though, that we needed to specify a rationing rule in case accumulated supply exceeds (realized) demand; we chose a proportional rationing rule (see Appendix B for details).

5 Repetition does not change our null hypothesis because the finiteness of the game was commonly known and because of the uniqueness of the one-shot equilibrium; at the same time, feedback across rounds may facilitate learning and help subjects converge to an equilibrium.
Figure 3 shows the interface that subjects saw on their screens. Supply functions could be entered using the scrollbars located in the middle and submitted by pressing the button on the right. The numbers above the scrollbars indicated which price belonged to which unit. In addition, the supply function was drawn on the top part of the screen (see Appendix B for examples).

As soon as all supply functions were submitted, the computer generated the demand outcome, calculated the quantities and prices and showed them graphically to the subjects. More specifically, at the end of every round each subject received information about the group supply function (displayed graphically at the bottom of the screen), the demand realization, the market clearing price, own units sold, own profit and own accumulated profit (all shown in the top-left corner). The demand realization and the market clearing price were displayed graphically in the lower part of the screen together with the aggregate supply function. The market clearing price was depicted in the upper graph together with the individual supply function.

All expressions are translated from German. For T3, the screen design was slightly different, specifically depending on the firm type. Screenshots of the treatment can be found in the Appendix C. The experimental software was developed in Visual Basic.
Prior to the experiment, each group played five dry runs that were not payoff relevant. Both, dry runs and payoff relevant rounds were always conducted within the same group, so that each group represents a statistically independent observation. Altogether, we collected 11/11/10 independent observations in treatment T1/T2/T3.

All payments were made in experimental currency units (ECU) which were converted into Euro at a rate of $1/1100, 1/3000 and 1/2500$ for T1, T2 and T3, respectively. The sessions lasted more than 1.5 hours, but less than 2 hours. Average gains (standard deviation) were $21.58 (6.92)$ Euros in T1, $21.53 (3.61)$ Euros in T2, and $17.18 (6.52)$ and $29.27 (10.55)$ Euros in T3 for ordinary and large firms, respectively.

4 Results

Figure 4 summarizes the bidding behavior in our three treatments. Each of the four graphs shows the actual average supply function of each market in the respective treatment (thin, dashed lines), an estimate of the corresponding overall average supply function (thick dashed line) along with a 95 percent confidence interval around that estimate (shaded area), and finally the predicted SFE behavior (thick, continuous line). Figure 4(a) shows the supply in treatments T1 and T2, Figure 4(b) shows the supply for treatment T3, separately for ordinary and large firms.

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7 The exchange rates were different for the different treatments since expected payments in ECU differed across treatments. Prior to the experiment we ran a pilot session of T3 in order to adjust conversion rates and to decide on details of the design such as the decision time to give the subjects in each round. No data of this session was used in our analysis. However, results do not change when including the data.

8 The equivalent values in US dollars for the average gains are 27.2 in T1, 27.13 in T2, and 21.65 for ordinary and 36.89 for large firms in T3. The values are calculated using an average exchange rate of the days, when the sessions took place.

9 Each estimate is based on a non-parametric Gaussian kernel and a local polynomial regression estimator of order 2; the bandwidth is selected using the rule-of-thumb (see e.g. Li and Racine (2007, Ch. 2)). Actual overall averages do not much differ from estimated averages, but, as is obvious from looking at individual market data in Figure 4, the confidence interval of the actual average curve will be larger than the confidence interval of the estimated curve of averages.
In line with SFE predictions, the figures show that, on average, firms offer the first unit at prices close to marginal cost, additional units at (mostly convexly) increasing prices, and ask for prices close to the maximum possible price at the maximum capacity. These patterns support what might be interpreted as the central qualitative prediction of SFE: higher demand is accompanied by increasing mark-ups. Naively bidding a constant markup on (marginal) costs would have just led to a constant bid function.

That said, the figures also reveal important and systematic quantitative deviations from SFE. In particular, while there is considerable heterogeneity across markets, the estimated average supply functions of ordinary firms in T1-T3 tend to be less competitive than predicted in almost the whole price-range (only for very small and very large prices is the SFE prediction within the 95 percent confidence interval of our estimate). In stark contrast, large firms bid less
competitively than predicted only at small prices, yet generally (for prices above 10) bid more aggressively than predicted.

Comparing the bid functions across different demand conditions in T1 and T2, we also find that, unlike predicted by SFE, firms in T1 generally behave more competitively than in T2. Only at prices 0 and 1 and in the interval [39, 50], we cannot reject the hypothesis that the estimated averages in T1 and T2 are equal. Observe that, because in treatment T2 the demand's support is [80, 120], the SFE is relevant only for quantities in [20, 30], corresponding to the price interval [15, 50]. A lack of disciplining market feedback for lower quantities may have fostered withholding of supply in this area, which however seems to have spilled over to the relevant quantities, between 20 and 25.

FIGURE 5: Average group supply functions in T1 and T3

Turning to our comparison of T1 and T3, Figure 5 shows that aggregate supply is larger in T3 than in T1 at all price levels above 16. The effect is due to the rather competitive bidding of large firms. In fact ordinary firms’ aggregate supply is even slightly (but insignificantly) lower in T3 than in T1 at all prices. Clearly, large firms do not exploit their price setting power as predicted by theory; starting at low prices, they rather increase their market shares above what is
expected by SFE, probably in an attempt to win a share that reflects more accurately their share of total capacity.\footnote{We can reject both, the hypothesis that the average market share of large firms equals the theoretically predicted market share of 29 percent, as well as the hypothesis that it equals 50 percent, which is the large firms’ share of total capacity (Wilcoxon signed-rank tests, $p = 0.0069$ and $p = 0.0051$, respectively).}

![Figure 6: Average Distance to SFE](image)

Figure 6 closes the results section by showing that there is no systematic dynamic time trend in bidding behavior. More specifically, we calculate the "Distance to SFE" by summing up bids over all groups and all prices in a certain round and subtracting the sum of the equilibrium quantities (again over all groups and prices). This gives a measure of how close the observed market performance comes to the equilibrium prediction on average. The figure shows that, on average, aggregate supply is rather constant over time in T1 and T2, while it non-monotonically fluctuates in T3. There appears to be no systematic time trend, such as convergence to SFE or last round effects. For instance, seven groups in T1 and three groups in T2 moved somewhat closer to the SFE from the first to the last quarter of the experiment, while four and eight groups, respectively, moved somewhat away.
5 Discussion and Conclusion

We conducted the first behavioral robustness check of SFE, testing key predictions of supply function competition. Overall, SFE organizes bidding behavior well. The shape of the supply functions (increasing and mostly convex) are qualitatively in line with what is predicted by SFE. However, symmetric firms and small firms in an asymmetric case provide smaller quantities than predicted by SFE, while the large firm in our asymmetric case behaves (for larger prices) more competitively than SFE suggests. We also find that the demand uncertainty matter in ways not captured by SFE.

Our findings add a behavioral perspective to some of the phenomena observed in the field. For one, we find that the demand distribution matters when it should not: less demand uncertainty (in the sense that low demand becomes unlikely) makes it easier for firms to reach collusive outcomes. This 'behaviorally' reinforces the robustness of earlier findings from field studies (see Baldick and Hogan (2002) for an analysis of electricity supply in the England and Wales market in 1999) and from experiments with 'adaptive agents' simulating the behavior of oligopolistic electricity generators (see Bower and Bunn (2001)) that requiring supply functions to remain fixed over an extended time horizon such that there is a larger variation in demand reduces the incentive and capability to mark up prices. Second, we find that (with unequal firm sizes) large firms generally fail to fully exploit their market power. This suggests that bounded rationality also contributes to the observation that prices are sometimes below what can be expected from strategic modeling.\textsuperscript{11}

Regarding the experimental literature on oligopolistic competition, our observations generalize a common finding from pure quantity and pure price competition experiments: outcomes tend to be somewhat less competitive than theoretically expected (Holt (1995), Huck, Norman, and Oechssler (1999, 2004), and Hinloopen and Normann (2009)). Laboratory supply function competition allows us to additionally observe that the effect is strongest for low prices and for outcomes that are unlikely to occur – that is, when the incentive to outbid others is rather small.

\textsuperscript{11} See Wolfram (1999). Also, the study by London Economics (2007) on behalf of the European Commission indicates 'too little' exploitation of market power of pivotal firms: e.g., for 2005, the largest supplier in Germany was calculated to be pivotal in more than 50 percent of all hours, but price mark-ups on short run marginal costs were computed to be 15.2 percent, which appears too low given the strong pivotalness. The result is also in accordance with Mason, Phillips, and Nowell (1992) who found Cournot markets with asymmetric firms to be more competitive than markets with symmetric (equal costs) firms.
Our laboratory environment is held simple in order to provide a first test whether SFE can in principle organize bidding behavior. Like in theoretical work, our conclusions are conditional on our framework. The next step would be to check the robustness of our results in more complex environments, similar to what has been done in the already mature literature on laboratory quantity and price competition. Because the typical application of SFE is the electricity spot market, and electricity generation is plagued by non-standard costs (Stoft (2002)), we think that promising extensions will include variations in the cost structure such as increasing marginal costs, investment and fixed costs, cost asymmetries, and non-convex costs. Also, controlled laboratory research might help to separate competing (behavioral and institutional) explanations for some field data phenomena not easily predicted by SFE, as they are discussed in the theoretical and empirical literature. That said, we hypothesize, given the success of the simple SFE model in organizing central bidding patterns in our study, that SFE will prove to be a behaviorally useful benchmark in more complex environments.
References


Appendix A: Equilibrium Predictions

This section sketches how the supply function equilibrium can be derived for our experimental markets. Exact proofs are found in Holmberg (2007, 2008).

We consider a market with $n$ firms with constant marginal costs $c$. Bids submitted by each firm are piecewise twice continuously differentiable and non-decreasing supply functions $S_i(p)$, where $p$ is the price. $S_{-i}(p)$ represents the aggregate supply of the competitors of firm $i$, and $S(p)$ the total supply. Demand $\epsilon$ is perfectly inelastic. Its density function $f(\epsilon)$ is continuously differentiable and has a convex support set with $f(\epsilon) > 0$. When maximizing the expected profit in response to $S_{-i}(p)$ on an interval $[\mu, \nu]$ where $S_{-i}(p)$ is differentiable, player $i$ faces a degenerate control problem.

\[
\max_{p(\epsilon) \in [\mu, \nu]} \int_{\mu}^{\nu} [\epsilon - S_{-i}(p(\epsilon))](p(\epsilon) - c)f(\epsilon)d\epsilon
\]

It is degenerate because $p' = dp/d\epsilon$ does not enter the goal function. If $i$ can use only non-decreasing supply functions, $p(\epsilon)$ has to obey the restriction $p'(\epsilon) \leq 1/S'_{-i}(p)$. This restriction holds in the equilibria derived below. Under such conditions, $i$ maximizes the expected profit by choosing the optimal $p(\epsilon)$ for all $\epsilon$ separately. The respective first order condition is

\[
[\epsilon - S_{-i}(p(\epsilon)) - S'_{-i}(p(\epsilon)) \cdot (p(\epsilon) - c)]f(\epsilon) = 0
\]

Equation (2) provides us with a system of $n$ differential equations for the $n$ supply functions $S_i(p)$. Taking $S_i(p) = \epsilon - S_{-i}(p)$ into account, a symmetric\textsuperscript{12} supply function equilibrium (SFE) has to satisfy the following system of differential equations\textsuperscript{13}

\[
S_i(p) - (n-1)S'_i(p)(p - c) = 0, \quad i = 1, \ldots, n
\]

The general solution of equation (3) is

\[
S_i(p) = a(p - c)^{1/(n-1)}, \quad a = \text{const} > 0
\]

which implies the inverse market supply function

\textsuperscript{12} There are also asymmetric solutions of equation (2), see Bolle (1992), Genc and Reynolds (2004), and Holmberg (2007). These solutions violate monotonicity of supply functions when prices are close to marginal costs. However, aggregate supply has the same functional form as in symmetric supply function equilibria.

\textsuperscript{13} For $\epsilon$ satisfying $f(\epsilon) > 0$. The remaining choices are irrelevant.
\[ p(\varepsilon) = c + \left( \frac{\varepsilon}{na} \right)^{n-1} \]

\( \alpha \) is an arbitrary positive parameter which allows for a continuum of equilibria. In case there are a price cap \( \bar{p} \) and capacity constraints \( \bar{e}_i \leq \bar{e}_2 \leq \ldots \leq \bar{e}_n \) that become binding with positive probability, Holmberg (2007, 2008) shows that there is a unique equilibrium with identical bids as long as aggregate demand is smaller than or equal to \( \varepsilon^* = \sum_{i=1}^{n-1} \bar{e}_i + \bar{e}_{n-1} \). If \( p = \bar{p} \), any demand \( \varepsilon \) with \( \varepsilon^* \leq \varepsilon \leq \sum_{i=1}^{n} \bar{e}_i \) is supplied.

**Treatment T1** (Four firms with capacities \( \bar{e}_i = 30 \) and marginal cost \( c = 0 \), and demand is uniformly distributed on \([0, 120]\)): The unique SFE is described by equations (2) and (3).\(^{14}\)

\[ S_1(p) = 30 \left( \frac{p}{\bar{p}} \right)^{1/3} \]

(4)

The inverse aggregate supply function is

\[ p(\varepsilon) = \bar{p} \left( \frac{\varepsilon}{120} \right)^3 \]

(5)

**Treatment T2** (As T1, but demand is uniformly distributed on \([80, 120]\)): Equation (4) describes the bids, and equation (5) the inverse demand function, but only for individual bids above 20 (or market demand above 80). From \( \varepsilon = 0 \) to \( \varepsilon = 80 \), \( p(\varepsilon) \) is an arbitrary increasing function with \( p(\varepsilon) \leq \bar{p}(80/120)^3 \) for \( \varepsilon < 80 \).

**Treatment T3** (Three firms have a capacity of 30, the fourth firm has a capacity of 120, and demand is uniformly distributed on \([0, 180]\)): Equations (4) and (5) describe the market up to \( \bar{p} \) where \( \varepsilon^* = 120 \) is supplied (or more if demand is higher). Beyond 120, additional demand is supplied only by the large firm.

\(^{14}\) Holmberg’s (2007) proof requires only that demand in \( [\varepsilon^* - \mu, \varepsilon^*] \) occurs with a positive probability for all positive \( \mu \).
**Appendix B: Instructions**

In the following, we provide the instructions for T1. The instructions for T2 are identical except for the demand interval used. In T3 the instructions are slightly adjusted in order to account for the asymmetry of the market configuration. All instructions are translated from German.

**Instructions**

Welcome to the experiment and thank you for participating. Please read the instructions carefully. They are identical for all participants.

If you have any questions, please raise your hand. An experimenter will then come to you. From now on any communication among the participants is forbidden. In case you do not adhere to this rule, you will be excluded from the experiment and the payout. Please switch off your mobile phone now.

During the experiment all monetary amounts are indicated in ECU (Experimental Currency Units). The conversion rate $1€ = 1100$ ECU is used to calculate the payout at the end of the experiment. You get $2.50€$ for participating and can earn a higher amount in the course of the experiment. How much you will earn in total depends on your decisions and those of the other participants. All your decisions are confidential.

**Making the decision**

You compete with three other participants as suppliers in a market. You and the other participants act as producers who make decisions about the supply of a fictitious good. The demand for that good is simulated by the computer. Your profit depends on your supply decision, the supply decisions of the other three producers in your market, and the simulated demand.

The experiment has several rounds. In every single round you and the other producers have to make new supply decisions while the computer determines a new demand realization. The same four producers stay together throughout the whole experiment. The identities of the other producers, however, are not disclosed at any time.
At the beginning of the experiment you and the other producers in your market will play 5 training rounds that do not count for the final payout. Here you can test different behaviors. After that you will play 60 rounds that do count for the final payout.

**Demand**

Every round the computer buys between 1 and 120 units of the good that you and the other producers in your market supply. In each round the demand realization is generated randomly. All quantities between 1 and 120 have the same probability.

The computer pays the same *market price* for all units bought. This price is determined by the intersection between supply and demand, as we will explain later on. The computer will never pay a price higher than 50 ECU per unit.

**Decisions about supply**

In each round you and the other producers in the market can produce a maximum of 30 units of the good. There are no costs of production.

In each round you have to indicate for each of the 30 units the minimum price you are willing to accept. Different prices can be assigned to different units. The price assigned to a certain unit cannot be lower than the one chosen for the previous unit. For instance, if you choose a price of 10 ECU for the fourth unit, you have to assign at least a price equal to 10 ECU to the fifth unit. However, the price for the fifth unit can also be higher than 10 ECU.

A unit will only be sold if the price you ask for is equal to or smaller than the market price. We will show later how the market price is calculated.

You are not allowed to ask for a price higher than 50 ECU, since the computer does not pay a price higher than that.
How do I submit the supply function?

In each round you see the entry mask as shown above, which you can also see right now on your screen. Use the top part of the screen to indicate your supply. You can choose the minimum selling prices by using the scroll bars below the diagram in the upper part of the screen. You can raise the price by clicking the top arrow, and lower it by clicking the bottom arrow. If you raise the price for a unit, the prices for the following units will be adjusted automatically to at least that level. The reason is that for any of those units you have to ask as least as much as for the previous units. You can now test this on your computer.

In every round the supply decision from the previous round is adopted as start position for the next round. However, prices can always be modified for as many units as you want.

The market price

Once the four producers have chosen their minimum selling prices for all 30 units (= their individual supply curves), the computer adds up individual supplies at each price. The result is the aggregate supply curve of the market in that particular round. In the following figure we illustrate with an example how the aggregate supply curve is determined. You can see the four entry screens with four individual supply curves. They are chosen arbitrarily to illustrate the
spectrum of possibilities. On the screen showing the supply curve of all producers you can see the resulting aggregated supply function.

Producer 1:

Producer 2:

Producer 3:
Producer 4:

Supply Curve of all Producers:

Suppose, for example, the price is 20, and the first (second, third, fourth) producer is willing to supply 2 (27, 30, 9) units according to their supply decisions. Then, aggregate supply equals $2 + 27 + 30 + 9 = 68$ at a price of 20.

The intersection of the aggregate supply curve and the demand realization (between 0 and 120) determines the market price and the number of units sold at this price. All units offered at minimum prices lower than the market price are sold at the market price. The market price is equal to the highest minimum selling price at which the computer buys.

The following graphic shows an example. You can see the aggregate supply curve of the market. Furthermore, you see that the demand realization is 90 units in this round. In the example, the minimum price for the 90th unit, according to the aggregate supply curve, is 40 ECU. Consequently, this is also the market price that is paid for all 90 units sold.
Supply function, demand and market price:

You will always sell all units that you have offered at a price strictly lower than the market price. However, it may occur that a firm does not sell units which it has offered at a price equal to the market price. This happens whenever multiple units have been supplied at the market price, but the computer does not buy all of them. In this case ‘proportional rationing’ is used. The following example makes clear how the rationing rule works.

Example: Suppose that demand is 20 units and the market price is 25 ECU. 19 units are being offered at a price lower than 25 ECU, and 4 units at exactly 25 ECU. (The minimum selling price for the rest of the units is higher than 25 ECU). Supposed you have offered one unit at a price equal to 25 ECU and 7 units at a lower price. Then you will sell the 7 units that you have offered at a price lower than 25 ECU in any case. However, out of the 4 units offered at exactly 25 ECU, only one unit will be bought by the computer, since it will buy no more than 20 units, and 19 units were already offered at prices less than 25 ECU. You have a share of 25 % in the units offered exactly at the market price. Thus, you will supply 1/4 of the demand of one unit that still has to be satisfied. You therefore sell 7.25 units at a market price equal to 25 ECU. Your profit is hence 7.25 * 25 ECU = 181.25 ECU.

Feedback

At the end of each round you obtain the following information:

- the demand of the computer,
- the market price,
• the number of units that you have sold,
• your profit in the current round,
• your total profit up to the current round.

In addition, you also see a graphic containing the following information:
• the aggregate supply curve,
• the demand,
• the market price.

The training periods

Before the experiment begins, you will practice during 5 rounds with the other 3 firms in your market to get used to the software. The profits from these training periods are not being paid out. When the training periods are over, the system will be reset, and the experimental rounds relevant for the final payout begin.
Appendix C: Screenshots of T3

Large firm

Ordinary Firm