QUANTITY CHOICES AND MARKET POWER IN ELECTRICITY MARKETS

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Acknowledgments

Once, sitting in a restaurant in London, some friends and I were discussing the process of creativity. One of us, a painter, described his own peculiar process as follows: "I close my eyes, shake my head back and forth, and the painting appears; then I just need to draw it"[1]. Back in Stockholm, I was eager to apply this magic rule to my work. I soon realized that my creativity process is very different. Its main characteristic is that it is fed by the people surrounding me. Reaching the end of my Ph.D., time has come to thank all these people.

First, I wish to express my sincere gratitude to my main supervisor, Lars Bergman. Despite being puzzled by my Frenco-English, he has offered me support since the very beginning of my Ph.D.-studies. I am especially grateful that he always forced me to connect my research to the "real world" of the electricity market. Thanks Lars for giving me the opportunity to do this Ph.D.!

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[1] To appreciate how well this works for him, take a look at www.kaimccall.clara.co.uk.

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(un dicton pour finir: "Jamais deux sans trois"... c'est une plaisanterie!)

Stockholm, April 2003

Contents

Introduction and summary

Competitive power markets from different countries exhibit a common market design, especially because of the nature of electricity (lack of storage, inelastic load, and strong seasonal effects on multiple time scales).[1] For example, a majority of countries have created a spot market where electricity is traded hourly. The design of the spot markets reflected an ambition of providing strong incentives for efficient and least-cost production. Subsequently, the spot market price has been considered as a reference price for other existing electricity markets such as the contract market or the real-time market. However, empirical studies on electricity markets find some evidence of abnormally high markups (Wolfram (1998, 1999), or Borenstein and Bushnell (1999)). This evidence confirms the theoretical predictions of Green and Newbery (1992) and von der Fehr and Harbord (1993) that there is scope for market power in the electricity spot market.

The literature on the electricity spot market mainly focuses on the producers' pricing decisions (see von der Fehr and Harbord (1998) for a survey). A common result is that the level of demand (relative to given available capacities) is important for explaining high market prices on the electricity spot market. However, we argue that available capacities, unlike installed capacity, are choice variables in the short run, since plants can be rendered "unavailable" for maintenance and other reliability considerations (see Wolak and Patrick (1997) for empirical evidence on this subject). Considering pro-

[1] Joskow and Schmalensee (1983) explain how these characteristics of supply and demand are reflected in the organization of the competitive power markets.

ducers' available quantity decisions is therefore pertinent for understanding market power on the electricity spot market.

Another part of the literature focuses on the impact of having a contract market before the spot market (von der Fehr and Harbord (1992), Powell (1993), Newbery (1998), Green (1999), Wolak (2000)). This literature finds that the access to a contract market reduces the scope of market power on the electricity spot market. We argue, however, that an analysis taking into account the repeated nature of electricity markets may lead to the opposite conclusion.

The present thesis argues that quantity choices, both in terms of available as well as contracted quantities, are crucial for understanding market power in electricity markets.

Part one: Available quantities, price competition and market power

The first two chapters analyse the scope for market power in a setup similar to that Kreps and Scheikman (1983) where firms simultaneously commit to a capacity level before competing in prices. Their seminal result is that the Cournot outcome is a subgame-perfect equilibrium. By modifying some of their assumptions, we challenge their result. In the first chapter, we analyze a uniform-price auction where demand is fixed (features of the electricity market) and in the second chapter, we study strategies of players with different levels of experience.

Chapter I: Strategic Use of Available Capacities in the Electricity Spot Market

The literature on deregulated electricity markets generally assumes available capacities to be given. In contrast, this chapter studies a model where firms choose capacities, then submit price bids in a uniform-price auction. The market price equals the highest price bid, if demand is higher than the available capacity of the lowest price bidder. Otherwise, the market price equals the lowest price bid. As long as there is not "too much" capacity available, they can drive the price in the auction to some maximum level. This means that the firms have an incentive to withhold capacity from the market in the first stage, in order to raise the price in the second stage. The analysis sheds light on recent empirical findings, namely that firms use their available capacity to obtain high market prices (Wolak and Patrick, 1997). The presence of inelastic demand implies that the second stage price is at the exogeneous maximum, rather than at the Cournot level as in Kreps' and Scheikman's model (they assumed Bertrand competition against a downwards-sloping demand curve). There are two equilibria in this model. In one, the low-cost firm ensures that it is not able to supply the entire market, so that the hight-cost firm, which is also unable to meet the demand on its own, is required to produce a small amount of output at a high price. This outcome is inefficient, if we assume that the low-cost firm actually had enough capacity to meet the entire demand. The second equilibrium involves the high-cost firm withholding enough capacity to commit itself to bid low in the second stage of the game. As a result, the low-cost firm bids high and sells the residual demand. The high-cost firm keeps its capacity sufficiently low to make this residual demand an attractive choice for the low-cost firm.

Chapter II: Do Opponents' Experience Matter? Experimental Evidence from a Quantity Precommitment Game

This chapter investigates why subjects in laboratory experiments on quantity precommitment games consistently choose capacities above the Cournot level - the subgame-perfect equilibrium (Davis (1999), Muren (2000), Anderhub et al. (2002)). We argue that this puzzling regularity may be attributed to players' perceptions of their opponents' skill or level of rationality. By level of rationality, in the spirit of McKelvey and Palfrey (1995) and Sargent (1994), we mean the degree of precision with which a player observes his payoff and we refer to less than perfect precision as bounded rationality. In our experimental design, we use the level of experience (the number of periods played) as a proxy for the level of rationality and match subjects with different levels of experience. The implicit assumption is that experienced players can be expected to play more rationally (make fewer mistakes) than inexperienced ones. We first find evidence of capacity choices decreasing, and prices increasing, with the opponent's experience. Futhermore, we investigate the observed behavioural patterns by using the agent-form quantal response equilibrium model by McKelvey and Palfrey (1998). In particular, this framework takes into account any interaction between a player's own experience and that of his opponent. We show how the predictions of this theoretical framework fit well with the experimental data. This suggests that a potential explanation for the observed regularity may either be that subjects have a tendency to underestimate the rationality (the experience) of their opponents or that rationality is truly limited for a large proportion of subjects.

Part two: Contracted quantities, price competition and market power

The last two chapters analyze the scope of market power when firms can sell their good on a forward contract market as well as on a spot market. Allaz and Vila (1993) argue formally that generators may have less incentive to exercise market power if they have large contract positions. A firm may obtain a leadership position by selling contracts before going on the spot market. Motivated by this opportunity, all players participate in the contract market and, as a consequence, compete more aggressively overall. As a result, having a contract market before the spot market decreases the market price. We question the prediction of Allaz and Vila by experimentally testing it (third chapter) and by considering a dynamic setup, which we view as a better description of the electricity markets (fourth chapter).

Chapter III: Do Forward Contract Markets Enhance Competition? Experimental Evidence

This chapter investigates whether forward contract markets constitutes an effective tool for improving competition in an oligopoly, compared to other means (especially the entry of additional competitors). Our n-firm version of the Allaz and Vila model predicts that introducing a forward market raises competitiveness to the same degree as when squaring the number of competing firms. We report the results of a laboratory experiment designed to test this hypothesis. Moreover, we employ two benchmark conditions where either two or four sellers engage in standard Cournot competition and thus solely trade on a spot market. In the other experimental markets, two (or four) firms can first sell units on a forward market, before entering the spot stage. If they make transactions on the forward market, the sellers commit to produce at least their forward quantities. In addition they can produce more units, which are then sold to the residual demand on the spot market. We find that forward contract markets enhance competition and efficiency (higher total production levels and lower prices than under the Cournot benchmark). However, our experimental results also indicate that the effect of introducing a forward trading institution is not as strong as suggested by theory. Our experimental evidence rejects the hypothesis that a forward market is as effective as increasing the number of firms on the market. Instead, it proves to be far more effective to increase the number of competitors in the market.

Chapter IV: Long-term Supply Contracts and Collusion in the Electricity Market

The analysis of Allaz and Vila is based on a framework with a finite horizon. As a result, the access to a contract market gives rise to a situation reminiscent of the prisoners' dilemma; each producer has an incentive to offer a contract but when all do so, everyone is worse off. The repeated nature of electricity markets raises the question of whether Allaz's and Vila's result is applicable to the electricity market. The purpose of this chapter is to check the robustness of the argument that the access to contract markets reduce the market power of generators. In particular, it investigates the sensitivity of this result with respect to the finite horizon assumption. We consider a setting where firms first offer a long-term supply contract with a ceiling spot price. Then, they repeatedly interact on the spot market, by choosing prices. We show that the contract market enables collusion on the spot market when firms would compete in the absence of such a market. Access to a contract market reduces the firms' incentive to deviate from the collusive agreement. When firms collude on the spot market, they have already committed to some contracted quantities. As a result, a firm deviating from the monopoly price will not enjoy the full benefit of monopoly profit, as in classical repeated price games. The reason is that its rival is ensured to sell its contracted quantity at the market price. The deviation profits are thus smaller than in usual repeated price games. An immediate consequence is that contracts with a ceiling spot price, which reduce the exposure to spot market prices, do not imply a reduction of the price paid for electricity.

Chapter I

Strategic Use of Available Capacities in the Electricity Spot Market[1]

1

1 Introduction

Many countries have created an electricity spot market in order to deregulate their electricity sector. Spot markets are supposed to provide strong incentives for efficient and least-cost production. However, empirical studies indicate large markups during periods of high demand (e.g. von der Fehr and Harbord (1993), Wolfram (1998, 1999), or Borenstein and Bushnell (1999)). Moreover, there is evidence that major generators use their available capacity strategically in order to enhance their market power. For the period 1991 to 1995, Patrick and Wolak (1997) find empirical evidence of such strategic behavior in the British market. During the first quarter of 1999, the Spanish competition authority accused the two major firms of reducing their available capacity in areas with high demand. In January 2000, the Nordic electricity spot market experienced unexpectedly high prices, due to a reduction in available nuclear production (Nord Pool, 2000). During the summer of 2000 in California, the monthly electricity bills were three times higher than usual, while several units were declared unavailable and simultaneously taken out of service (Joskow and Kahn, 2002).

This chapter is motivated by the above empirical observations. Available capacities (unlike installed capacity) are choice variables in the short run,

[1] I would like to thank Lars Bergman, Tore Ellingsen, Guido Friebel, Sven-Olof Fridolfsson, Per-Olov Johansson, Dan Kovenock, Jens Josephson, Maria Saez-Marti, and Lars Sørgard for helpful comments.

since plants can be rendered "unavailable" for maintenance and other reliability considerations.[2] In an electricity spot market, producers make a price bid to supply a given amount of electricity (their available capacity) and the market clearing price is determined by a uniform price auction. As a result, the potential for market power depends heavily on this available capacity.

This chapter proposes a two-stage duopoly model with asymmetric cost firms. In the first period, firms simultaneously choose their available capacity. After observing the capacity levels, the firms set the minimum price for this available capacity. The analysis shows that two subgame perfect equilibria exist where at least one firm withholds its available capacity to induce the maximum price.

Due to the uniform price auction in the price subgame, the market price equals the highest price bid, if demand is higher than the the available capacity of the lowest price bidder. Otherwise, the market price equals the lowest price bid. The lowest price bidder then has an incentive to withhold its capacity, that is to offer an available capacity below demand. In this case, the market price equals the highest bid, the lowest price bidder sells its entire capacity and the other sells the residual demand. Interestingly, the high-cost firm is the lowest price bidder and obtains a relatively large market share in one of the two equilibria.

Withholding capacity has two negative welfare implications. First, when firms are free to choose their capacities, they obtain a market price above the competitive outcome. This is costly for consumers. Second, the low-cost firm, which is able to supply the entire demand, does not do so since the high-cost firm has a positive market share. This implies that production costs are not minimized.

The literature on the restructured electricity market mainly focuses on the producers' pricing decision.[3] Von der Fehr and Harbord (1993) construct a well-known model where generators compete by submitting bids specifying the prices at which they are willing to make their production available. This

[2] Installed capacity determines the firms' overall production capacity. In contrast, available capacity is the capacity used at short notice, which takes into account breakdowns or other unforseeable events.

[3] For a recent survey of the theoretical and empirical literature, see von der Fehr and Harbord (1998).

setup allows them to identify the price bidding strategies.[4] In particular, they show that the level of demand (relative to given available capacities) is important for explaining high market prices on the electricity spot market. This chapter extends the von der Fehr and Harbord (1993) model by endogenizing the firms' capacity choices. It complements their analysis by showing how firms may manipulate their available capacities in order to obtain substantial markups.

Like Kreps and Scheinkman (1983), I consider a two-stage game where firms choose capacities and then compete in prices. However, I obtain different results despite the similarity in the timing of the game. In particular, the reduced-form profit function has the Monopoly form (instead of the Cournot form in the Kreps and Scheinkman model). The most important reason is that the second stage, in line with the actual design of many electricity spot markets (see section 2 for details), is modeled as a uniform-price auction (instead of Bertrand competition).[5]

Section 2 introduces the model. Pure strategy Nash equilibria in price bids for given capacity combinations are derived in section 3. This yields reaction functions in the capacity space (section 4), which I use to find subgame perfect equilibria for the two-stage game (section 5). The final remarks are given in section 6.

2 The Model

Five features are important for capturing the strategic behavior of producers on an electricity spot market. First, a day is divided into periods[6] and, for

[4] An alternative way of modelling price competition in the electricity spot market has been proposed by Green and Newbery (1992). They assume that firms compete by submitting continuous supply functions, rather than discrete step functions. In the electricity sector, one unit of capacity is a power plant. Therefore I consider capacity as a discrete variable and I adopt the von der Fehr and Harbord's setup.

[5] Deneckere and Kovenock (1996) show that the two-stage game does not necessarily yield the Cournot outcome if firms have different marginal cost for providing capacity. The result of Kreps and Scheinkman is thus also sensitive to the assumption of symmetric costs.

[6] On the electricity spot market, the period is usually one hour or half an hour and it is called the load.

each period, a uniform-price auction takes place to determine the electricity spot price. Second, the responsible for the market (namely the dispatcher) forecasts a fixed level of demand for each period. Third, producers are responsible for the supply by declaring how much they can produce (available capacity) and at what price (price bid). Since the production of electricity must be planned, the available capacity is determined the day before the transaction and differs from the installed capacity. If a plant is declared unavailable, it is usually announced and published on the home page of the dispatcher. When producers set their prices, they thus play a capacity-constrained game. Fourth, the electricity market has an oligopolistic structure, often with two dominant actors.[7] Fifth, different production technologies characterized by different costs are used.[8] All these five features are taken into account in the formalization below.

Consider a market for a homogeneous good supplied by two firms. The demand for this good is fixed and given by d. Firms interact in two periods. In the first period, firms 1 and 2 simultaneously and independently choose their available capacities denoted k_1 and k_2, respectively, where capacity k_i means that firm i ($i = 1, 2$) subsequently produces up to k_i units of electricity at a specific marginal cost.[9] At the end of the first period, each firm learns about the capacity of its opponent, and in the second period, firms 1 and 2 simultaneously and independently name price bids p_1 and p_2, respectively. The firms have different marginal costs, namely c_1 and c_2, where $c_1 < c_2$. [10]

Let $s = (s_1, s_2)$ be the bids submitted by firms 1 and 2, where $s_i = (k_i, p_i)$. When bids are given by s, let $P(s)$ denote the market price and and $x_i(s)$ denote the output sold by firm i.

Without loss of generality, I assume that $c_1 = 0$ and $c_i \leq p_i \leq p^m$, where

[7]We consider only the case of high demand hours, when fringe supply has reached its full output capacities and large players in the market are able strategically to affect the market outcome.

[8]Most electricity is generated by burning fossil fuel (coal, oil, or natural gas) or by nuclear fuel, or by water power (hydroelectricity). Clearly, the costs associated with these production technologies differ.

[9]Note that each firm has an installed capacity exceeding the level of demand. However, their available capacity might be lower than the demand level.

[10]It is commonly assumed that there are no start-up costs and constant marginal costs for available capacity (as opposed to installed capacity).

p^m is the maximum price.[11] Demand is allocated efficiently, that is, in the case of tie in prices, the low cost firm sells its capacity first.

In a uniform-price auction, firms sell their production at the *same* market price, which equals the lowest price bid only if the lowest price bidder can meet the entire demand. Otherwise, the market price equals the highest price bid. Hence,

$$P(s) = \begin{cases} p_i = \min\{p_1, p_2\} & \text{if } k_i \geq d; \\ \max\{p_1, p_2\} & \text{otherwise.} \end{cases} \tag{1}$$

Note that the low-cost firm (firm 1) supplies $\min\{k_1, d\}$, whenever $p_1 \leq p_2$, and the residual demand $\max\{0, d-k_2\}$, whenever it submits a strictly higher price bid. Hence:

$$x_1(s) = \begin{cases} \min\{k_1, d\} & \text{if } p_1 \leq p_2; \\ \min\{k_1, \max\{0, d-k_2\}\} & \text{if } p_1 > p_2. \end{cases} \tag{2}$$

Firm 2 (with the highest cost) sells the residual demand $\max\{0, d-k_1\}$, whenever $p_1 \leq p_2$, and $\min\{k_2, d\}$, whenever it submits a strictly lower price bid:

$$x_2(s) = \begin{cases} \min\{k_2, d\} & \text{if } p_2 < p_1; \\ \min\{k_2, \max\{0, d-k_1\}\} & \text{if } p_1 \leq p_2. \end{cases} \tag{3}$$

Note that in a uniform price auction, the lowest price bidder can sell its entire capacity at the highest price bid. This is the case when this firm cannot meet the entire demand. Firm i's profit, as a function of the bids submitted by firms i and j, is given by

$$\pi_i(s_i, s_j) = [P(s) - c_i]\, x_i(s), \qquad i, j = 1, 2 \text{ and } i \neq j. \tag{4}$$

Each firm seeks to maximize its profits, and the above structure is common knowledge between firms.

Now, we derive the subgame-perfect equilibria of the two-stage game by backward induction. First, we compute the pure strategy Nash equilibria in price bids for given capacity combinations. This yields reaction functions in the capacity space, which we use to find subgame perfect equilibria for the two-stage game.

[11] Note that without a maximum price, profits can be infinite, since demand is perfectly inelastic. The maximum price can be interpreted as a price cap corresponding to the highest production cost of power plants.

3 The Capacity-Constrained Subgame

In this section we characterize the equilibrium price bids in the last stage of the game. Assuming that the firms have chosen the pair of capacities $(k_1, k_2) \in R^2_+$ in the first stage of the game, a pair (p_1^*, p_2^*) is a Nash equilibrium of the subgame in prices if

$$\begin{aligned} p_1^* &\in \arg\max_{p_1} P\left[(p_1, k_1), (p_2^*, k_2)\right] x_1 \left[(p_1, k_1), (p_2^*, k_2)\right] \text{ and} \\ p_2^* &\in \arg\max_{p_2} \left(P\left[(p_1^*, k_1), (p_2, k_2)\right] - c_2\right) x_2 \left[(p_1^*, k_1), (p_2, k_2)\right]. \end{aligned}$$

where the functions P and x_i are defined in equations (1)-(3) respectively.

It is convenient to partition the possible configurations of capacities into the four following categories of supply: weak (at most, the firms together supply total demand), strong (each firm supplies total demand on its own), asymmetric (one firm only supplies total demand), and intermediate (the firms supply total demand, but together only).

Proposition 1 *The following prices constitute Nash equilibria of the subgame in prices.*

1.*(Strong supply). If* $\min\{k_1, k_2\} \geq d$*, then*

$$p_i^*(k_1, k_2) = c_2, \text{ for } i \in \{1, 2\}.$$

2. *(Weak supply). If* $k_1 + k_2 \leq d$*, then*

$$p_i^*(k_1, k_2) = p^m, \text{ for } i \in \{1, 2\}.$$

3. *(Asymmetric supply). If* $\min\{k_1, k_2\} < d \leq \max\{k_1, k_2\}$*, then*

$$\begin{aligned} p_1^*(k_1, k_2) &= \begin{cases} p^m & \text{if } k_2 \leq (1 - c_2/p^m)\, d < d \leq k_1 \\ c_2 & \text{otherwise} \end{cases} \\ p_2^*(k_1, k_2) &= \begin{cases} p^m & \text{if } k_1 < d \leq k_2 \\ c_2 & \text{otherwise} \end{cases}. \end{aligned}$$

4. *(Intermediate supply). If* $\max\{k_1, k_2\} < d$ *and* $k_1 + k_2 > d$*, then*

$$(p_1^*(k_1, k_2), p_2^*(k_1, k_2)) \in \begin{cases} \{(c_2, p^m)\} & \text{if } k_2 > d - (c_2/p^m)\, k_1 \\ \{(c_2, p^m), (p^m, c_2)\} & \text{otherwise} \end{cases}.$$

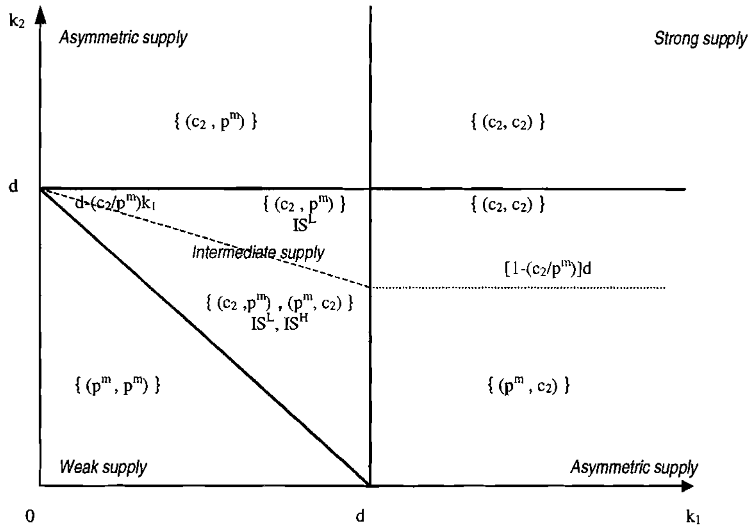

Figure 1: Pure Strategy Nash equilibria in price bids (p_1^*, p_2^*)

Proof: see Appendix A

The four categories of capacity configurations (weak, strong, asymmetric, and intermediate supplies) are illustrated in Figure 1. The equilibria in price bids found in Proposition 1 are given by the vectors in brackets in Figure 1. For example, consider the case of weak supply when $k_1 + k_2 \leq d$. In this case, $\{(p^m, p^m)\}$ indicates that $p_1^* = p^m$ and $p_2^* = p^m$ is the equilibrium in price bids. Note also that there are multiple equilibria in the case of intermediate supply when $k_2 \leq d - (c_2/p^m)\, k_1$. In this case, two equilibria exist given by the vectors of price bids (c_2, p^m) and (p^m, c_2). For later reference, we label these different equilibria in the case of intermediate supply. Let IS^L denote the equilibrium where firm 1 submits the lowest price bid c_2 (in which case, firm 2 submits p^m). Similarly, let IS^H, denote the equilibrium where firm 1 submits the highest price bid p^m (in which case, firm 2 submits c_2).

Proposition 1 does not characterize the complete set of equilibria. For example, in the cases of asymmetric and intermediate supplies, there also exists equilibria where the lowest bidder charges a price strictly larger than

c_2. All these equilibria are, however, payoff equivalent with those identified in Proposition 1 since the highest bidder still charges the maximum price p^m. Furthermore, when there are multiple equilibria in the case of intermediate supply, there also exists a mixed-strategy equilibrium (see von der Fehr and Harbord who analyse the properties of this equilibrium). We restrict our attention to the equilibria identified in Proposition 1. The reason is that it is sufficient to focus on these equilibria to derive our main result, namely that the firms may withhold capacity in order to increase prices (see Propositions 2 and 3).

Von der Fehr and Harbord identify most equilibria in Proposition 1. The main difference is that we identify pure strategy equilibria for all possible capacity configurations. In contrast, they do not analyze the case of asymmetric supply. Note that characterizing equilibria for all capacity configurations is crucial in order to analyze the game in capacities.[12]

Note also that strategies in prices (and therefore the market clearing price) depend both on the number of firms being able to supply the entire demand on their own and on the cost difference between the firms. Due to the uniform-price auction, the firms sell their production at the highest bid price, if the firm bidding the lowest price cannot supply the whole market. As a result, the market price is high if the capacities of both firms are needed to meet the entire demand. Figure 2 displays the equilibrium market price for each configuration of capacity (note that the market price equals p^m in the case of intermediate supply, irrespective of whether the firms play equilibrium IS^L or equilibrium IS^H).

Finally, note that the low-cost firm may submit the highest price bid, even though it is able to satisfy the entire demand. Wolfram (1998) and Garcia-Diaz and Marin (2000) find evidence for this behavior, namely that the largest participants in the electricity market in England and Spain bid more for their units than their smaller competitors.

[12] Von der Fehr and Harbord show that pure-strategy equilibria do not exist if the uncertainty of demand is large. However, in many cases, the uncertainty about the level of demand is small since producers bid the day before the transaction takes place.

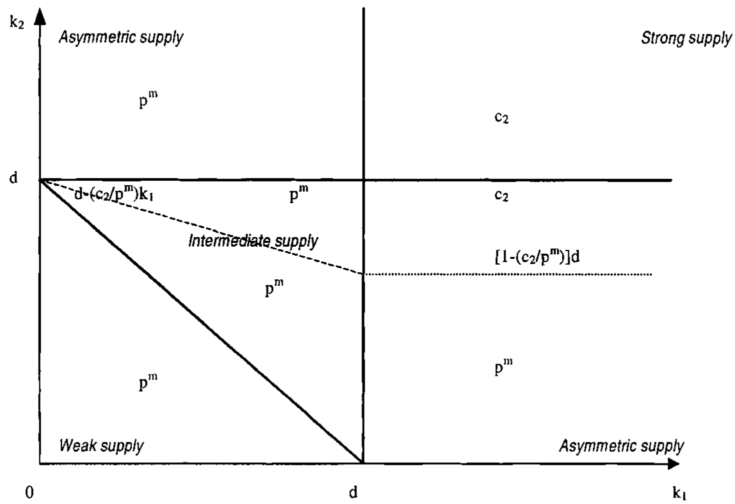

Figure 2: Equilibrium market price

4 The Capacity Game

In this section, we analyze the firms' choices of available capacities. So far, available capacity has been described as a continuous variable. In reality, the total available capacity for supplying electricity is the sum of the capacity levels of generating units.[13] Therefore, available capacity is better described as a discrete rather than a continuous variable. For this reason, we assume that the size of one generating unit is given by $\kappa \equiv d/n$, where $n \geq 2$ is a natural number.[14]

Assumption 1 *Firm i's total available capacity k_i, $i \in \{1,2\}$, is a discrete variable such that $k_i \in \{\kappa, 2\kappa, 3\kappa, ...\}$.*

In what follows, I characterize the subgame perfect equilibria in capacities. For all (k_1, k_2) such that there are multiple equilibria in price bids when sup-

[13]A single generator and its directly associated equipment are termed as a generating unit. Although individual units can be and usually are dispatched separately, they often belong to one producer.

[14]Since $n \geq 2$, a firm can choose its available capacity to be less than the entire demand, without reducing it to 0.

ply is intermediate, let superscripts L and H indicate that the firms select the equilibrium IS^L and IS^H respectively. Note that Proposition 1 defines firm i's price bid p_i^*, $i \in \{1,2\}$, as a function of each configuration of capacities (k_1, k_2). Due to the multiplicity of equilibria in the price game, I define two such functions for each firm $i \in \{1,2\}$, which are denoted $p_i^L(k_1,k_2)$ and $p_i^H(k_1,k_2)$.[15] For $j \in \{L,H\}$, let firm 1's and firm 2's best reply correspondences be

$$\beta_1^j(k_2) = \arg\max_{k_1} P\left(s_1^j, s_2^j\right) x_1\left(s_1^j, s_2^j\right) \tag{5a}$$

$$\beta_2^j(k_1) = \arg\max_{k_2} \left[P\left(s_1^j, s_2^j\right) - c_2\right] x_2\left(s_1^j, s_2^j\right) \tag{5b}$$

respectively, where $\left(s_1^j, s_2^j\right) = \left(\left(p_1^j(k_1,k_2), k_1\right), \left(p_2^j(k_1,k_2), k_2\right)\right)$ and the functions P and x_i are defined in equations (1)-(3). A pair $\left(k_1^j, k_2^j\right)$, $j \in \{L,H\}$, is an equilibrium in capacities if and only if

$$\begin{cases} k_1^j \in \beta_1^j\left(k_2^j\right) \\ k_2^j \in \beta_2^j\left(k_1^j\right). \end{cases}$$

4.1 Capacity Withholding by Both firms

In this section, I assume that the firms play equilibrium IS^L when supply is intermediate.

Proposition 2 *If firms play equilibrium IS^L when supply is intermediate, Assumption 1 holds, and $\kappa < (1 - c_2/p^m)\, d$, then the strategy $[(p^m, d-\kappa), (p^m, \kappa)]$ is a subgame perfect equilibrium.*

Proof: The proof proceeds in two steps. The first step solves the game in capacities assuming that k_2 is a continuous variable. In fact, it turns out to be convenient to make the following assumption:

Assumption 2 $k_1 \in [0, d-\kappa] \cup [d, +\infty)$ *and* $k_2 \in [0, +\infty)$.

[15] It is possible to define other such functions. Indeed, the firms could play equilibrium IS^L for only a subset of capacity configurations when there are multiple equilibria. In my view, coordinating on such equilibria is more complex and therefore I rule out such type of behavior.

The second step essentially consists in showing that the equilibria identified in the first step, also are equilibria given that Assumption 1 holds.

Step 1: This step is summarized in Lemma 1 below, which is proved in Appendix B.

Lemma 1 *If firms play equilibrium IS^L when supply is intermediate, Assumption 2 holds, and $\kappa < (1 - c_2/p^m)\, d$, then the pairs $\left(k_1^L, k_2^L\right)$, such that $k_1^L = d - \kappa$ and $k_2^L \in [\kappa, +\infty[$, are equilibria in the capacity game.*

Step 2: By Lemma 1, the pair $\left(k_1^L, k_2^L\right) = (d - \kappa, \kappa)$ is an equilibrium under Assumption 2. Since Assumption 2 allows for a larger set of deviations than Assumption 1 does, it follows that $\left(k_1^L, k_2^L\right) = (d - \kappa, \kappa)$ must be an equilibrium, also under Assumption 1.■

Lemma 1 being crucial for the proof of Proposition 2, it deserves a few remarks on its own. It is proved by constructing the best reply correspondences of firms 1 and 2, namely

$$\beta_1^L(k_2) = \begin{cases} [d, +\infty) & \text{if } k_2 \le \kappa \\ d - \kappa & \text{if } k_2 \ge \kappa. \end{cases} \tag{6}$$

and

$$\beta_2^L(k_1) = \begin{cases} [d - k_1, +\infty) & \text{if } k_1 \le d - \kappa \\ (1 - c_2/p^m)\, d & \text{if } k_1 \ge d \end{cases} \tag{7}$$

respectively. These correspondences are illustrated in Figure 3. Firm 1's correspondence is illustrated as the grey rectangular area and the thick grey line. Firm 2's correspondence is illustrated as the black area and the black thick line. The equilibria identified in Lemma 1 are straightforward to identify in Figure 3. They are given by the intersection of the two best reply correspondences, that is the thick grey line and the black area where $k_1 = d - \kappa$ and $k_2 \ge \kappa$.

To obtain an intuition for firm 1's best reply correspondence, it is sufficient to compare firm 1's profits when it chooses between $k_1 = d - \kappa$ and $k_1 \ge d$. The benefit of choosing $k_1 = d - \kappa$ is that firm 1 then sells all its capacity for the high market price p^m. By instead choosing $k_1 \ge d$, firm 1 either sells the residual demand only, or obtains the low market price c_2. As a result, firm 1

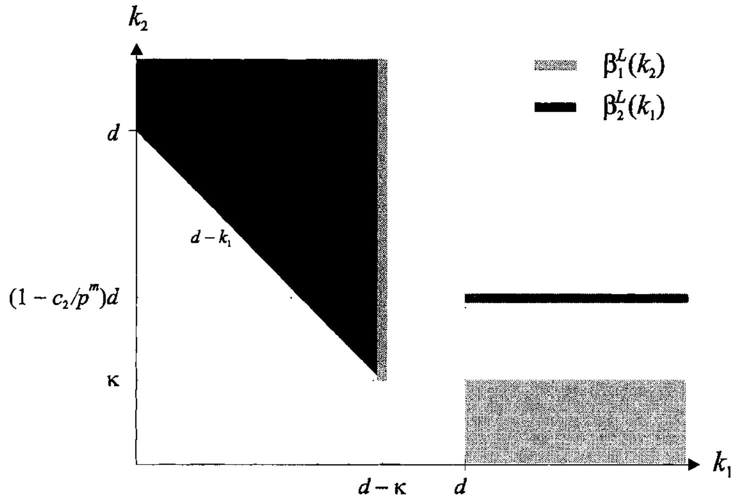

Figure 3: Best Reply Correspondence with IS^L

is in most cases better off by choosing $k_1 = d - \kappa$, which is illustrated as the thick grey line in Figure 3. In fact, the opposite is true in one instance only, namely when k_2 is so low ($k_2 \leq \kappa$), that firm 1's residual demand is larger than $d - \kappa$, which is illustrated as the grey rectangular area in Figure 3.

To obtain an intuition for firm 2's best reply correspondence, consider first the case when $k_1 \leq d - \kappa$. By choosing $k_2 \geq d - k_1$, firm 2 sells the residual demand for the high market price p^m. Consequently, firm 2 must be indifferent between all $k_2 \geq d - k_1$, which corresponds to the black area in Figure 3. Second, consider the case when $k_1 \geq d$. Note that firm 2's profits then is equal to 0 if it chooses $k_2 > (1 - c_2/p^m)\, d$, since the market price then equals firm 2's marginal cost. Hence, firm 2's optimal choice of capacity must be lower than $(1 - c_2/p^m)\, d$. Since firm 2 sells all its capacity k_2 at the high price p^m if $k_2 \leq (1 - c_2/p^m)\, d$, it follows immediately that firm 2 chooses $k_2 = (1 - c_2/p^m)\, d$ if $k_1 \leq d$. This is illustrated as the black line in Figure 3.

Finally, note that firm 1 would have little incentive to withhold capacity if κ is very large. Therefore, the condition $\kappa < (1 - c_2/p^m)\, d$ is not surprising, since it provides an upper bound on κ.

Clearly, the intuition for Proposition 2 is the same as the one for Lemma 1. Since the equilibrium capacities are given by $k_1 = d - \kappa$ and $k_2 = \kappa$, an immediate consequence of Proposition 2 is the following.

Remark 1 *If firms play equilibrium IS^L when supply is intermediate, both firms withhold their capacity.*

4.2 Capacity Withholding by the High-Cost firm

Consider once more the capacity game, but assume that the firms play equilibrium IS^H when supply is intermediate. When $\kappa < (1 - c_2/p^m)\, d$, let

$$\bar{k}_2 = \max\{k_2 \in \{\kappa, 2\kappa, ...\} : k_2 \leq (1 - c_2/p^m)\, d\}.$$

Proposition 3 *If firms play equilibrium IS^H when supply is intermediate, Assumption 1 holds, and $\kappa < (1 - c_2/p^m)\, d$, then the strategy $\left[(p^m, d), (c_2, \bar{k}_2)\right]$ is a subgame perfect equilibrium.*

Proof: As in the proof of Proposition 2, we proceed in two steps. The first step solves the game in capacities under Assumption 2. The second step essentially consists in showing that the equilibria identified in the first step, also are equilibria given that Assumption 1 rather than 2 holds.
Step 1: This step is summarized in Lemma 2 below, which is proved in Appendix C.

Lemma 2 *If firms play equilibrium IS^H when supply is intermediate, Assumption 2 holds, and $\kappa < (1 - c_2/p^m)\, d$, then the pairs $\left(k_1^H, k_2^H\right)$, such that $k_1^H = [d, +\infty)$ and $k_2^H = (1 - c_2/p^m)\, d$, are equilibria in the capacity game.*

Step 2: By Lemma 2, the pair $\left(k_1^H, k_2^H\right) = (d, (1 - c_2/p^m)\, d)$ is an equilibrium under Assumption 2. Under Assumption 1, however, firm 2's equilibrium capacity must be a multiple of κ. As a result, $k_1^H = d$ and $k_2^H = \bar{k}_2$ becomes an equilibrium. To see this, note that firm 2 reduces its profits to 0 if it increases unilaterally its capacity above $\bar{k}_2$, since the market price then equals firm 2's marginal cost. Moreover, firm 2 reduces its profits if it reduces its capacity below $\bar{k}_2$, since firm 2 then sells a lower quantity without affecting the equilibrium market price. Finally, note in Figure 4 that $k_1^H = d$ constitutes a best reply to $k_2^H = \bar{k}_2$, since Assumption 2 allows for a larger set of deviations than Assumption 1 does and since $\bar{k}_2 \in [\kappa, (1 - c_2/p^m)\, d]$.■

Lemma 2 being crucial for the proof of Proposition 3, it deserves a few remarks on its own. It is proved by constructing the best reply correspondences of firms 1 and 2, namely

$$\beta_1^H(k_2) = \begin{cases} d - \kappa & \text{if } \; k_2 > d - (c_2/p^m)(d - \kappa) \\ [d, +\infty) & \text{if } \; (1 - c_2/p^m)\, d < k_2 \leq d - (c_2/p^m)(d - \kappa) \text{ or } k_2 \leq \kappa \\ [d - k_2, +\infty) & \text{if } \; \kappa \leq k_2 \leq (1 - c_2/p^m)\, d \end{cases} \tag{8}$$

and

$$\beta_2^H(k_1) = \begin{cases} (1 - c_2/p^m)\, d & \text{if } \; k_1 \geq d \\ d - (c_2/p^m)\, k_1 & \text{if } \; k_1 \leq d - \kappa \end{cases}. \tag{9}$$

respectively. These correspondences are illustrated in Figure 4. Firm 1's correspondence is illustrated as the grey area and as the grey thick line. Firm 2's correspondence (which is a function) is illustrated as the two black thick lines. The equilibria identified in Lemma 2 are straightforward to identify in Figure 4. They are given by the intersection of the two best reply correspondences, that is the thick black horizontal line. Note also that the point where $k_1 = d - \kappa$ and $k_2 = (1 - c_2/p^m)\, d$ is not an equilibrium. The reason is that the thick grey line does not include that point (this can be verified in the first line of the expression for $\beta_1^H(k_2)$).

To obtain an intuition for firm 1's best-reply correspondence, consider first the case when $\kappa \leq k_2 \leq (1 - c_2/p^m)\, d$. By choosing $k_1 \geq d - k_2$, firm 1 sells the residual demand for the high market price p^m. Consequently, firm 1 must be indifferent between all $k_1 \geq d - k_2$. This is illustrated in Figure 4 by the grey triangle and the grey area to the right of that triangle. In the other cases, the interesting options for firm 1 are to choose between $k_1 = d - \kappa$ and $k_1 \geq d$. If k_2 is low $[k_2 < \kappa]$, the market price equals p^m, irrespective of firm 1's choice of capacity. Furthermore, k_2 is so low that

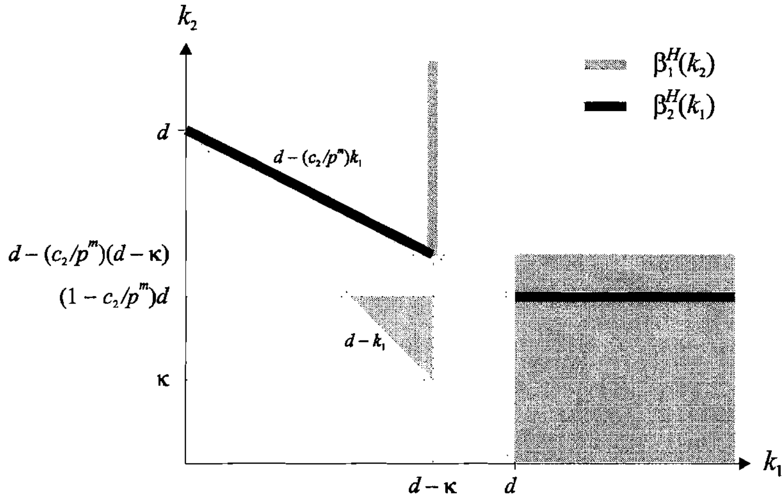

Figure 4: Best Reply Correspondence with IS^H

$d-\kappa$ is lower than $d-k_2$. To be able to cover the residual demand, firm 1 thus chooses $k_1 \geq d$. This is illustrated in Figure 4 to the right of d on the x-axis, where $k_2 < \kappa$. If instead k_2 is large $[k_2 > (1-c_2/p^m)\,d]$, the benefit for firm 1 of reducing its capacity from d to $d-\kappa$ is that the market price increases from c_2 to p^m. The cost, however, depends on the magnitude of k_2. By choosing $k_1 = d-\kappa$, firm 1 still sells all its capacity $d-\kappa$ if k_2 is very large $[k_2 > d-(c_2/p^m)\,(d-\kappa)]$, while it only sells to the residual demand $d-k_2$ if k_2 is moderately large $[k_2 \leq d-(c_2/p^m)\,(d-\kappa)]$. As a result, the reduction in capacity is optimal in the former case only. Hence, firm 1's best reply is given by the grey thick line in Figure 4 if $k_2 > d-(c_2/p^m)\,(d-\kappa)$ while it is given by the grey area above the black thick horizontal line if $(1-c_2/p^m)\,d < k_2 \leq d-(c_2/p^m)\,(d-\kappa)$.

To obtain an intuition for firm 2's best-reply correspondence, consider first the case when $k_1 \geq d$. Then firm 2 sells all its capacity for the market price p^m as long as k_2 is not too large $[k_2 \leq (1-c_2/p^m)\,d]$. Otherwise it sells nothing. Hence, firm 2's best-reply must be $k_2 = (1-c_2/p^m)\,d$, which is illustrated in Figure 4 by the thick black horizontal line. Second, consider the case when $k_1 \leq d-\kappa$. The benefit of choosing $k_2 \leq d-(c_2/p^m)\,k_1$, is that firm 2 then sells all its capacity for the high market price p^m. If firm 2 instead chooses $k_2 > d - (c_2/p^m)\, k_1$, then it only sells the residual demand for the low market price c_2. Hence, firm 2's best reply must be $k_2 = d - (c_2/p^m)\, k_1$, which is illustrated in Figure 4 by the thick black line with a negative slope.

Finally, note that the equilibrium market price is p^m. The reason is that firm 2 chooses its capacity in such a way that firm 1, given its equilibrium capacity $k_1^H = d$, bids the maximum price. In fact, firm 2's equilibrium capacity $[k_2^H = \bar{k}_2]$ is chosen as high as possible in order to induce the desired behavior by firm 1. The result is that firm 2 sells all its equilibrium capacity $k_2^H = \bar{k}_2$. Moreover, firm 1 satisfies the residual demand only, despite the fact that it is able to undercut firm 2 and thereby satisfy all the demand. Hence, firm 2 uses its available capacity strategically, thereby obtaining a market share much larger than in equilibrium IS^L.

Remark 2 *If firms play equilibrium IS^H when supply is intermediate, the least efficient firm strategically withholds its available capacity so that the most efficient firm submits the maximum price bid.*

5 Concluding remarks

The two-stage model analyzed in this chapter illustrates the strategic use of available capacity in the electricity spot market. More precisely, the analysis shows that withholding capacity can be sufficient to obtain high markups. [16]

The strategy of withholding capacity has two negative welfare implications. First, when firms are free to choose their capacities, they obtain a market price above the competitive outcome, which is costly for consumers. Second, the low-cost firm does not supply the entire demand, since the high-cost one has a positive market share. Hence, both Propositions 2 and 3 predict productive inefficiency. Note that in Proposition 2, however, the productive inefficiency may be small, in particular if κ is small. In Proposition 3, the productive inefficiency does not depend on the size of κ but only on

[16] Note that Ausubel and Cramton (1998) argue that buyers may have withheld their quantity for the auctions of spectrum rights in the United States.

the ratio c_2/p^m. Hence, if the cost of firm 2 is not too large (c_2 is not too close to p^m), the productive inefficiency may be large.

The strategy of withholding capacity is not explicitly taken into account by competition authorities, although some of these have been concerned by the Californian or Nordic examples discussed in the Introduction. Note also that the concentration index often used by competition authorities cannot detect that type of strategy. Indeed, the results in this chapter indicate that if a dominant firm chooses to withhold its capacity, the market price remains high even though the market concentration decreases. The ideal thing would be Ideally, one would like to combine a concentration index such as the Hirschmann-Herfindahl Index with a markup ratio such as the Lerner index.[17]

Detecting such a strategy is not suffisant and the market design should be changed so as to avoid such a strategy. Reducing the price cap is one option, although this may have negative effects, in the short as well as in the long run. In the short run, producers may be induced to export their production. This happened in California when the regulator decided to reduce the price cap on the wholesale market, from \$750/MWh to \$250/MWh in the summer of 2000. As a result, the producers stopped supplying the Californian market and instead exported electricity to neighboring states. In the long run, high price caps may induce players to invest in new power production. Changing the auction mechanism might be a better option for avoiding a withholding strategy. The theoretical and empirical literature as it stands today, does not provide clear-cut recommendations, however.

[17]Note that Borenstein et al. (1999) discussed this issue for horizontal market power in the electricity market.

A Proof of Proposition 1

It is straightforward to show points 1 (weak supply) and 2 (strong supply) in Proposition 1. Therefore I focus on the two more complicated cases.

Asymmetric supply and price equilibrium: The supply is asymmetric when $\min\{k_1, k_2\} < d \leq \max\{k_1, k_2\}$. First, the firm with a small capacity has no incentive to submit the highest price, since then it sells nothing as the other firm satisfies total demand. Hence if $k_i < d$ and $k_j \geq d$ where $i, j = \{1, 2\}$ and $i \neq j$, firm i submits the lowest price ($p_i \leq p_j$) and supplies its capacity at price p_j.[18] Therefore firm i always submits c_2. According to the merit order the market price then equals p_j. Second, the firm with a large capacity plays differently whether it is firm 1 or firm 2. If $k_2 \geq d$ (so that $p_1 = c_2$), then firm 2 obtains the same residual demand $(d - k_1)$ for any price higher than or equal to c_2. Therefore firm 2 chooses p^m. In contrast, if $k_1 \geq d$ (so that $p_2 = c_2$), then firm 1 faces the following trade-off. On the one hand, by submitting the low price $p_1 = c_2$, the market price equals c_2 and firm 1's profit is $c_2 d$. Firm 1 serve total demand at a low price c_2. On the other hand by submitting a high price $p_1 = p^m$, the market price equals p^m and firm 1's profit is $p^m (d - k_2)$. Firm 1 sells the residual demand $(d - k_2)$ for a high price p^m. Therefore firm 1 chooses p^m only if $k_2 \leq (1 - c_2/p^m)\, d$.

Intermediate supply and price equilibrium: The supply is intermediate when $\max\{k_1, k_2\} < d$ and $k_1 + k_2 > d$. According to equation (1) the market price is then $P(s) = \max\{p_i, p_j\}$, where $i, j = \{1, 2\}$ and $i \neq j$. If firm i submits the lowest price ($p_i = c_2 < p_j$), it supplies its capacity at price p_j. Given firm i's optimal strategy, firm j gets the residual demand. By submitting a price less than the maximum price ($p_j < p^m$) firm j makes less profit than by submitting $p_j = p^m$ since $(p_j - c_j)(d - k_i) < (p^m - c_j)(d - k_i)$. Therefore firm j submits p^m. Note, however, that $p_1 = p_m$ is the best response to $p_2 = c_2$ if and only if $c_2 k_1 \leq p^m (d - k_2)$ which is equivalent to $k_2 \leq d - (c_2/p^m)\, k_1$.

[18] Due to the efficient rationing rule, however, firm 2 sells nothing even though $p_2 = c_2$ if $k_1 > d$ and $p_1 = c_2$. Nevertheless, note that $p_2 = c_2$ is a best reply to $p_1 = c_2$ also in this case.

B Proof of Lemma 1

The proof proceeds in four steps. First, it defines the firms' equilibrium price bids as a function of (k_1, k_2). Second, it derives the equilibrium market price as a function of (k_1, k_2). The third and fourth step derive firm 1's and firm 2's best reply correspondence, respectively.

Step 1: Since the firms play equilibrium IS^L, firm i's equilibrium price bid, denoted $p_i^L(k_1, k_2)$, is equal to $p_i^*(k_1, k_2)$ in Proposition 1 whenever $p_i^*(k_1, k_2)$ is a singleton. Otherwise, $p_1^L(k_1, k_2) = c_2$ and $p_2^L(k_1, k_2) = p^m$.

Step 2: Note that $\min\{p_1^L, p_2^L\} = p_1^L = c_2$ if $k_1 \geq d$ and $k_2 > (1 - c_2/p^m)\, d$. Moreover, $\max\{p_1^L, p_2^L\} = p_1^L = p^m$ if $k_1 \geq d$ and $k_2 \leq (1 - c_2/p^m)\, d$. Also, $\max\{p_1^L, p_2^L\} = p_2^L = p^m$ if $k_1 \leq d - \kappa$. By equation (1), the equilibrium market price is thus given by:

$$P\left(\left(p_1^L, k_1\right), \left(p_2^L, k_2\right)\right) = \begin{cases} c_2 & \text{if } k_1 \geq d \text{ and } k_2 > (1 - c_2/p^m)\, d \\ p^m & \text{otherwise.} \end{cases} \tag{10}$$

Step 3: Note that the following three (in)equalities are true. First, $p_1^L = c_2 < p_2^L = p^m$ if $k_1 \leq d - \kappa$. Second, $p_1^L = c_2 = p^m$ if $k_1 \geq d$ and $k_2 > (1 - c_2/p^m)\, d$. Third, $p_1^L = c_2 < p_2^L = p^m$ if $k_1 \leq d - \kappa$ or $k_1 \geq d$ and $k_2 \leq (1 - c_2/p^m)\, d$. By equation (2), firm 1's final supply is thus given by:

$$x_1\left(\left(p_1^L, k_1\right), \left(p_2^L, k_2\right)\right) = \begin{cases} k_1 & \text{if } k_1 \leq d - \kappa \\ d & \text{if } k_1 \geq d \text{ and } k_2 > (1 - c_2/p^m)\, d \\ d - k_2 & \text{if } k_1 \geq d \text{ and } k_2 \leq (1 - c_2/p^m)\, d. \end{cases} \tag{11}$$

By equation (4), firm 1's profits are given by Px_1, since $c_1 = 0$. By equations (10) and (11), firm 1's profits are thus given by:

$$\pi_1\left(\left(p_1^L, k_1\right), \left(p_2^L, k_2\right)\right) = \begin{cases} p^m k_1 & \text{if } k_1 \leq d - \kappa \\ c_2 d & \text{if } k_1 \geq d \text{ and } k_2 > (1 - c_2/p^m)\, d \\ p^m (d - k_2) & \text{if } k_1 \geq d \text{ and } k_2 \leq (1 - c_2/p^m)\, d. \end{cases} \tag{12}$$

Use this expression for π_1 in (5a) and solve the maximization problem. It is easily verified that the solution yields the expression for $\beta_1^L(k_2)$ in equation (6), provided that $\kappa < (1 - c_2/p^m)\, d$.

Step 4: Recall that the following three (in)equalities are true. First, $p_1^L = c_2 < p_2^L = p^m$ if $k_1 \leq d - \kappa$. Second, $p_1^L = c_2 = p^m$ if $k_1 \geq d$ and $k_2 > (1 - c_2/p^m)\, d$. Third, $p_1^L = c_2 < p_2^L = p^m$ if $k_1 \leq d - \kappa$ or $k_1 \geq d$ and $k_2 \leq (1 - c_2/p^m)\, d$. By equation (3), firm 2's final supply is thus given by:

$$x_2\left(\left(p_1^L, k_1\right), \left(p_2^L, k_2\right)\right) = \begin{cases} k_2 & \text{if } k_2 < d - k_1 \text{ and } k_1 \leq d - \kappa \\ d - k_1 & \text{if } k_2 \geq d - k_1 \text{ and } k_1 \leq d - \kappa \\ 0 & \text{if } k_2 > (1 - c_2/p^m)\, d \text{ and } k_1 \geq d \\ k_2 & \text{if } k_2 \leq (1 - c_2/p^m)\, d \text{ and } k_1 \geq d. \end{cases} \tag{13}$$

By equation (4), firm 2's profits are given by $(P - c_2)\, x_2$. By equations (10) and (13), firm 2's profits are thus given by:

$$\pi_2\left(\left(p_1^L, k_1\right), \left(p_2^L, k_2\right)\right) = \begin{cases} (p^m - c_2)\, k_2 & \text{if } k_2 < d - k_1 \text{ and } k_1 \leq d - \kappa \\ (p^m - c_2)\,(d - k_1) & \text{if } k_2 \geq d - k_1 \text{ and } k_1 \leq d - \kappa \\ 0 & \text{if } k_2 > (1 - c_2/p^m)\, d \text{ and } k_1 \geq d \\ (p^m - c_2)\, k_2 & \text{if } k_2 \leq (1 - c_2/p^m)\, d \text{ and } k_1 \geq d. \end{cases} \tag{14}$$

Use this expression for π_2 in (5b) and solve the maximization problem. It is easily verified that the solution yields the expression for $\beta_2^L(k_2)$ in equation (7).■

C Proof of lemma 2

The proof follows the same logic as the proof in Appendix C. Therefore, I only report the significant differences between the two proofs.

Step 1: Since the firms play equilibrium IS^H, firm i's equilibrium price bid, denoted $p_i^H(k_1,k_2)$, is equal to $p_i^*(k_1,k_2)$ in Proposition 1, whenever $p_i^*(k_1,k_2)$ is a singleton. Otherwise, $p_1^H(k_1,k_2)=p^m$ and $p_2^H(k_1,k_2)=c_2$.

Step 2: Using equation (1) and the functional forms of $p_1^H(k_1,k_2)$ and $p_2^H(k_1,k_2)$, it can be shown that the equilibrium market price is given by:

$$P\left(\left(p_1^H,k_1\right),\left(p_2^H,k_2\right)\right)=\begin{cases} c_2 & \text{if } k_1\geq d \text{ and } k_2>\left(1-c_2/p^m\right)d \\ p^m & \text{otherwise.}\end{cases} \tag{15}$$

Step 3: Using equation (2) and the functional forms of $p_1^H(k_1,k_2)$ and $p_2^H(k_1,k_2)$, it can be shown that firm 1's final supply is given by:

$$x_1\left(\left(p_1^H,k_1\right),\left(p_2^H,k_2\right)\right)=\begin{cases} k_1 & \text{if } k_1\leq d-\kappa \text{ and } k_2\leq d-k_1 \\ d-k_2 & \text{if } k_1\leq d-\kappa \text{ and } d-k_1<k_2\leq d-\left(c_2/p^m\right)k_1 \\ k_1 & \text{if } k_1\leq d-\kappa \text{ and } k_2>d-\left(c_2/p^m\right)k_1 \\ d & \text{if } k_1\geq d \text{ and } k_2>\left(1-c_2/p^m\right)d \\ d-k_2 & \text{if } k_1\geq d \text{ and } k_2\leq\left(1-c_2/p^m\right)d.\end{cases} \tag{16}$$

By equation (4), firm 1's profits are given by Px_1, since $c_1=0$. By equations (15) and (16), firm 1's profits are thus given by:

$$\pi_1\left(\left(p_1^H,k_1\right),\left(p_2^H,k_2\right)\right)=\begin{cases} p^m k_1 & \text{if } k_1\leq d-\kappa \text{ and } k_2\leq d-k_1 \\ p^m\left(d-k_2\right) & \text{if } k_1\leq d-\kappa \text{ and } d-k_1<k_2\leq d-\left(c_2/p^m\right)k_1 \\ p^m k_1 & \text{if } k_1\leq d-\kappa \text{ and } k_2>d-\left(c_2/p^m\right)k_1 \\ c_2 d & \text{if } k_1\geq d \text{ and } k_2>\left(1-c_2/p^m\right)d \\ p^m\left(d-k_2\right) & \text{if } k_1\geq d \text{ and } k_2\leq\left(1-c_2/p^m\right)d.\end{cases} \tag{17}$$

Use this expression for π_1 in (5a) and solve the maximization problem. It is easily verified that the solution yields the expression for $\beta_1^H(k_2)$ in equation (8), given that $\kappa<\left(1-c_2/p^m\right)d$.

Step 4: Using equation (3), and the functional forms of $p_1^H(k_1,k_2)$ and

$p_2^H(k_1, k_2)$, it can be shown that firm 2's final supply is given by:

$$x_2\left(\left(p_1^H, k_1\right), \left(p_2^H, k_2\right)\right) = \begin{cases} k_2 & \text{if } k_2 \leq d - (c_2/p^m)\, k_1 \text{ and } k_1 \leq d - \kappa \\ d - k_1 & \text{if } k_2 > d - (c_2/p^m)\, k_1 \text{ and } k_1 \leq d - \kappa \\ 0 & \text{if } k_2 > (1 - c_2/p^m)\, d \text{ and } k_1 \geq d \\ k_2 & \text{if } k_2 \leq (1 - c_2/p^m)\, d \text{ and } k_1 \geq d. \end{cases} \tag{18}$$

By equation (4), firm 2's profits are given by $(P - c_2)\, x_2$. By equations (15) and (18), firm 2's profits are thus given by:

$$\pi_2\left(\left(p_1^H, k_1\right), \left(p_2^H, k_2\right)\right) = \begin{cases} (p^m - c_2)\, k_2 & \text{if } k_2 \leq d - (c_2/p^m)\, k_1 \text{ and } k_1 \leq d - \kappa \\ (p^m - c_2)\, d - k_1 & \text{if } k_2 > d - (c_2/p^m)\, k_1 \text{ and } k_1 \leq d - \kappa \\ 0 & \text{if } k_2 > (1 - c_2/p^m)\, d \text{ and } k_1 \geq d \\ (p^m - c_2)\, k_2 & \text{if } k_2 \leq (1 - c_2/p^m)\, d \text{ and } k_1 \geq d. \end{cases} \tag{19}$$

Use this expression for π_2 in (5b) and solve the maximization problem. It is easily verified that the solution yields the expression for $\beta_2^H(k_2)$ in equation (9).■

Chapter II

Do Opponents' Experience Matter? Experimental Evidence from a Quantity Precommitment Game[1]

This chapter has been written with Jon Thor Sturluson[2]

2

1 Introduction

One of the most prominent solutions to the Bertrand paradox is to take capacity constraints into consideration when studying at price competition Kreps and Scheinkman (1983), henceforth KS, consider a game where firms simultaneously commit to a capacity level before they compete in prices, à la Bertrand. Their seminal result was that the unique subgame-perfect equilibrium implies capacities equal to the Cournot Nash equilibrium.

A puzzling empirical regularity has been identified in several experiment studies focusing on the KS model. A large majority of subjects consistently choose capacities above the Cournot equilibrium level. This has been the case even when the experiments were designed to respect all the assumptions[3] under which the Cournot outcome is the unique subgame-perfect equilibrium. In the first paper that specifically testing the KS result Davis (1999) examines the effect of capacity investments (or its equivalent production to stock) on the outcome of a posted-offer market. According to his results, capacity precommitment has significant positive effects on

[1]The authors would like to thank Tore Ellingsen for his insightful comments in the project's infancy, Urs Fischbacher for allowig us to use the z-Tree software and Hans-Theo Norman for technical help. We thank Magnus Johannesson and Tobias Lindqvist, as well, for their detailed comments. We gratefully acknowledge financial support from the Nordic Energy Research Program.

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[3]Some important assumptions made by Kreps and Scheinkman have been criticized for being too restrictive, e.g., concave demand, efficient rationing and perfect information (see for example Davidson and Deneckere (1986) or Reynolds and Wilson, (2000)).

prices and negative effects on output. However, the increase in prices and the reduction in output are much smaller than predicted by the KS model. Outcomes are volatile and generally fail to converge to the subgame-perfect equilibrium (the Cournot outcome), and excess capacity prevails throughout the sessions. In an independent but similar paper, Muren (2000) reports on two experimental treatments with inexperienced and experienced players, respectively, in a pure KS game. The deviations from the Cournot outcome, in the form of larger capacities and lower prices than those predicted by KS, decrease with experience but do not disappear. She argues that excess capacity could result from subjects not fully understanding the mechanism of the game, in particular the efficient rationing rule which creates a discontinuity in payoffs. Anderhub et al. (2002) took a closer look at Muren's argument. Their experimental environment differs from previous studies in that they set up a heterogenous-goods duopoly with 'soft' capacity constraints. The capacity choice is still important because all production in excess of the target capacity level is penalized by an additional cost, chosen to be higher than the equilibrium price. Furthermore, they repeat the price subgame for 10 periods after each quantity choice stage. Both these features are intended to make it easier for subjects to find the subgame equilibrium in prices. Even though price choices are, in general, consistent with the subgame perfect prediction, the selected capacities do more often than not exceed the Cournot prediction, thereby suggesting that failure to understand the structure of the game is not a principal explanation for the mentioned regularity.

Understanding the implications of capacity chosen in the first stage for optimal price choice in the second stage, as induced in Anderhub et al. (2002), is one thing. To grasp the full consequences of ones own capacity choice on future price choices, particularly those by others, is quite another. Moreover, if players (being fully rational themselves) expect their opponents not to be fully rational - they may deviate from optimal strategies at times - the Cournot equilibrium might not be the best prediction of a rational player's capacity choice. In fact, we show that if a player thinks that his opponent can make mistakes, e.g., by offering a price higher than the market clearing price, he will will find it optimal to choose a capacity above the Cournot level.

This paper reports on an experiment designed to test if players' perceptions of their opponents' skills, or level of rationality, have a systematic effect on bahavior. By level of rationality we mean the degree of precision with which a player observes his payoff and refer to less than perfect precision as bounded rationality, in the spirit of McKelvey and Palfrey (1995) and Sargent (1994). While unable to directly control for players' level of rationality directly, we can use their level of experience in playing the game as a reasonable proxy.[4] By matching subjects with different levels of experience (both being aware of each others experience level), we can test our main hypothesis, namely, that beliefs about opponents' rationality are of importance and that pessimistic beliefs can be an important cause of observed overcapacity in KS games.

In all previous KS experiments, the subjects have played in fixed pairs or groups throughout their sessions. Hence, large capacities may be due to individual attempts to become dominant producers. If a player succeeds in convincing his opponents that he will choose a high capacity regardless of what the others do, their best response is to reduce their capacity as if the first player were a Stackelberg leader who had committed to a high capacity level. Here we choose to randomly match subjects in order to eliminate any such motives. One session was run with fixed pairs, in part to check if our experimental design would yield results consistent with previous experiments.

The remainder of this paper is structured as follows. The next section provides a general description of the experimental design and procedures. Using a simple example, we illustrate how a fully rational player can be expected to choose capacity above the Cournot level if he expects his opponent to be irrational. Section 3 presents the results of the experiment which support our main hypothesis i.e. that an opponent's experience level significantly affects behaviour. Capacities are larger and prices lower, on average, when opponents are inexperienced, compared to when they are experienced. A comparison of treatments with similarly experienced subjects and different matching rules, does not support the hypothesis of a strategic motive is the cause of overcapacity. We further investigate the observed behavioural the patterns in section 4. The predictions provided in secion 2 are generalized using the agent-form quantal response equilibrium model McKelvey and Palfrey (1998). Section 5 concludes by discussing some important implications of the results and suggestions for further research.

[4]The implicit assumption is that experienced players can be expected to play more rationally (make fewer mistakes) than inexperienced ones.

2 Experimental Design

2.1 General description

We start off by briefly presenting the simple Kreps-Scheinkman (KS) model used in the experiment and the standard game-theoretic prediction of behaviour. Then, using a simple example, we proceed to illustrate that when a rational player expects his opponent to play irrationally he chooses a capacity level that is greater than the Cournot output level as well as a price that is below the Cournot price level.

2.1.1 The benchmark model

Consider a simple version of Kreps' and Scheinkman's (1983) symmetric duopoly model with a homogenous product, constant marginal cost and linear demand, played by perfectly rational players. The game consists of two stages. In the first stage, players simultaneously choose their capacity level q_1 and $q_2 \in \mathbb{R}_+$, respectively. In the second stage, having learned the capacity choices made by their opponent, they simultaneously choose prices , p_1 and $p_2 \in \mathbb{R}_+$. Adopting the efficient rationing rule, player i's payoff is given by:[5]

$$\pi_i(q_i, q_j, p_i, p_j) = \begin{cases} p_i \min(q_i, d(p_i)) - cq_i & \text{if } p_i < p_j, \\ p_i \min(q_i, \max(d(p_i) - q_j, d(p_i)/2)) - cq_i & \text{if } p_i = p_j, \\ p_i \min(q_i, \max(d(p_i) - q_j, 0)) - cq_i & \text{if } p_i > p_j. \end{cases} \tag{1}$$

where $i, j \in \{1, 2\}$ and $i \neq j$, and $d(p_i) = \alpha - \beta p_i$. In our experimental setup we chose the parameters $\alpha = 120$, $\beta = 1$ and $c = 30$ which are, in relative terms, similar to those used by Muren (1999). With these parameters, the Cournot equilibrium is stable and significantly different from the competitive solution. It is also easy to verify that the subgame-perfect equilibrium is unique and equal to the Cournot outcome in terms of capacities, prices and profits:[6]

$$q_i^c = 30,\ p_i^c = 60 \text{ and } \pi_i^c = 900 \quad \text{for } i \in \{1, 2\}. \tag{2}$$

[5]The payoff function was not described to the subjects in algebraic form, but using words. See the complete instructions in the Appendix.

[6]Follows straight from proposition 2 in Kreps and Scheinkman (1983).

In comparison, a competitive market would yield aggregate output equal to 90, prices equal to marginal cost, 30, and zero profits.

2.1.2 A simple example with one irrational player

Now, consider a variation of the benchmark model where players can only choose among three capacity levels $\{20, 30, 40\}$ and three price levels $\{55, 60, 65\}$. Notice that the feasible choices are symmetric around the Cournot outcome. Player 1 is perfectly rational as before. He chooses a strategy maximizing his expected payoff given a consistent belief about player 2's strategy. The main change from the benchmark case is that player 2 is irrational. More specifically, he chooses strategies at random.

Let us consider player 1's optimal strategy. If player 1 chooses the Cournot output, 30, his optimal price strategy[7] is

$$p_1^* \left(q_1 = 30, q_2 = \begin{bmatrix} 20 \\ 30 \\ 40 \end{bmatrix} \right) = \begin{bmatrix} 65 \\ 60 \\ 55 \end{bmatrix}. \tag{3}$$

and since player 2 chooses each available price level with probability $\frac{1}{3}$, player 1's expected profit is

$$E(\pi_1 | q_1 = 30) = \frac{1}{3} \times 65 \times 30 + \frac{1}{3} \times 60 \times 30 + \frac{1}{3} \times 55 \times 30 - 30 \times 30 = 900.$$

Notice that he manages to sell all his capacity whatever player 2 does. If, however, player 1 chooses $q_1 = 40$, his optimal price strategy, depending on q_2 is

$$p_1^* \left(q_1 = 40, q_2 = \begin{bmatrix} 20 \\ 30 \\ 40 \end{bmatrix} \right) = \begin{bmatrix} 60 \\ 55 \\ 55 \end{bmatrix} \tag{4}$$

[7]The optimal price strategy (3) comes straight from (1). Take for instance the case when $(q_1, q_2) = (30, 30)$. If player 1 selects $p_1 = 65$ he will not be able to sell to full capacity. With probability $\frac{2}{3}$, when $p_2 = 55$ or 50, player 1 can only sell the residual demand $120 - 30 - 65 = 25$ and with probability $\frac{1}{3}$, $p_2 = 65$ the aggregate demand is split leaving $\frac{55}{2}$ for player 1. His expected revenue is then $65 \times \left(\frac{2}{3} \times 25 + \frac{1}{3} \times \frac{55}{2}\right) = 1679.2$. If he chooses $p_1 = 60$, he will be able to sell all his capacity, no matter what p_2 is, giving him the expected revenue $60 \times 30 = 1800$. Clearly $p_1 = 55$ is inferior as sales are already at the capacity level at $p_1 = 60$.

and his expected profit is

$$E(\pi_1|q_1=40)=\frac{1}{3}\times 60\times 40+\frac{2}{3}\times 55\times\left(\frac{2}{3}\times 40+\frac{1}{3}\times\frac{65}{2}\right)-30\times 40=975.$$

Going from the left to the right, the right hand side is obtained as follows. Player 2 chooses $q_2 = 20$ with probability $\frac{1}{3}$, in which case player 1's revenue is 60×40. But if player 2 chooses $q_2 = 30$ or 40, player 1 should react by choosing a low price, $p_1 = 55$ by (3). Then he is able to sell to capacity as long as player 2 chooses a higher price (with probability $\frac{2}{3}$) and receive 55×40 in revenue. However, with probability $\frac{1}{3}$ player 2 will match firm 1's low price and demand is equally split between the two players resulting in the revenue $\frac{65}{2} \times 40$ for player 1. Cost is independent of actual sales and is always $30 \times 40 = 1200$. The expected profit is 975 compared to 900 when the capacity is equal to the Cournot output. Hence, choosing a capacity level considerably greater than the Cournot output is optimal under these circumstances.

This example is very specific. One player is perfectly rational - observes his payoff with certainty and has correct beliefs about the other player's strategy - and one player is completely irrational - choosing strategies at random. On top of that, the action space is quite restrictive. Still, this serves to illustrate that players' perceptions about their opponents skill or level of rationality are of importance for the outcome of the game. Furthermore, this can be generalized for any level of skill, using the agent-form quantal response equilibrium McKelvey and Palfrey (1998), where the level of rationality is defined as the accuracy with which players observe their true payoff function. We discuss this theoretical setup in section 4. It turns out that overcapacity is predicted for any combinations of players with different levels of rationality.

Let us make it clear that by level of rationality we mean the degree of precision with which a player observes his payoff, and refer to less than perfect precision as bounded rationality, as do McKelvey and Palfrey (1995) and Sargent (1994). While we are unable to control for players' level of rationality, we can use their level of experience in playing the game as a reasonable proxy. We explicitly matched subjects with different levels of experience (each subject beeing aware of its opponent's level of experience) to test our main hypothesis, namely, that beliefs about opponents' rationality are of importance and that pessimistic beliefs could be the cause of observed overcapacity in KS games. The implicit assumption being that experienced players can be expected to play more rationally (making fewer mistakes) than

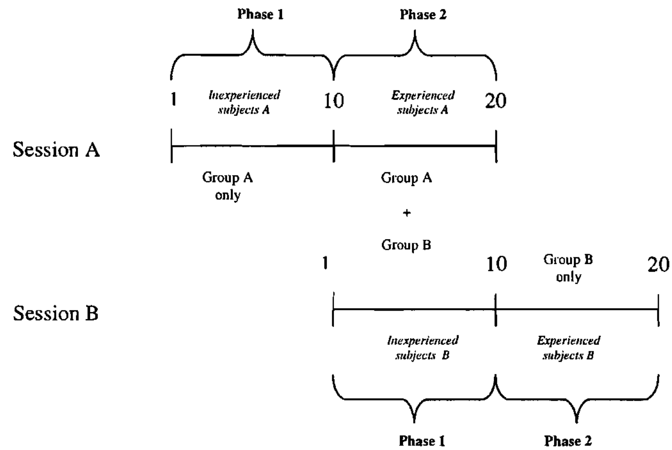

Figure 1: Experimental procedure for sessions A and B

inexperienced ones.

2.2 Experimental procedures

In three separate sessions (A, B, C), sixty subjects took the roles of firms in a duopoly market. Each subject played the game for 20 periods excluding 2 to 4 non-paying practice periods.

Our first treatment variable is the level of experience, which is measured by the number of periods played so far. We say that a subject is *inexperienced* when he is in the first phase of the game (periods 1-10) and we use the subscript $_1$ to indicate that a subject (A_1, B_1 or C_1) is inexperienced. Similarly a subject is *experienced* when he is in the second phase of the game (periods 11-20) and we use the subscript $_2$ to indicate that a subject (A_2, B_2 or C_2) is experienced. The experiment is designed so that subjects with different levels of experience play against each other. The experiment proceeds as follows (see figures 1 and 2). In their first phase (periods 1-10), subjects A_1 (as well as subjects C_1) play internally, against subjects with the same experience level. In their first phase (periods 1-10), subjects B_1 meet subjects A_2 who have played the game for 10 periods already, i.e., inexperienced players B_1 meet experienced players A_2. In their second phase (periods 11-20) subjects B_2 (as well as subjects C_2) play internally, with subjects at the same experience level.

The matching procedure is the second treatment variable we emphasize. A

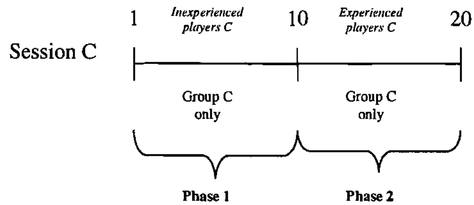

Figure 2: Experimental procedure for session C

Table 1: Five treatments

	Random matching	*Fixed matching*
Inexperienced only	A_1A_1	C_1C_1
Experienced only	B_2B_2	C_2C_2
Experienced and Inexperienced	A_2B_1	-

random-matching procedure was used for group A and group B, where subjects played against a new randomly selected opponent in each round and never against the same opponent twice. A fixed-group procedure was used for group C, where the matchings were not changed during the twenty periods. The subjects were informed of the matching rule.

Thus, we employed five treatments (see Table 1). In phase 1, Group A's subjects play among themselves (treatment A_1A_1). The notation refers to a member of group A in phase 1 playing against members of group A, also in phase 1. Similarly, in treatment B_2B_2 members of group B in phase 2 play against members of group B, also in phase 2. In treatment A_2B_1 members of group A in their second phase meet members of group B in their first phase. Finally treatments C_1C_1 and C_2C_2 refer to the first and second phase of play within group C.[8]

The experiment was conducted in May 2002 at the Stockholm School of Economics.[9] The subjects in the experiment were first year students at the Stockholm School of Economics, and were recruited by e-mail or announcements in classroom. The participants earned, on average, 302kr, with a minimum of 150kr and a maximum of 480kr. A full session lasted about an hour and a half, including time spent reading the instructions. Subjects were paid according to their total profits earned

[8] C_1C_1 and C_2C_2 are not really two separate treatments. Subjects in group C played in fixed pairs for 20 periods. The separation into two treatments is purely artificial but simplifies the comparison with other treatments.

[9] We used the z-Tree sofware package developed by Urs Fischbacher (2002), Institute for Empirical Research in Economics, University of Zurich.

during a sessions plus a 100kr showup fee. We used an artificial laboratory currency, "experimental dollars" (e\$) where 1kr (0.116 US\$) equals 50e\$.

When the subjects arrived at the laboratory they were randomly seated in front of computer terminals and handed written instructions.[10] Communication between subjects was not permitted throughout the session and the individual workstations were separated so that subjects could not see each other's screens. The experiment was fully computerized with subjects entering choices on their terminals. In each period, subjects observed three different screens. On the *quantity choice screen* each subject entered a quantity of his choice in the interval 0 to 90 with a maximum of two decimals. On the *price choice screen* his chosen output level and current opponent's output level were displayed. He then entered a price level between 0 and 120 with up to two decimals.[11] The *result screen* then displayed all choices made by him and his opponent and the resulting profits, calculated according to (1). The quantity choice and price choice screens both featured a profit calculator, where subjects could insert different hypothetical values for their own and their opponent's quantities and prices and compare the resulting profits.

The primary sessions, with randomly matched opponents were run on two separate days. Each day, 12 participants played as type A players and 12 played as B. On the first day, one subject had to leave the experiment, but was replaced by an assistant. All observations from that subject are skipped, before and after the substitution. This should have no impact on other players actions, however, since this subject played against other subjects in a different room, and his opponents were not informed about the switch and had no means of learning about it. Data from trial periods was not used in the analysis except in instances with lagged variables or differenced variables, in which case we use the last practice period to calculate the first period differences.

3 Experimental results

The random-matching procedure, used in all principal sessions, requires the use of subject-level data instead of market-level data as in David (1999), Muren (2000) and Anderhub et al. (2002). Subject level data are also more useful for our purposes as subjects with different levels of experience are paired together in treatment A_2B_1.

[10] See the appendix for full text instructions.

[11] The allowable quantity and price ranges correspond to all rationalizable strategies (Pearce 1984).

Figure 3 shows, for each period and group, the mean of chosen capacities and prices. In should be remembered that subjects in groups A and B played against a different group of opponents in periods 1-10 and 11-20, respectively. Subjects in group A first play against other subjects in group A in 10 periods and then against members of group B in another 10 periods. In their first 10 periods, subjects in group B face subjects in group A, who have already played the game for 10 periods. Then, in their last 10 periods they played internally (see figure 1).

In the first five periods, the average capacity level in groups B and C is close to half of the competitive output level, or 45. Subjects in group A chose even higher levels, 52 on average. The per-period averages rapidly decline in periods 6 to 10 and level off after that. In the last 5 periods, the average capacities are between 35-37, depending on the respective group. The average capacity is higher in group A than for group B in almost all periods. Groups B and C show similar patterns, though B has slightly larger capacities on average. These patterns confirm our main hypothesis that players facing inexperienced opponents tend to choose higher capacities than when facing experienced opponents.

Histograms of capacity choice in groups A and B (see figures 8 and 9 in the appendix), show considerable dispersion in the first periods and slow convergence to a bimodal distribution, with modes at 30 (the Cournot output) and 40, where the frequency of capacity levels around 40 is about twice as high for group A than B in the last few periods.[12]

Let us now turn to testing the formal hypotheses that should help us to answer the three following questions:

1. Do we replicate the results of earlier experimental KS oligopolies, i.e., do subjects choose capacities significantly above (and prices below) Cournot levels?

2. Do subjects respond to their opponents' level of experience? In particular, do players facing inexperienced opponents tend to choose higher quantities and lower prices than when facing experienced opponents.

3. Can an intertemporal strategic motive, such as an attempt to become a Stackelberg leader, be an alternative explanation for observed high capacity levels?

The following regression model, adopted from Noussair et al. (1995), is helpful in answering all three questions. Where x_{it} is the observed capacity or price choice

[12] Anderhub et al. (2002) report a similar pattern.

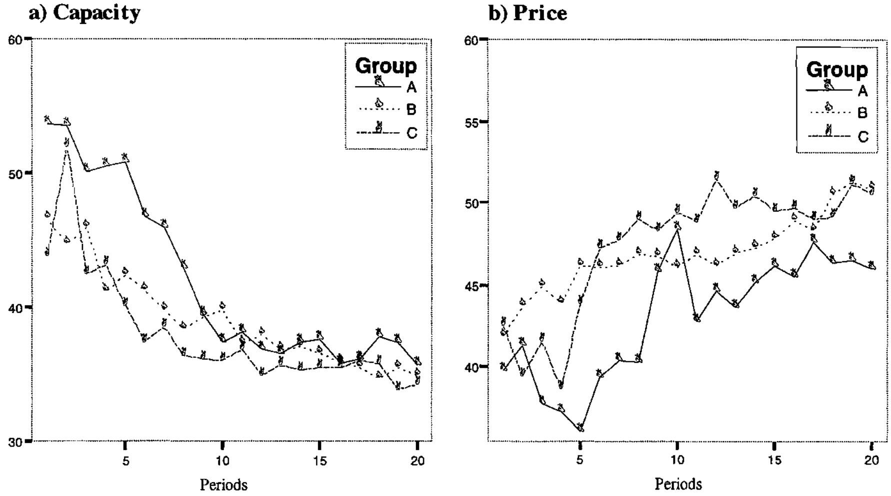

Figure 3: Mean capacity and price, by period and group

of individual i, we estimate

$$x_{it} = \beta_i \frac{1}{t} D_i + \beta_A \frac{t-1}{t} D_A + \beta_B \frac{t-1}{t} D_B + \beta_C \frac{t-1}{t} D_C + \varepsilon_{it} \qquad \text{(I)}$$

where D_i is a subject dummy variable and D_A, D_B and D_C are group dummies. The weights in front of the subject dummy variables ($\frac{1}{t}$ in front of D_i) are greater for observations in early periods than in later periods. The weights on the group dummies ($\frac{t-1}{t}$) are low in early periods and higher in later periods. This setup is based on the assumption that while individual behavior may diverge considerably within each group, such deviations are less considerable in later periods. The advantage of this method is that we can use the whole dataset to draw conclusions about treatment effects, while still controlling for individual deviations to a large extent.

Equation (I) is simultaneously estimated for all subjects in the three groups.[13] The period index t refers to the number of times the game is played in each phase of the sessions. First, we run the regressions for the first phase of all subjects. This represents group A in treatment A_1A_1, group B in treatment A_2B_1 and group C in treatment C_1C_1. The second regression is for the second phase and concerns group A in treatment A_2B_1, group B in treatment A_1B_2 and group C in treatment C_2C_2.

[13]The exception is subject 6 in group A. Its data are omitted for reasons explained above.

Table 2: Regression results

	Model I				Model II	
	Phase 1		Phase2		Phase 1	Phase2
Parameter	*Capacity*	*Price*	*Capacity*	*Price*	*Capacity*	*Capacity*
β_A	43.15	42.15	36.23	46.54	42.99	36.56
	(1.38)	(1.19)	(1.11)	(1.05)	(1.13)	(0.55)
β_B	39.63	46.82	35.76	49.57	39.43	35.47
	(1.35)	(1.16)	(1.09)	(1.02)	(1.11)	(0.54)
β_C	38.67	46.62	34.39	50.42	-	-
	(1.91)	(1.64)	(1.54)	(1.45)	-	-
β_{EQ}	-	-	-	-	0.146	0.146
	-	-	-	-	(0.054)	(0.13)
R^2	0.38	0.20	0.41	0.31	0.44	0.47
n	590	590	590	590	470	470
$p^*_{Courn.}$	0.00	0.00	0.00	0.00	-	-
$p^\dagger_{A \text{ vs. } B}$	0.04	0.01	0.23	0.32	0.01	0.08
$p^\ddagger_{A \text{ vs. } C}$	0.03	0.01	0.38	0.02	-	-

Estimation and testing of models (I) and (II) with capacities and prices as dependent variables. Model (I) is corrected for first order autocorrelation. Standard errors are corrected for heteroscedasticity (White's method).

* The critical level of significance (p-value) for the single-sided test of $\beta_i = (30, 60)$.

† The critical level of significance (p-value) for the single-sided test of $\beta_A = \beta_B$.

‡ The critical level of significance (p-value) for the single-sided test of $\beta_A = \beta_C$, periods 1-10 and $\beta_B = \beta_C$, periods 11-20.

The parameter estimates are corrected for first order autocorrelation and standard errors for potential heteroscedasticity by White's method. Parameter estimates are listed in table 2.

To answer the first question, we test if the null hypothesis that the group dummies are equal to the Cournot prediction can be rejected. The group dummies measure the central tendency in each group, putting more weight on later periods, while allowing individual effects, particularly in the early periods, to be picked up by the subject dummies. The following single-sided F-tests:

$$\begin{aligned} \text{Quantities:} \quad & H_0 : \beta_g = 30 \quad H_1 : \beta_g > 30 \\ \text{Prices:} \quad & H_0 : \beta_g = 60 \quad H_1 : \beta_g < 60 \end{aligned}$$

where $g \in \{A, B, C\}$, were both rejected at the 0.01 level of significance. Table 2 reports the p values in each case (see $p_{Courn.}$). We can summarize the answer to the first question as follows.

Result 1 *Capacities and prices fail to converge to the Cournot values,* 30 *and* 60 *respectively in all three groups.*

This is consistent with earlier experimental results that aggregate market output converges to a capacity significantly above the Cournot level, both in triopoly markets (Davis, 1999 and Muren, 2000) and duopolies (Anderhub, 2002).

The second question is more interesting. Namely, do subjects adjust their behavior in response to their opponents' level of experience. In particular, do they choose lower quantities when playing against experienced subjects, relative to when they play against inexperienced subjects. And similarly, do they choose higher prices, on average, when playing against experienced subjects.

First, we test the null hypothesis of equal medians of capacities and prices in each period against the one sided alternative of quantities being larger, and prices and profits lower in group A than in group B.

In the first phase (periods 1-10) when subjects are inexperienced, the Wilcoxon-Mann-Whitney test (WMW) rejects the null hypothesis for groups A and group B, in 4 (7) cases out of 10, at the 5% (10%) level of significance. With the alternative H_1 that the median in group A is lower than in B the H_0 of equal medians is only rejected once (in period 10). In the case of prices, the H_0 is rejected 7 times out of 10 at the 5% level of significance.

In the second phase (periods 11-20), when subjects are more experienced, the null hypothesis is only rejected at the 10% significance level in one case, i.e., that of quantities. When it comes to prices, the H_0 is rejected 3 times out of 10 at the 5% level of significance and 6 times out of 10 at the 10% level.

The limited number of rejections of the null hypothesis may be due to the small number of observations in each period (23 for group A and 24 for group B). It is therefore interesting to see if we get clearer results when data from all periods within each phase are pooled together in a single regression dataset. Here we report on tests based on the regression model (I), but almost identical results were produced using a two-factor fixed-effects panel regression.[14] The hypotheses tested are the following:

$$\text{Quantities:}\quad H_0 : \beta_A = \beta_B \quad H_1 : \beta_A > \beta_B$$
$$\text{Prices:}\quad H_0 : \beta_A = \beta_B \quad H_1 : \beta_A < \beta_B$$

[14]Such a model has more general individual and time effects but the tests are less intuitive.

where β_A and β_B are estimates of the converging values in group A and B respectively. The resulting critical p-values of the F-tests are reported in parentheses in table 2. In the first phase, the hypothesis of $\beta_A = \beta_B$ is rejected for both variables at the 5% level of significance. In the second phase, however, the hypothesis is rejected for prices but not for quantities.

It is apparent from figure 3 that subjects have a tendency to choose rather high capacities in early periods and that capacities are, on average, larger in group A than in group B. While this is consistent with our hypothesis that the opponent's experience is of importance, there might be other factors influencing the result, which might distort the comparison. Subjects might, for instance, form beliefs about (the central tendency of) future opponents' capacity choices based on past observations and choose their strategy accordingly. In that case, we should expect subjects who have observed relatively high capacities in the past to choose lower capacities than the average in the future. This behaviour is generally defined as fictitious play in the literature (see Fudenberg and Levine, 1998, especially chapter 2). To allow for such adaptive learning, we estimate a second model for groups A and B

$$x_{it} = \beta_i \frac{1}{t} D_i + \beta_A \frac{t-1}{t} D_A + \beta_B \frac{t-1}{t} D_B + \beta_{EQ} \times \left(EQ_{it} - \overline{EQ}_{\cdot t,g} \right) + \varepsilon_{it} \qquad \text{(II)}$$

where the added variable EQ_{it} is a measure of what subject i expects his opponent's capacity to be in period t, and corresponds to the weighted average capacity observed from past opponents. The weights are chosen so that recent observations weigh more heavily than old ones. $\overline{EQ}_{\cdot t,g}$ is the average of EQ_{it} for player i's group (either A or B). The deviations form is preferred for two reasons. On the one hand, this independent variable shares a common trend with the dependent variable. Using it in the regression in levels would give spurious results. On the other hand, a priori we can expect EQ_{it} to be larger in group A than in group B, which causes multicollinearity with respect to the group dummy variables. The hypothesis $\beta_A = \beta_B$ is more strongly rejected in model (II) than in model (I). The sign on the parameter β_{EQ} is not consistent with the the fictitious play, but there several different possible explanations, e.g., imitation or reinforcement learning (see for example, Rassenti et al. ,2000, for a description of different models of learning in a context of Cournot experiments). The conclusions can be summarized as follows.

Result 2 *Inexperienced subjects (Phase 1) choose significantly higher quantities and* *lower prices, on average, when playing against similarly inexperienced subjects than when playing against subjects with more experience.*

Result 3 *Experienced subjects (Phase 2) choose significantly lower prices, on average, when playing against inexperienced subjects than when playing against subjects with similar experience as themselves. The difference in average quantities is marginally significant.*

These two results raise the question that, even while opponents' experience has a negative effect on capacity choice, the effect is decreasing in own experience. The simple example in section 2 did not account for any interaction between a player's own experience and that of his opponent. The more detailed model discussed in the next section, on the other hand, allows for varying degrees of experience. The predictions turn out to be consistent with these results.

The comparison between fixed- and random matching treatments allows us to evaluate the third question stated above. One suggested cause of the large capacities selected in KS-experiments is that subjects may be trying to bully their opponents to accept disproportionately small output levels (Davis, 2000). Indeed, if a player succeeds in convincing his opponent that he will choose a high capacity regardless of what the opponent does, the opponent's best response is to reduce his own capacity, as if the bully were a Stackelberg leader and had already committed to a high capacity level. This strategy is never a Nash equilibrium if the game is played for a finite number of periods. Still, non-equilibrium intertemporal strategies are frequently observed, perhaps because some subjects fail to grasp the immanent breakdown of such schemes in the final period. Or, more subtly, a rational player may suspect that his opponent fails to understand this reasoning. However if subjects never meet the same opponent more than once, there is no point in adopting intertemporal strategies.

To test if there is evidence of such strategic behavior, we compare the choices of group A in treatment A_1A_1 to C in treatment C_1C_1 on the one hand, and group B in treatment B_2B_2 to C in treatment C_2C_2 on the other. The level of experience (in terms of the number of periods played) is the same in each case. Only the matching procedure is different, random (perfect stranger) for groups A and B and fixed for group C. For the capacity variable, we test the following hypotheses:

$$\begin{array}{lll} \text{Phase 1:} & H_0 : \beta_A = \beta_C & H_1 : \beta_A < \beta_C \\ \text{Phase 2:} & H_0 : \beta_B = \beta_C & H_1 : \beta_B < \beta_C \end{array}$$

while in the case of prices and profits the inequality in the H_1 hypothesis is reversed. The H_0 hypothesis is never rejected against the one-sided alternative of median capacity being smaller, and prices and profits greater, in groups A and B in the respective phases and group C, respectively. The few p-values for the WMW test that show a significant difference (see table 4), apply to the opposite one-sided H_1 hypothesis, that is, in a majority of the first phase periods, we find median capacity to be significantly larger in group A than in group C. We summarize the answer to question 3 as follows.

Result 4 *We find no support for the strategic motive, such as an attempt to become a Stackelberg leader.*

4 Further analysis using quantal response equilibrium

So far we have only presented a simple example of how an opponent's experience level is of importance for the outcome of KS games. However, results 2 and 3 indicate that a more complete theoretical setup is needed to better understand the experimental results, in particular, a framework allowing for varying degree of player's experience. In this section we apply the quantal response equilibrium (QRE), developed by McKelvey and Palfrey (1995) to the KS game and show how important predictions of the model fit well with the experimental data.

4.1 Logit-AQRE applied to KS game

The QRE framework can be looked at as an extension of Nash equilibrium. Players are not expected to play best responses with probability one, but rather probabilistic best response functions. The probability with which each strategy is played is related to the associated expected payoff. While the probability put on a particular strategy is specified as a linear function of expected payoff in Rosenthal's (1989) model of bounded rationality in games, the QRE derives choice probabilities from a quantal response statistical model, as the name suggests. Each element in a player's payoff function is subject to an error, usually assumed to be identically and independently distributed. A corresponding equilibrium concept for extensive form games is the agent quantal response equilibrium (AQRE) (McKelvey and Palfrey, 1998). This extension uses the concept of the agent-strategic form where, in each information set, a separate agent plays on behalf of the relevant player Selten (1975). The crucial assumption is that errors in the payoff function are independently distributed, even for different agents of the same player.

The model. We assume errors to be identically and independently log-Weibull distributed so that the quantal response functions take the logit form,

$$b^*_{i,q_i} = \frac{e^{\lambda_i \overline{\pi}(q_i, b^*)}}{\sum\limits_{q'_i \in A_q} e^{\lambda_i \overline{\pi}\left(q'_i, b^*\right)}}, \quad i \in \{1,2\} \tag{5}$$

for $q_i \in A_q$ and

$$b^*_{i,p_i|\mathbf{q}} = \frac{e^{\lambda_i \overline{\pi}(p_i, b^*)}}{\sum\limits_{p'_i \in A_p} e^{\lambda_i \overline{\pi}\left(p'_i, b^*\right)}}, \quad i \in \{1,2\} \tag{6}$$

for $p_i \in A_p$, where b^*_{i,q_i} is the equilibrium probability of player i selecting a capacity level q_i and $b^*_{i,p_i|q}$ the probability assigned to the price level p_i conditional on both player's capacity choices. The complete strategy profile is denoted by b^*. The term $\overline{\pi}\left(q_i, b^*\right)$ describes the expected payoff when the player in question chooses the capacity level q_i with probability one while the opponent's strategy and own price strategy follow b^*. Similarly, $\overline{\pi}\left(p_i, b^*\right)$ is the expected payoff when the strategy profile b^* is played, except that own price is p_i with probability one. The expected payoff functions are are calculated from (1) assuming that the beliefs are consistent with b^*. Finally, λ_i is the logit distribution parameter, a measure of the accuracy with which player i observes his payoff function. The logit-AQRE is found by solving a system of equations (5) and (6) for all information sets for particular levels of λ_i.[15]

Two special cases are of particular interest. When $\lambda_i = 0$ the errors completely dominate any information about the payoff function and players choose all strategies with equal probability. On the opposite extreme, when $\lambda_i \to \infty$ the errors become negligible, in which case each player chooses his best response with probability one and the unique subgame-perfect equilibrium, the Cournot outcome, appears. These

[15]See McKelvey and Palfrey (1998) for a complete exposition of the AQRE.

two extremes were combined in the simple example in section 2, where a fully rational player played against someone choosing strategies at random.

When a particular experiment is repeated, subjects gain experience and can be expected to make more precise estimates about the payoffs resulting from different strategies. The precision with which subjects observe their payoffs can be affected by many factors, but it is reasonable to expect that the level of experience monotonically affects precision. The experiment is designed bearing this in mind, thus subjects with different levels of experience are paired while other factors remain constant. What is not reasonable to assume is that subjects behave as if they observe their payoffs with either perfect or minimal precision, as in the example. The AQRE framework allows us to study the outcome of the game when the two players have asymmetric but intermediate values of λ.

Simulated results. It turns out to be extremely difficult, if not impossible, to find a closed form solution to this problem. The main reason being discontinuities in the payoff function (1). The problem is, however, easily solved numerically[16] with a relatively dense approximation of the action space used in our experiment, $A_q = A_p = \{10, 15, 20, ..., 80\}$, yielding a manageable number of nonlinear equations, $2 \times (15 \times 15 + 1) \times 15 = 6780$. For computational reasons we need to restrict the action space to multiples of five.[17]

The means of capacities and prices generated by the equilibrium strategies of an arbitrary player 1 are shown in figure 4, for several levels of player 1's precision level, λ_1, and player 2's (his opponent's) precision level, λ_2.[18] Each curve shows the relationship between player 1's average capacity and his precision level, for a given precision level for player 2.

Observe from the left hand graph in figure 4 that player 1's average capacity decreases in his own precision, and seems to converge toward the Cournot output level. This is especially true when the opponent's experience level is high. In other words, when both players observe their payoffs with high precision the logit-AQRE converges to the unique subgame-perfect equilibrium. An increase in λ_2 corresponds to a downward shift in figure 4, which implies that player 1's average capacity is

[16]The program was solved using the GAMS/PATH mixed complimentarity problem solver. The code is available at http://www.hi.is/~jonthor.

[17]While continuous space techniques exist for normal form games (Anderson et al., 1998) we are unaware of similar tools for extensive form games. The results do not seem to be too sensitive to the discreet approximation of the action space.

[18]The numerical values of the λ's are specific to the model and can only be compared in relative terms. The model is not solveble for λ's much larger than 2.

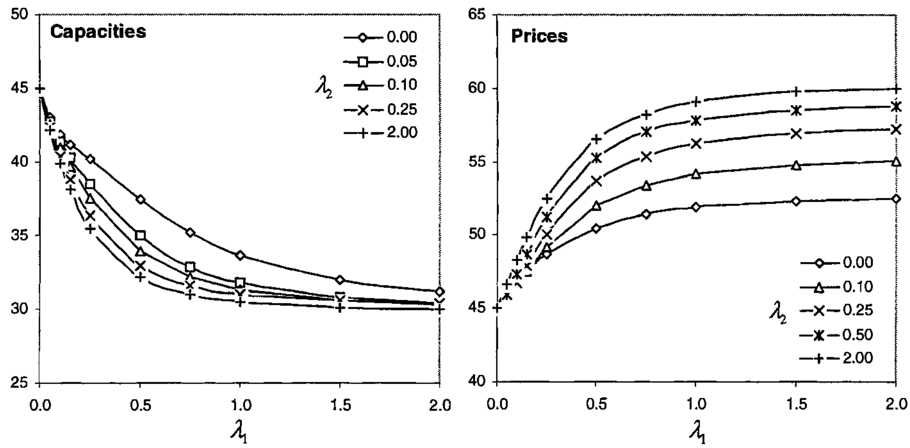

Figure 4: Mean capacities and prices in logit-AQRE equilibrium

decreasing in λ_2. This effect is important for intermediate λ_1 but very small for low or high λ_1.

From the right hand graph in figure 4 we can see that the average price increases with the player's own precision (λ_1) but does not converge to the Cournot outcome when the opponent lacks precision (λ_2 is low), as opposed to capacity. An increase in λ_2 has a positive effect on the expected price of player 1 and the effect is strenghtened by an increase in λ_1. The fact that the standard deviation of capacities and prices decrease in both λ_1 and λ_2 as expected and need not be discussed in detail.

The bias towards larger capacities and lower prices when the opponent is considered to have limited rationality, seems robust to changes in levels of the precision parameters λ_1 and λ_2. It is also qualitatively consistent with the regression analysis presented in table 2. Recall from result 3, that the difference between the capacities chosen by experienced players when playing against experienced and inexperienced opponents, respectively, was not significant while mean and median prices were. Figure 4 illustrates quite well that this may be expected since there being a close link between experience and individual rationality. The variability in average capacity caused by the opponent 's experience level is very small, when the player's own experience level is high. Thus, it may be easier to detect the effect of the opponent's experience level in price decisions rather than in capacity decisions.

The reader might wonder, at this point, if the bias depends more on the particular specifiation of the action space rather than the players' level of rationality. As it turns out, both matter. If, for instance, we select the actionspace such that the expected quantities and prices are equal to the Cournot outcomes, when $\lambda_1 = \lambda_2 = 0$, the relationship between mean of capacity and λ_1 is no longer monotonic. However, for any $\lambda_1 > 0$ the expected capacity is larger and the price lower than predicted by the Cournot outcome. The pattern of the bias is affected though, especially in the case of prices. We deal with this issue in more detail in Appendix A.

4.2 Estimating the AQRE model- Data analysis

The predictions of the logit-AQRE fit qualitatively well with the experimental results of section 3. The question remains, however, whether the predictions are quantitatively accurate. In seach of an answer we look at two features. We estimate the precision parameters (λ) that best fit the experimental data and compare the predicted and actual average capacities and prices.

For each treatment (excluding C_1C_1), we estimate the precision parameters (λ), maximizing the following likelihood function,

$$ln\mathcal{L} = \sum y_{i,t}\left(q_i, q_j, p_i\right) \times \ln\left(b_{q_i}\left(\lambda_1, \lambda_2\right) + b_{p_i|q}\left(\lambda_1, \lambda_2\right)\right). \tag{III}$$

The summation applies to subjects, a subset of periods and all possible combinations of q_i, $q_j \in A_q$ and $p_i \in A_p$. The index variable $y_{it}(q_i, q_j, p_i)$ takes the value of 1 if subject i selects quantity q_i and price p_i in round t while his current opponent chooses q_j or else the value zero.[19] The b functions are the equilibrium response functions as defined in (5) and (6). Each treatment is broken down into five experience levels with two periods in each. In treatments A_1A_1 and B_1B_1, where all subjects have the same amount of experience we estimate a single precision parameter, λ_A or λ_B respectively, while in treatment A_2B_1 a separate parameter is estimated for each group. The estimates together with the log-likelihood values ($ln\mathcal{L}_{\text{AQRE}}$) are reported in table 5.

The estimates for λ_A and λ_B generally increase with the experience level (see Figure 5) reflecting the tendency for subjects to choose strategies with higher payoffs as they become more experienced in playing the game. The learning process can vary substantially between individuals and depend on other variables than the number of periods played. It is, for instance, interesting to note that λ_B is higher than λ_A

[19] Selected quantities and prices are rounded up or down to the nearest point in the discrete action space.

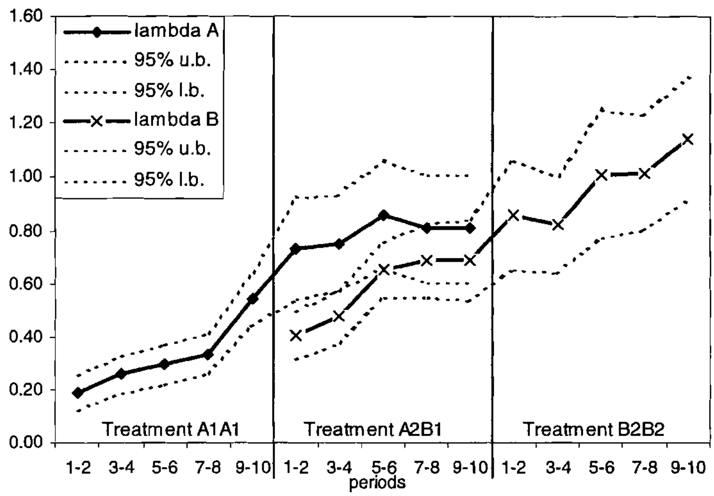

Figure 5: Estimated λ and 95% confidence intervals

for any given level of experience. It is doubtful, though, whether the opponent's experience level affects the speed of learning, since the difference in λ is more or less of the same magnitude for different experience levels. A more plausible reason is that inexperienced subjects in group B, knowing that they will face experienced players A, put more effort into finding their best strategy, compared with similarly experienced A players who meet similarly inexperienced players.

A comparison of $ln\mathcal{L}_{\text{AQRE}}$ to the log likelihood of the random model $ln\mathcal{L}$ (i.e., when $\lambda_A = \lambda_B = 0$) for each row in table 5 in turn, suggests an improved fit when subjects gain experience. In table 6, we compare the predictions based on the estimated logit-AQRE model for each experience level, and the actual choice (adjusted for the discrete action space). It is clear that, even though the model provides fairly good qualitative predictions, it systematically underpredicts quantities and overpredicts prices. The predicted standard deviations are close to the actual levels, however.

The logit-AQRE is a better prediction of behavior than the three alternative models we considered, which are similar to those used by Rassenti et al. (2000) in the context of Cournot games. In the *partial Cournot equilibrium model*, a player chooses the Cournot output as his capacity level with a specific probability or alternatively, any strategy at random. In the *partial fictitious play model*, each player chooses a capacity, which is a best response to a weighted average of previously observed capacity choices made by opponents, with a certain probability or alternatively, any strategy at random. The weights are chosen so that recent observations weigh more heavily than old ones. Finally, in the *partial imitation model*, subjects imitate the capacity choice they have observed resulting in the highest profit. These models are all called partial models, as they only differ with respect to the capacity choice. Due to the complexity of price strategies, a simple ad-hoc price strategy is chosen.[20] All three models have two parameters, one for the probability of choosing the described capacity strategy, θ_q, and one for the probability of choosing the resulting market clearing price, θ_p. The respective log likelihood values are displayed in columns 5-7 in table 5.

All these models are rather crude, and their main purpose is to provide some reference for the AQRE model. As it turns out the AQRE model performs better than the alternative learning models. All these models (excluding the AQRE model) perform similarly well in treatments when subjects have similar experience. In the A_2B_1 treatment however, the imitation model is clearly the second best model, after the AQRE model.

5 Conclusion

The purpose of this paper is to improve our understanding of why subjects consistently choose capacities above, and prices below, the predicted subgame-perfect equilibrium in experimental Kreps and Scheinkman games. We argue that players' perceptions of their opponents skill, or level of rationality, are important in this context. Using experience in playing the game as a proxy for the level of rationality in our experimental design, we find that capacities are relatively higher when the opponents' level of experience (the number of periods played) is relatively low and that prices are relatively low when opponents lack experience.

We further explore the experimental results using the quantal response equilib-

[20]For all learning models, we assume that subjects choose the market clearing price with a minimum level equal to the marginal cost, $p_{mc} = \max(120 - (q_1 + q_2), 30)$, plus/minus 2.5, with probability θ_p or choose a random price strategy with probability $(1 - \theta_p)$. While the market clearing price is only a Nash equilibrium for sufficiently low capacities, it is probably a better approximation in this simple framework than the average price of the respective mixed strategy equilibrium. While the average price of a mixed strategy equilibrium can certainly go below the marginal cost, which is sunk at the pricing stage, there were practically no such cases in the entire experiement.

rium framework. Predictions, based on a logit agent-form quantal response equilibrium model, turn out to be qualitatively consistent with the experimental findings, some of which seem inconclusive at first.

Since the Cournot model is often used as a benchmark in applied economics, e.g., in competition policy where the Cournot model is the theoretical foundation of the use of concentration indices in merger guidelines, the results obtained are highly relevant. They suggest that the performance in oligopolies depends on the experience of market participants and how well participants are informed about their competitors' experience.

It is somewhat disappointing that the logit-AQRE model, as specified here, does not give quantitatively accurate predictions. The observed deviations are much larger than predicted by the model, thereby indicating that the current model specification is too restrictive. At least two extensions seem worthy of further research.

1) A closer inspection of the distribution of capacity choices, as shown in figures 8 for group A and 9 for group B, suggest that there may be considerable heterogeneity within each group. The distribution of capacity is bimodal for a reasonably experienced subject pool. In the last two periods of play, almost a third of the subjects in group B chose the Cournot output level 30, while another third chose a capacity level close to 40. Allowing for different levels of rationality within each group would account for this, and possibly increase the level of the predicted bias.

2) Extending the AQRE model to allow for inconsistent response functions is another interesting alternative. Weizsacker's (2001) extension of the normal form QRE allows for response functions which depend on the perceived opponent's choice distributions, which must not necessarily have to be consistent with the opponents actual equilibrium strategy. Estimations on experimental data suggest that perceptions are quite frequently biased in the direction of underestimating the rationality of other players. In the logit quantal response framework, this amounts to a downward bias in players' perception of their opponents' precision level. If the same bias were to appear in the KS model the predictions of such a model would probably be closer to the actual outcome, as the average quantities should increase, given that beliefs about the opponent's precision level decrease, as shown in figure 4.

Appendix A - Choice of Action Space

If players randomize completely, the average capacity is determined by the mean of the action space. In most conceivable configurations of the KS model, the average of all feasible capacity levels is higher than the Cournot output, while the opposite is true for prices. This might affect the prediction of the logit-AQRE model. It is therefore interesting to compare the above predictions to the case where the action space is symmetric around the Cournot outcomes, $A_q = \{0, 5, ..., 60\}$ and $A_p = \{30, 35...90\}$. In this setup the expected capacity and price chosen by a totally clueless player (with $\lambda_1 = 0$) is simply the Cournot outcome. Figure 6 illustrates average capacity and price choices in the logit-AQRE equilibrium profile. With a symmetric action space, average capacity is no longer uniformly decreasing in own precision level (λ_1). For positive levels of λ_2 it first increases and then decreases. Furthermore, capacity only converges to the Cournot output level when both λ_1 and λ_2 increase simultaneously. The case of prices is more complicated, as the average price is not monotonic with respect to λ_2 either.

In the simple example presented in section 2, the action space was intentionally chosen to be symmetric around the Cournot equilibrium in order to eliminate the additional bias caused by the distribution of quantity and levels in the action space. A symmetric action space would be difficult to impose on our experiment[21] and, for this reason, we can expect a further bias towards high capacities in the case of inexperienced subjects, for this reason. It is very hard, if not impossible, to control for how subjects think about the action space. Judging from how subjects started out with average capacities close to 45, the average of rationalizable capacity levels, we believe the specification used to be appropriate. The comparison of these two configurations is still helpful. It suggests that the presence of a bias towards larger capacities and lower prices does not seem to be caused by the choice of action space, although it is an important determinant of the shape of the bias with respect to the level of players' rationality and their perceptions about the rationality of others.

[21] Cournot equilibrium prices and quantities are rarely at the center of what is naturally perceived as feasible prices and quantities. Without any knowledge of what subjects perceive to be a natural action space we specify the action space as those actions belonging to all rationalizable strategies (Bernheim, 1984).

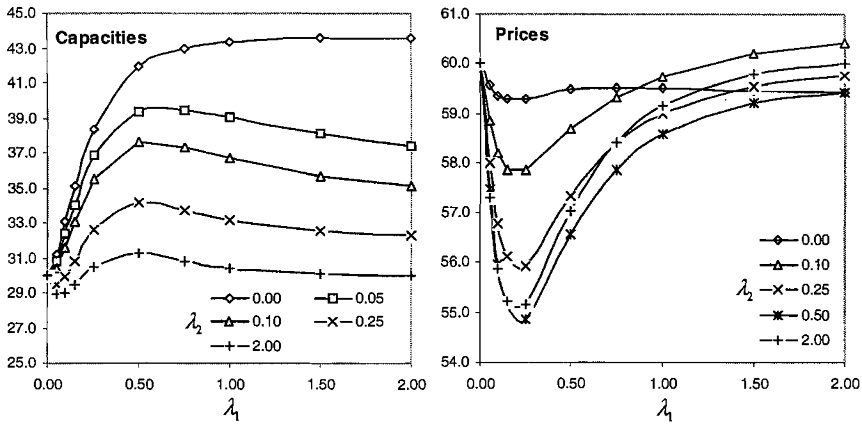

Figure 6: Mean capacities and prices in logit-AQRE equilibrium - Action space symmetric around Cournot outcome

Appendix B - Instructions

{}: group A, []: for group B and, * *: group C

Welcome to this experiment in the economics of decision making, which should take approximately 90 minutes. You will be paid a minimum of SEK 100 for your participation, but you can earn much more if you make good decisions. At the end of the session you will be paid, in private and in cash, an amount that will depend on your decisions. Please read the instructions carefully. If you have any questions please raise your hand, and you will be helped privately.

General Rules

This experimental session will consist of several periods. In each period you play the role of a firm which produces a good and sells it in a market.

{One other firm, represented by a randomly selected participant, sells his product in the same market in each period. For the first 10 periods you will play against other participants sitting in this room. You will never face the same participant more than once. After period 10 the experiment will restart, but now you will play against a different group of participants located elsewhere. *Unlike you, these participants have no prior experience of this experiment.* As before, you will only play against each of the new participants once.}

[One other firm, represented by a randomly selected participant, sells his product in the same market in each period. For the first 10 periods you will play against a different group of participants located elsewhere. *Unlike you, these participants have experience of this experiment, they have played the game before.* You will never face the same participant more than once. After period 10 the experiment will restart, but now you will play against other participants sitting in this room. As before, you will only play against each of the new participants once.]

One other firm, represented by another participant, sells his product in the same market. You will play against the same participant in all 20 periods. The true identity of your opponent will not be revealed to you, neither will your identity be revealed to him.

By making good decisions you can earn profits in experimental dollars (e-dollars). At the end of the session you will be paid SEK 100 plus the e-dollars you have earned at the exchange rate of 1 SEK for every 50 e-dollars. Simply put, the more experimental dollars you earn the more cash you will receive at the end of the session.

In each period you make two separate decisions for your firm. First you decide how much you would like to produce (Q1) and then, after you have observed the production level of your competitor (Q2), you choose your price (P1).

Production stage

At the beginning of each period you decide how many units of the good to produce (Q1). You make your decision by entering a number in the box on the left hand side of the screen and then press OK. **Any positive number between 0 and 90, with up to 2 decimals** is acceptable. (Example: 10, 20.6, and 33.33 are valid but -12, 50.123 are not). Please use a dot (.) as the decimal separator.

The amount you produce has consequences for your profit in that period, since you have to pay a production cost of 30 e-dollars for each unit; regardless of how much you sell. Note that no inventories can be carried to future periods.

Before you enter in your quantity you should think carefully about your choice. You can use the calculator displayed on the right hand side of the computer screen. There you can enter prospective production quantities and prices for your firm and its competing firm, press CALCULATE and observe the results in the table on the lower right hand side. Table 3 explains the columns.

Price stage

When all participants have entered their production levels you will automatically go to the price stage. On the left hand side you can see your own chosen production level as well as your competing firm's production level. You enter a price of your choice in the box below this information and press OK when you are ready. **Any positive number between 0 and 120, with up to 2 decimals** is acceptable. (Example: 10, 20.6, and 33.33 are valid but -12, 50.123 are not). Please use a dot (.) as a decimal separator. You may want to do some more calculations before you set your price. You still have the calculator on your right hand side, but this time you can only alter the prices (P1 and P2). The previously chosen quantities (Q1 and Q2) are fixed at this stage.

How much you sell is determined by your price (P1) and its relation to your competitor's price (P2). Consumer demand is calculated by a computer program and follows a simple equation

$$D = 120 - P.$$

where D is demand and P is a price. This means for instance that at the price 0 consumers are willing to purchase 120 units of the product. At the price of 25.5 consumers are willing to purchase 94.5 units. There is no demand for the product at price levels equal to or greater than 120. Figure 7 illustrates demand and unit cost.

Consumers strictly prefer buying from the firm offering the lower price. Hence, the firm with the lower price will sell all its production up to the demand level at that price. The firm with the higher price can only sell the product to consumers who are not supplied by the lower pricing firm, and never more than the demand level at its price, or its produced quantity. If both firms choose the same price, demand will be split equally between them up to the capacity limits (the respective production levels).

Table 3: Calculator table legend

Q1	Your production
Q2	Competitor's production
X1	Your sold quantity
X2	Competitor's sold quantity
P1	Your price
P2	Competitor's price

Example 1: Say that Q1 = 35, Q2 = 45, P1 = 45 and P2 = 55. Since demand at the lower price level is 75, you (firm 1) can sell all your produced quantity. Your revenue is $45 \times 35 = 1575$ and your total cost is $30 \times 35 = 1050$. Your profit is $1575 - 1050 = 525$. Your opponent (firm 2) can only sell 30 units. The demand for his product equals $120 - 55 = 65$, by the demand equation. From that we have to subtract what is already supplied by your firm, or 35 units. Hence, he sells $65 - 35 = 30$ units at the price of 55. His revenue is $55 \times 30 = 1650$, his total cost is $45 \times 30 = 1350$ and he makes a 300 e-dollar profit.

Example 2: Say that $Q1 = Q2 = 15$ and $P1 = P2 = 55$. Demand at this price is greater than the sum of the production levels but you can only sell what you produce. Your profit is $55 \times 15 - 30 \times 15 = 375$.

Result display

When all participants have entered their prices the result display will appear. You can then see a summary for that period, for yourself and your competitor. Press continue when you have studied the results.

Periods

To help you familiarize yourself with the computer interface and the calculations, you get to practice for two periods. *The result of these periods will not affect your payoff.*

{Then, you will play for 10 periods, once with each of the participants in your room. Then, after a short break, the experiment restarts, and now you play against inexperienced participants. Again you go through two practice periods (for the others) and then 10 periods, where you can earn money, against each of the inexperienced participants.}

[The result of these pratice periods will not affect your payoff. Then you will play for 10 periods, once with each of the experienced participants in the other room. Then, after a short break, the experiment restarts and now you play for 10 periods against participants sitting in your room, who have the same level of experience as you do]

Then you will play for 20 periods for which you can earn money.

Before you leave, we ask you to fill out a short questionnaire about the experiment. We will use the time while you complete it to calculate your earnings.

Everything described here is not only valid for you, but also for all other participants in this experiment.

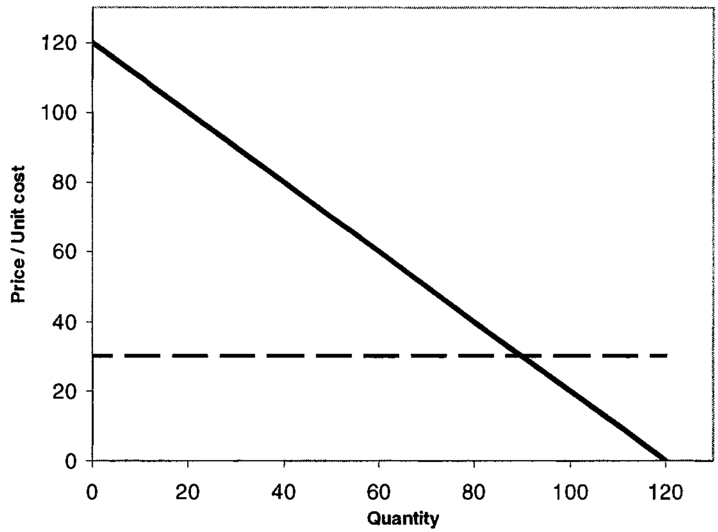

Figure 7: The demand function (solid line) and the unit cost function (dotted line)

Now you should be ready to start the experiment. Please raise your hand if you have any questions. We prefer to answer your questions privately. Good luck!

Table 4: Summary statistics and non-parametric tests

	A		B		C			
Period[1]	Mean	St.d.	Mean	St.d.	Mean	St.d.	$p^2_{A,B}$	$p^3_{A/B,C}$
a) Quantity choice								
1	53.7	18.7	46.6	15.5	43.9	14.3	**0.076**	**0.082**
2	53.5	19.2	44.8	11.3	52.0	17.2	**0.039**	0.462
3	50.1	15.8	46.0	15.1	42.6	10.1	**0.091**	**0.058**
4	50.6	17.2	41.1	8.0	43.3	6.5	**0.012**	**0.060**
5	50.9	16.5	42.4	14.7	40.1	15.0	**0.011**	**0.014**
6	46.8	16.4	41.3	11.5	37.4	7.3	**0.079**	**0.030**
7	46.0	16.2	39.8	12.2	38.5	10.4	**0.037**	**0.069**
8	42.9	11.7	38.3	8.7	36.4	7.4	0.104	**0.060**
9	39.5	13.0	39.4	7.5	36.2	8.1	0.381	0.202
10	37.4	13.4	39.8	8.2	36.1	7.3	**0.041**	0.355
11	38.2	9.2	37.4	6.0	36.9	8.2	0.401	0.372
12	36.9	9.5	38.0	5.1	34.9	7.8	0.158	0.154
13	36.6	9.2	36.9	5.4	35.7	6.8	0.276	0.292
14	37.4	8.1	37.2	6.0	35.3	6.6	0.337	0.239
15	37.6	9.8	36.6	6.1	35.6	6.9	0.455	0.354
16	35.9	7.7	35.9	6.7	35.6	6.9	0.356	0.503
17	36.2	7.4	35.6	5.2	36.0	7.7	0.498	0.450
18	37.8	7.9	34.7	5.9	35.9	7.2	**0.071**	0.299
19	37.5	7.0	35.6	6.7	33.9	5.8	0.212	0.275
20	35.7	9.0	34.9	5.6	34.3	4.1	0.397	0.335
b) Price choice								
1	39.8	9.6	41.8	10.6	42.5	6.4	0.146	**0.039**
2	41.3	13.7	43.7	9.3	39.4	7.9	**0.042**	0.344
3	37.7	8.6	44.9	12.3	41.5	9.1	**0.017**	0.118
4	37.2	8.9	43.8	10.3	38.7	8.5	**0.005**	0.294
5	36.0	8.0	46.2	11.0	43.9	10.5	**0.000**	**0.015**
6	39.3	11.6	46.1	10.0	47.3	11.3	**0.008**	**0.026**
7	40.3	12.4	46.2	8.6	47.7	15.3	**0.010**	**0.062**

Table 4: (continued)

	A		B		C			
Period[1]	Mean	St.d.	Mean	St.d.	Mean	St.d.	$p^2_{A,B}$	$p^3_{A/B,C}$
8	40.3	12.0	46.9	9.3	49.0	13.2	**0.003**	**0.014**
9	45.9	15.0	46.8	8.1	48.3	13.1	0.159	0.243
10	48.4	12.2	46.1	9.2	49.4	12.1	0.261	0.415
11	42.7	10.6	46.9	7.7	48.8	13.1	**0.027**	0.477
12	44.6	8.6	46.1	7.2	51.5	11.1	0.228	0.107
13	43.6	10.5	46.9	7.3	49.7	11.9	**0.075**	0.373
14	45.2	9.7	47.2	8.1	50.4	11.9	0.172	0.278
15	46.2	11.0	47.8	7.1	49.5	13.0	0.146	0.484
16	45.5	9.4	48.9	9.0	49.7	12.7	**0.081**	0.477
17	47.6	8.1	48.3	6.9	49.0	13.5	0.319	0.386
18	46.4	9.4	50.5	8.6	49.2	13.5	**0.076**	0.348
19	46.5	8.6	51.3	9.6	51.2	11.4	**0.044**	0.444
20	46.0	8.3	50.9	7.7	50.5	7.5	0.035	0.424

[1] The n-th period played by the respective group of subjects

[2] The critical significance level of a single-sided Mann-Whitney test of equal choice distribution in groups A and B

[3] The critical significance level of a single-sided Mann-Whitney test of equal choice distribution in groups A and C (in the first 10 periods) and B and C (in the last 10 periods)

Table 5: Maximum likelihood estimation of the logit-AQRE model

Periods	λ_A	λ_B	$ln\mathcal{L}_{\text{AQRE}}$	$ln\mathcal{L}_{\text{Nash}}$	$ln\mathcal{L}_{\text{Fict.}}$	$ln\mathcal{L}_{\text{Immit.}}$	$ln\mathcal{L}$
			a) Treatment A_1A_1				
1-2	0.19		-205.9	-225.8	-227.3	-226.5	-249.1
	(0.03)						
3-4	0.26		-201.2	-233.5	-233.6	-233.5	-249.1
	(0.04)						
5-6	0.29		-187.5	-217.0	-217.5	-216.6	-249.1
	(0.04)						
7-8	0.34		-196.9	-214.1	-217.3	-217.2	-249.1
	(0.04)						
9-10	0.54		-171.5	-203.4	-217.3	-216.0	-249.1
	(0.05)						
			b) Treatment A2B1				
1-2	0.73	0.40	-345.2	-429.0	-433.1	-406.1	-509.1
	(0.10)	(0.05)					
3-4	0.75	0.48	-341.1	-414.4	-418.6	-395.1	-509.1
	(0.09)	(0.05)					
5-6	0.86	0.65	-310.1	-374.3	-388.2	-362.4	-509.1
	(0.10)	(0.05)					
7-8	0.81	0.69	-315.2	-392.4	-405.8	-362.5	-509.1
	(0.10)	(0.07)					
9-10	0.81	0.69	-321.9	-411.3	-418.2	-370.3	-509.1
	(0.10)	(0.08)					
			c) Treatment B2B2				
1-2		0.86	-154.3	-207.2	-211.9	-202.8	-260.0
		(0.11)					
3-4		0.82	-157.8	-201.3	-208.8	-201.3	-260.0
		(0.09)					
5-6		1.01	-144.8	-188.1	-195.5	-196.6	-260.0
		(0.12)					
7-8		1.02	-144.0	-169.7	-179.9	-167.9	-260.0
		(0.11)					
9-10		1.141	-133.0	-180.9	-186.3	-184.6	-260.0
		(0.12)					

Standard errors in parantheses, estimated by the BHHH method.

Table 6: Actual vs. predicted quantities and prices

	q_A		q_B		p_A		p_B	
	Actual	*Predicted*	*Actual*	*Predicted*	*Actual*	*Predicted*	*Actual*	*Predicted*
				a) Treatment A1A1				
1-2	53.9	38.0			40.7	48.5		
	(18.5)	(18.2)			(11.5)	(17.5)		
3-4	50.5	36.1			37.5	50.3		
	(16.2)	(16.3)			(8.6)	(16.4)		
5-6	48.9	35.3			37.5	51.2		
	(16.4)	(15.3)			(10.1)	(15.8)		
7-8	44.5	34.5			40.3	52.2		
	(14.0)	(14.3)			(12.2)	(15.2)		
9-10	38.4	32.3			47.5	55.8		
	(13.1)	(10.6)			(13.7)	(12.4)		
				b) Treatment A2B1				
1-2	37.7	31.5	45.8	33.3	44.1	56.5	42.9	54.7
	(9.2)	(9.0)	(16.6)	(12.6)	(9.7)	(12.2)	(10.0)	(13.2)
3-4	37.1	31.4	43.3	32.6	44.7	56.9	44.5	55.6
	(8.4)	(8.8)	(15.9)	(11.4)	(10.2)	(11.7)	(11.2)	(12.3)
5-6	37.0	31.1	41.7	31.6	46.1	57.9	46.4	57.3
	(8.6)	(8.0)	(16.5)	(9.5)	(10.2)	(10.5)	(10.3)	(10.8)
7-8	37.2	31.2	38.9	31.5	47.0	57.8	46.5	57.4
	(7.4)	(8.3)	(14.6)	(9.1)	(8.8)	(10.6)	(8.8)	(10.7)
9-10	36.7	31.2	39.6	31.5	46.6	57.8	46.7	57.4
	(8.0)	(8.3)	(12.7)	(9.1)	(8.3)	(10.6)	(8.6)	(10.7)
				c) Treatment B2B2				
1-2			37.4	31.0			46.8	58.2
			(11.5)	(8.0)			(7.5)	(9.9)
3-4			37.1	31.1			47.3	58.1
			(11.6)	(8.2)			(7.8)	(10.1)
5-6			36.5	30.7			48.2	58.8
			(11.8)	(7.3)			(8.0)	(9.2)
7-8			35.3	30.7			49.5	58.8
			(11.5)	(7.2)			(7.7)	(9.1)
9-10			35.2	30.5			51.1	59.1
			(11.7)	(6.8)			(8.4)	(8.7)

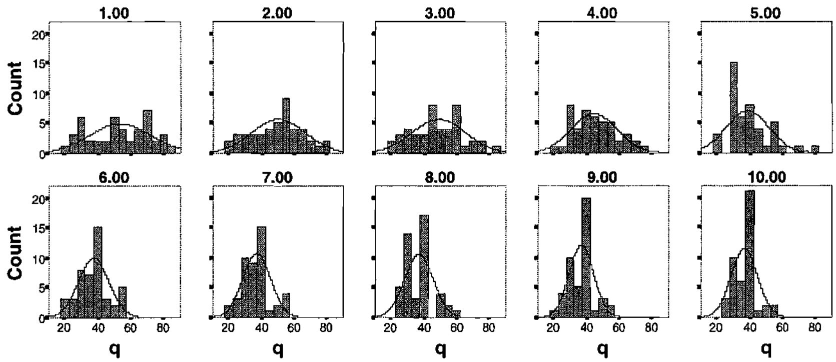

Figure 8: Distribution of quantity choices in group A, each graph indicates a particular experience level (two periods)

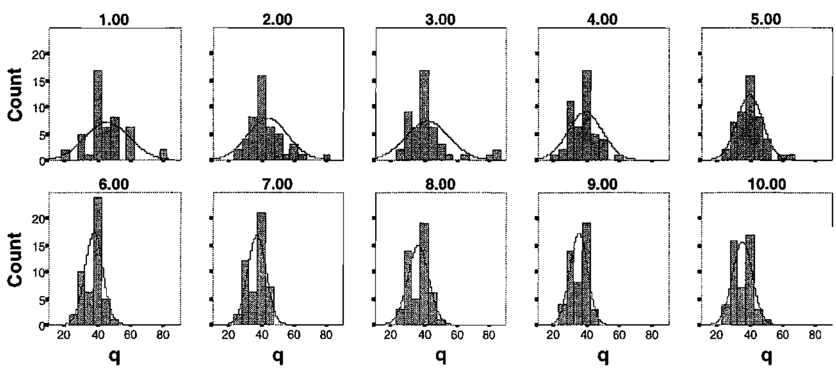

Figure 9: Distribution of quantity choices in group B, each graph indicates a particular experience level (two periods)

Chapter III

Do Forward Contract Markets Enhance Competition? Experimental Evidence[1]

This chapter has been written with Henrik Orzen[2]

1 Introduction

3

Forward contracts are binding agreements between sellers and buyers specifying the terms, including the price, of the delivery of a good at a future date. Forward trading has a long history in agriculture but has become increasingly important in other sectors, particularly in financial asset trading and, relatively recently, in energy markets. From a public policy perspective it is of interest whether forward trading has desirable effects on welfare and efficiency. This question can be of practical and acute significance for policy makers who must make decisions on market design. A prominent example is the recent energy crisis in California, which prompted an intense debate on the design flaws of the Californian electricity market. The Market Surveillance Committee (MSC), a group of independent advisers to the governing board of the Californian Independent System Operator, recommended the removal of any restrictions on forward contracting, suggesting that this would not only prevent seasonal price peaks but also significantly limit the ability of generators to exercise market power (MSC, 2000, p.15).

The idea that forward markets might enhance competition has also been discussed in the theoretical literature, especially Allaz and Vila (1993) (henceforth AV). Usually, it is argued that agents make forward transactions solely as a protection against volatile market prices and other risks, but AV suggest a further reason

[1]We are very grateful for many valuable comments from Klaus Abbink, Lars Bergman, Martin Dufwenberg, Tore Ellingsen, Magnus Johannesson, Georg Kirchsteiger, Martin Sefton, Ilias Skamnelos and Chris Starmer, as well as from participants in the GEW Conference 2002 in Wittenberg, Germany, and the European ESA Meeting 2002 in Strasbourg, France. Moreover, we would like to thank Laurent Muller, Mauro Pisu and Khemarat Teerasuwannajak for their help in conducting the experiments. We are gratefully acknowledge funding for the project from Sydkraft AB.

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for the existence of forward markets. In a simple model of duopolistic quantity competition they show that a firm may obtain a leadership position by selling forward. Motivated by this opportunity, both players participate in the forward market and as a consequence compete more aggressively overall. Thus, compared to the case of pure spot market trading, production levels rise and prices fall, which generates an increase in consumer surplus and total welfare.

This is an intriguing result, and a number of theoretical studies that were published around the same time in fact came to similar conclusions, see for example Bolle (1993) and Powell (1993). How effective, however, is the introduction of a forward market compared to other means of improving competition in an oligopoly? In this paper we show that, relative to the increase in competitive pressure that would be caused by the entry of additional competitors, the competition-enhancing effect of forward trading is surprisingly strong in AV's model. Our n-firm version of the model predicts that introducing a forward market raises competitiveness to the same degree as squaring the number of competing firms. In the second part of the paper we report the results of a laboratory experiment, which we designed to test the predictions of AV's theory. We think experimental evidence can be helpful in assessing the relevance of AV's results, which seem sensitive to crucial assumptions (perfect foresight, conjectural variation, or observability), as it is already noticed in the theoretical literature (e.g. Allaz, 1992, or Hughes and Kao, 1997).

In our experiment we are explicitly testing whether and to what extent forward markets improve efficiency. While it is difficult to systematically study the effect of forward markets using field data because the important variables are hard to measure and control for, laboratory methods allow the experimenter to set and manipulate crucial parameters such as the number of competitors, cost functions, demand behavior and exogenous shocks. To the best of our knowledge we are the first to test AV's predictions in the laboratory. Previous experimental work has investigated other aspects of forward markets; Sunder (1995) reviews experiments studying the informational efficiency of forward markets. A work more closely related to this paper is Reynolds's (2000) study of durable-goods monopolies, where he experimentally examines the Coase (1972) conjecture. AV's finding resembles the Coase conjecture in that intertemporal competition is crucial in both approaches. However, there are also important differences most notably perhaps that in AV's setup a monopolist would not be affected by the introduction of a forward market. Consequently, we focus on competing firms and their strategic interactions, the key elements driving AV's theoretical result. Phillips, Menkhaus and Krogmeier (2001) report an experiment where four sellers and four buyers have access to a forward market and/or a spot market under a double auction trading mechanism. They find that consumer surplus and market efficiency are highest when trading is only allowed on the forward market and lowest when trading is only allowed on the spot market. When transactions can be made on both markets buyers' earnings and market efficiency are intermediate. However, Phillips et al. focus on price competition, and in their design inventory costs provide sellers with an additional incentive to operate on the forward market. Therefore the strategic effect of forward trading is not clear.

In our thirty-two laboratory-controlled experimental markets firms choose quantities in a repeated game with fixed matching, and prices are determined by a downward-sloping linear demand. We employ two benchmark conditions where either two or four sellers engage in standard Cournot competition and thus solely trade on a spot market. In the AV markets, two (or four) firms can first sell units on a forward market before entering the spot stage. If they make transactions on the forward market the sellers commit to produce at least their forward quantities. In addition they can produce more units, which are then sold to the residual demand on the spot market. The spot market prices are simply determined by the residual demand function. The forward market prices are determined by a forward market demand function reflecting the assumption that buyers expect equilibrium play in the spot stage for any given residual demand.

We find that forward markets enhance competition and efficiency. Total production levels in the AV treatments are systematically higher than under Cournot, and prices are significantly lower. Consumer surplus increases by 28.4% in the Two-seller treatments and by 67.4% in the Four-seller treatments. However, our experimental results also indicate that the effect of introducing a forward trading institution is not as strong as theory suggests. Our experimental evidence rejects the hypothesis that a forward market is as effective as increasing the number of firms on the market. Instead, it proves to be far more effective to change the number of competitors in the Cournot markets from two to four.

The remainder of the paper is organized as follows. In the next section we study AV's two-stage model for the case of n symmetric firms. From this we derive the relevant comparative static predictions for our experimental treatments, which are described in detail in Section 3. Section 4 presents the results of the experiment. We discuss the results and provide some concluding remarks in Section 5.

2 Theoretical background

In the following, we present AV's model for the case of an n-firm oligopoly. However, we restrict the analysis to a two-stage setup (one round of forward trading plus a spot market round), which is the relevant case in our experimental design and we focus on symmetric equilibria.

First, consider the case of pure spot market trading. Firms produce a single homogeneous good and, facing linear cost and demand schedules, they simultaneously choose their production levels to maximize

$$\pi_i(x_i) = (A - X)\,x_i - cx_i \tag{1}$$

where x_i is the quantity chosen by firm i, $X = \sum_{j=1}^{n} x_j$ represents total production in the market, A is the intercept of the inverse demand function, and c is a constant marginal cost. In equilibrium, aggregate production is

$$X^* = \frac{n}{n+1}(A - c) \tag{2}$$

and the equilibrium market price is

$$p^* = \frac{A + nc}{n+1} \tag{3}$$

Now assume that firms first go on the forward market before trading on the spot market. Note that information is complete so that risk-hedging does not constitutes a rationale for forward trading.[3] As we shall see, when market participants have access to a forward market they trade units of the good prior to the production stage for strategic reasons. First, sellers simultaneously choose their forward positions f_i, the aggregate forward quantity $F = \sum_{j=1}^{n} f_j$. A forward price p_F then emerges as a result of the market process. The way p_F is determined will be explained later. For the time-being, what is important to keep in mind, is that the firms take p_F as well as the forward contracts as given when they choose the spot quantities.

After signing the forward contracts, firms enter the production stage and face the following payoff function.

[3] See Allaz (1992) for a model incorporating uncertainty.

$$\pi_i(f_i, s_i) = p_F f_i + (A - F - S) s_i - c(f_i + s_i) \quad (4)$$

where s_i is the number of units firm i sells on the spot market and $S = \sum_{j=1}^{n} s_j$ is the aggregate output sold at the spot market. The first term in equation (4) represents firm i's revenues from its sales on the forward market, the second term represents its revenues from spot market sales and the last term represents its production costs. Important for the results is the fact that in this second stage of the game, the covered forward sales become strategically irrelevant for the competitors. The firms, being committed to deliver the forward quantities at the agreed contract price, now compete only for the residual demand on the spot market. Any quantity proposed on the spot will not reduce the price of the units that have already been sold forward. With $x_i = f_i + s_i$ and $X = F + S$, equation (4) can be rewritten as

$$\pi_i(x_i) = p_F f_i + (A - X)(x_i - f_i) - cx_i \quad (5)$$

Thus, in the spot stage, firms simultaneously choose production levels to maximize profits as displayed by equation (5). The forward obligations are fulfilled as agreed in the first stage, and any units exceeding the contracted production are offered on the spot market. In equilibrium this leads to a spot market price of

$$p_s^* = \frac{A + nc - F}{n + 1} \quad (6)$$

Because equilibrium behavior is expected for the spot stage, buyers are not willing to agree to a forward contract specifying a price above p_s^*. On the other hand, if $p_F < p_s^*$, a speculator would be willing to sign all available forward contracts. Therefore, the forward market equilibrium must yield a contract price equal to the spot price. A comparison between equations (3) and (6) shows that the market price in the two-stage setup is lower for any positive quantity signed in forward contracts. Moreover, firms have an individual strategic incentive to make forward transactions. To see this, consider once more firm i's total profits over both stages. Because $p_F = p_s^*$ these can now be written as

$$\pi_i(f_i) = \left(\frac{A - c - F}{n + 1}\right)\left(f_i + \frac{A - c - F}{n + 1}\right) \quad (7)$$

The first bracketed expression depicts the firm i's per unit profit, that is, the market

	Cournot Spot market only	AV Forward & Spot markets
Total forward quantity	–	$F^{AV}(n) = \left(\frac{n^2-n}{n^2+1}\right)(A-c)$
Total spot quantity	$S^C(n) = \left(\frac{n}{n+1}\right)(A-c)$	$S^{AV}(n) = \left(\frac{n}{n^2+1}\right)(A-c)$
Total production	$X^C(n) = \left(\frac{n}{n+1}\right)(A-c)$	$X^{AV}(n) = \left(\frac{n^2}{n^2+1}\right)(A-c)$
Price	$p^C(n) = \frac{A+nc}{n+1}$	$p^{AV}(n) = \frac{A+n^2c}{n^2+1}$
Profit per firm	$\pi_i^C(n) = \left(\frac{A-c}{n+1}\right)^2$	$\pi_i^{AV}(n) = n\left(\frac{A-c}{n^2+1}\right)^2$
Consumer surplus	$\theta^C(n) = \frac{1}{2}\left(\frac{n(A-c)}{n+1}\right)^2$	$\theta^{AV}(n) = \frac{1}{2}\left(\frac{n^2(A-c)}{n^2+1}\right)^2$

Table 1: Theoretical results

price minus the per unit production cost. The second part is firm i's production level with the first term being i's forward position and the second term being the anticipated spot quantity. On the one hand, forward contracts signed by firm i put the market price under pressure and reduce i's expected spot sales. However, these negative effects are mainly external: firm i's competitors must share these costs. On the positive side, by signing forward firm i gains directly by an immediate increase in sales. Firm i's optimal response function is

$$f_i = \left(\frac{n-1}{2n}\right)(A - c - F_{-i}) \tag{8}$$

where $F_{-i} = \sum_{j=1, j\neq i} f_j$.

If player i's competitors refrain from forward contracting, i.e. if $F_{-i} = 0$, the firm would obtain a Stackelberg leadership position by producing $x_i = \frac{A-c}{2}$. However, this is not an equilibrium. Solving for the equilibrium forward position yields

$$f_i^* = \left(\frac{n-1}{n^2+1}\right)(A-c). \tag{9}$$

From this, the equilibrium levels for all variables can be immediately derived. Table 1 summarizes the results and compares them with the case of pure spot market trading.

A number of comparative-static predictions can be derived from this Table.

1. An increase in the number of firms implies lower prices and higher output under both market institutions, i.e. $X^C(N) > X^C(n)$ and $X^{AV}(N) > X^{AV}(n)$ if and only if $N > n$.

2. For a given number of competitors, introducing a forward market enhances competition, i.e. $X^{AV}(n) > X^{C}(n)$.
3. In terms of total production, prices, total profits, and consumer surplus adding a forward stage has the same effect as squaring the number of competitors, i.e. $X^{AV}(n) = X^{C}(n^2)$.

Thus, compared to the rise in competitive pressure caused by an increase in the number of firms, the competition-enhancing effect of forward trading is strong. The forward market effect is a reminiscent of the prisoner's dilemma. If all competitors refrain from forward trading they achieve moderately high payoffs. However, by deviating from this strategy a single firm can increase its profits considerably by gaining a leadership position at the expense of its competitors. In the non-cooperative equilibrium solution of this game, all firms make forward transactions at relatively low profit levels.

3 Design of the experiment

In this section, we describe the design and the procedures used in our laboratory experiment to test the predictions derived from AV's model.

3.1 Treatments and Predictions

The experiment consisted of thirty-two independent multi-period oligopoly markets with symmetric firms and linear demand. We compared two market institutions, one where firms could only sell on a spot market (Cournot markets, henceforth C) and one where firms first had access to a forward market and then to a spot market (AV markets, henceforth AV). As a second treatment variable we studied the effect of varying the number of firms (two versus four). Thus, we employed four treatments in a 2x2 design as shown in Table 2. In all markets human sellers chose quantities with simulated buyers determining the market price. The treatment comparisons are based on a between-subjects design.

To simplify the decision problem for the subjects we abstracted from production costs (i.e $c = 0$). This does not alter the key characteristics of the theoretical

	Two sellers	Four sellers
Cournot: Spot market only	C2	C4
AV: Forward & Spot markets	AV2	AV4

Table 2: Four treatments

predictions. In all treatments participants could choose quantities from a finite grid of whole numbers between 0 and 1000. The demand side of the market was modeled with the computer buying all supplied units according to an inverse demand function. In the Cournot sessions the price was computed as

$$p_t = \max\{1000 - X_t, 0\} \tag{10}$$

where X_t denotes the total quantity in period t.[4]

Using automated demand is a standard procedure in Cournot experiments, but in the forward stage of the AV sessions it raises the question of how the model's perfect foresight assumption should be implemented. In our design we provided the artificial consumers with the expectation of Cournot play in the spot stage, exactly as in AV's model. This implies that the forward price was determined by equation (6) or, for the parameters we used, by

$$p_t^F = \max\left\{\frac{1000 - F_t}{n+1}, 0\right\} \tag{11}$$

where n is the number of firms (either two or four) and F_t is the total forward quantity chosen in period t.[5] The spot market price in the AV sessions was determined by Equation [11]. Payoffs were computed as the sum of revenues from the forward and spot markets.

The discreteness of the permissible choice space in the experiment introduces multiple, partly asymmetric equilibria for the stage games of some of our treatments (C2 and AV4). However, because the grid is relatively fine the equilibria of the discrete game are all very close to the equilibria of the continuous case. Hence, we use the latter for our point predictions. Table 3 lists the predictions derived from the model for all treatments. In Table 4 we have listed the predicted outcomes for

[4]The fact that we supplied each firm with the capacity to cover the whole demand makes it possible for total production to exceed 1000 units (in which case the market price is defined as zero). This has some implications for our statistical test procedures as explained in detail below.

[5]We refer to a "period" as the complete cycle consisting of the forward stage and the spot stage.

	C2	C4	AV2	AV4
Total forward quantity	_	_	400	706
Total spot quantity	_	_	400	235
Total production	666	800	800	941
Price (e$)[7]	3.33	2.00	2.00	0.59
Profit per firm (e$)	1111.1	400.00	800.00	138.80
Consumer surplus (e$)	2222.22	3200.00	3200.00	4429.07

Table 3: Equilibrium predictions for all treatments

	Collusion		Perfect competition	
	C markets	AV markets	C markets	AV markets
Total forward quantity	_	0	_	1000
Total spot quantity	_	500	_	0
Total production	500	500	1000	1000
Price (e$)	5	5	0	0
Total profits (e$)	2500	2500	0	0
Consumer surplus (e$)	1250	1250	5000	5000

Table 4: Benchmarks of collusion and perfect competition

two further important theoretical benchmarks, the cases of collusion[6] and perfect competition.

3.2 Experimental procedures

The computerized experiments were conducted in March 2002 at the Centre for Decision Research and Experimental Economics (CeDEx) based in the School of Economics at University of Nottingham. In total, 96 subjects participated, recruited by e-mail after having been randomly selected from a database of about 2000 Nottingham under-graduate students from all subject areas. No subject took part in more than one session and exactly sixteen subjects participated in each session. The participants earned, on average, £9.82 (about 14 US$ or €15.90 at the time of the experiment). The Cournot sessions lasted about one hour each, the AV sessions about two hours each, including the time spent reading the instructions. In total we conducted six sessions: one C2 session and one AV2 session with eight independent markets each, and two four-seller sessions in each the Cournot and the AV

[6]Perfect collusion in the AV setting involves two steps: (i) sellers must refrain from trading on the forward market, and (ii) they must then choose collusive quantities on the spot market.

treatment, with four independent markets per session. In all treatments subjects interacted for thirty periods, which was commonly known.[8]

Subjects were paid according to their total profits earned during a session plus a £2 flat fee. We used an artificial laboratory currency denominated in "experimental dollars" (e$) where 1 e$ is equal to 100 eCents. Since the predicted earnings differ substantially across treatments and since it could be expected that the AV sessions would last considerably longer than the Cournot sessions, we adjusted the exchange rates according to the treatments. We chose them such that the expected cash earnings under Nash would be around £13 in both AV treatments and around £8 in both Cournot conditions (including the flat fee).[9]

When the subjects arrived at the laboratory they were randomly seated at computer terminals. Communication between subjects was not permitted throughout the session and dividers separated the individual workplaces so that the subjects could not see each other's screens. At the beginning of a session the instructions were handed out and then read aloud by the experimenter.[10] The experiment itself was fully computerized with subjects entering choices on their terminals. Furthermore, to make the incentive structure of the situation more transparent we equipped our software with a "results calculator", which participants could use to experiment with hypothetical decisions prior to submitting a real choice.[11]

After all participants had submitted their choices in a decision round the computer calculated market prices and profits. At the end of each decision round – i.e. at the end of a period in the Cournot treatment and at the end of the forward stage or the spot stage in the AV treatment – the participants were shown a "Results Screen" on their terminals. This screen displayed the subject's own choice, total production in the relevant market, the market price and the profits. Before the participants entered the next stage/period a "History Screen" was shown listing all previous outcomes in the market in a summarized form.[12]

Before starting the decision-making part of a session, the sixteen participants were randomly allocated to either eight (two-seller conditions) or four (four-seller

[8]Note that thirty periods imply thirty decision rounds in the Cournot treatments but sixty decision rounds in the AV treatments, since the introduction of a forward market creates a two-stage game.

[9]The exact exchange rates were 60 eCents (C2), 20 eCents (C4 and AV2) and 4 eCents (AV4) per British Penny.

[10]A copy of the instructions can be found in Appendix A.

[11]A detailed description of the way the results calculator worked is given in Appendix B.

[12]Appendix C contains screenshots from different screens. The software was written in Visual-Basic.

conditions) separate markets. We used a fixed-group procedure; i.e. the matchings were not changed during the thirty periods. The subjects were informed of this, but they were also told that we would not reveal to them, neither during nor after the session, with whom they were interacting during the experiment. Since each market has a commonly known finite horizon, equilibrium predictions are unaffected by repetition. Nevertheless, using a fixed-group procedure instead of random matching can induce repeated game effects and facilitate collusive strategies, especially in duopolies. However, the assumption that oligopolists interact repeatedly is indisputably a natural starting point despite the fact that AV's model is static. In other words, the point made by AV can only be relevant for real markets if it does not break down in a dynamic setting with the same market participants competing over time. Harvey and Hogan (2000) argue that the AV setup is not realistic since it does not take into account that firms interact many times in most real markets. Thus, the fixed-matching procedure makes our test more challenging for AV's theory, but also more realistic.

4 Experimental results

Table 8 (in the Appendix) provides a summary of the data at an aggregate level, listing overall averages and standard deviations for each treatment. To formally test the predictions of the model, we only employ non-parametric tests at the market level. Since we use a fixed-group design, each market generates one independent observation. Our data analysis focuses on three sets of questions.

1. Does an increase in the number of firms enhance competition and efficiency in both trading institutions?

2. Does forward trading enhance competition and efficiency in both the duopoly and the four-seller oligopoly? Moreover, is the introduction of a forward market as effective as doubling the number of competitors?

3. How does the data fit the theoretical predictions and does behavior change over time? To what extent and in which way do the players use the forward market?

4.1 Test procedures and variables

We use a one-sided Wilcoxon rank-sum test to test the comparative static predictions. Our null hypotheses state that changes in either the number of firms or in the market institution do not have an impact on total production or market prices. We test the null hypotheses against the one-sided alternative hypotheses suggested by the model. Moreover, we test for systematic differences between the C4 and the AV2 treatment, but use a two-sided alternative hypothesis because theory does not predict any differences between C4 and AV2. For testing the point predictions we use a two-sided binomial test to assess whether forward/spot quantities and prices are systematically higher or lower than suggested by theory. The following gives a more detailed account of the variables used for our statistical analysis.

The question in which we are ultimately interested is whether and in what way welfare is affected by the treatment variables. A simple indicator of total welfare in a market is average total production. However, this indicator becomes partially flawed when total supply is above 1000 units (total demand) because the excessive part of the production does not increase welfare above the efficient level. Taking the surplus production into account when calculating the average quantity in a market would raise this average, incorrectly indicating a higher welfare level. Thus, when computing the average total quantities for the purpose of making comparisons across sessions, we disregard any excess units above the maximum demand that may occur in some markets in some periods, and treat production levels above 1000 units as equal to 1000 units. This makes our comparative-static tests more conservative. However, note that we do not use this procedure for testing the point predictions, where excessive supply should be fully accounted for as a deviation from theory. To make this distinction clear we will use the term "truncated quantities" when referring to averages based on the modified production levels.

The second measure we use for the comparative static tests is the average market price, which is a simple indicator for competitiveness and consumer welfare. Using this additional measurement for inter-market comparisons would be redundant in the Cournot treatments, as there is a strict negative relationship between total quantities, our first test variable, and prices. However, this is not the case in the AV treatments where the market price and the distribution of welfare depend on the number of units sold in the forward stage and in the spot stage, respectively. If the firms use both stages, they can even make profits when total production covers the whole demand of 1000 units. The reason is that buyers do not expect perfectly

		Truncated production		Average market prices	
	market	Cournot	AV	Cournot	AV
Two firms	1	628.73	584.20	3.71	4.11
	2	541.70	742.03	4.58	2.45
	3	652.57	800.17	3.47	2.02
	4	620.50	814.47	3.80	1.99
	5	697.63	714.00	3.02	2.62
	6	683.53	713.20	3.16	2.83
	7	594.17	705.13	4.06	2.32
	8	675.00	633.40	3.25	3.65
Four firms	1	869.67	936.77	1.30	0.60
	2	913.83	946.67	0.86	0.54
	3	769.63	936.40	2.30	0.70
	4	906.97	967.87	0.93	0.35
	5	794.23	985.30	2.06	0.31
	6	814.67	957.80	1.85	0.43
	7	871.37	910.33	1.29	0.90
	8	828.87	962.77	1.71	0.46

Table 5: Average truncated production levels and market prices

competitive prices on the spot market and are therefore willing to pay higher-than-competitive prices when buying on the forward market. Thus, the introduction of a forward market can have different effects on total welfare and the distribution of consumer surplus and profits, respectively. As our second test variable we therefore compute, for each period, the average of the forward price and the spot price, weighted by the number of units sold in each stage, and we then average the weighted prices across all periods. In the Cournot conditions we simply calculate the average prices in the different markets across periods.

4.2 Comparative-static findings

Table 5 lists the average truncated[13] production levels and the average prices for all markets and treatments.

Question 1: Do more firms imply higher quantities and lower prices? The answer is a very clear yes. When the number of sellers is changed from two to four, total (truncated) production increases by 32.9% in the Cournot markets and

[13]It is worth noting that the occurrence of excessive supply is asymmetric across treatments – it is virtually non-existent in the two-seller sessions but it does play a role in both four-seller treatments.

	Average total production		Average market prices	
versus	C4	AV2	C4	AV2
C2	H_1: $C4 > C2$ p-value: 0.0001	H_1: $AV2 > C2$ p-value: 0.0141	H_1: $C4 < C2$ p-value: 0.0001	H_1: $AV2 < C2$ p-value: 0.0141
AV4	H_1: $C4 < AV4$ p-value: 0.0002	H_1: $AV2 < AV4$ p-value: 0.0001	H_1: $C4 > AV4$ p-value: 0.0002	H_1: $AV2 > AV4$ p-value: 0.0001
AV2	H_1: $C4 \neq AV2$ p-value: 0.0018	_	H_1: $C4 \neq AV2$ p-value: 0.0018	_

Table 6: Wilcoxon rank sum test statistics, based on Table 6 (Ho: no change)

33.2% in the AV treatments. At the same time, average prices decrease by 57.6% (Cournot) and 80.5% (AV). Moreover, Table 5 shows that even the highest average production level among the two-seller markets is still lower than the lowest average production level among the four-seller markets. This is true for both the Cournot and the AV treatment, and we find the exact opposite result for average prices under both market institutions. Table 6 reports the results of the statistical tests.

Question 2: Does the introduction of a forward market stage enhance competition? Once more, our data produces clear results in favor of the theoretical prediction though the effect is somewhat weaker. The introduction of the forward market in the duopoly raises, on average, total quantities by 12.2% and reduces prices by 24.3%. In the case of four firms the increase in production is 10.8%, and the decrease in prices is 65.2%. Formal statistical results can once more be found in Table 6.Thus, we reject the null hypotheses in favor of the central theoretical predictions. At the same time, however, the data also produces strong evidence that the out-comes in four-seller Cournot condition and in the two-seller AV treatment are not identical as predicted by the model. In contrast to the prediction the two-sided rank-sum test indicates that total production in C4 is systematically higher and prices are systematically lower than in AV2. Thus, the introduction of a forward trading institution is not as effective as increasing the number of competitors from two to four. Figure 1, showing the theoretical and average price levels in all four treatments over time, illustrates the empirical differences between AV2 and C4 in graphical form. Average prices in the two-seller AV and the four-seller Cournot condition differ from the theoretical prediction as well as from each other. In contrast, the AV4 prices are relatively close to the predicted level. Based on this, one might hypothesize that the four-seller AV results could be similar to the outcomes of a sixteen-seller Cournot treatment, as would be predicted by theory. In fact, some experimental evidence indicates that markets with more than two firms tend to be more competitive than theoretically expected, and it has been suggested that "these deviations are increasing in the number of firms" (Huck et al., 2001).

4.3 Theoretical vs. observed production and price levels

In this section, we examine in more detail to what extent our data fits the theoretical predictions in absolute terms (Question 3). Figure 2 displays the average production levels[14] in all 32 markets, together with the corresponding theoretical predictions (dotted lines).

[FIGURE 2 HERE]

The figure suggests that quantities in the two-seller treatment tend to be lower than predicted, whereas they are generally above the theoretical levels in both four-seller conditions. However, when applying a sign test to the data, only in C4 do we detect a systematic, i.e. statistically significant, deviation from the predicted production level. With regard to prices, only in AV2 does the sign test detect a statistically significant deviation from the prediction (see Table 8 for details). Thus, in addition to our above finding that C4 and AV2 are significantly different from each other, there is also some evidence in our data suggesting that C4 and AV2 both differ from the theoretical prediction, with C4 being more and AV2 less competitive than predicted.

Generally, our findings in the benchmark treatments replicate previous experimental results on Cournot competition,[15] but do sellers in the AV treatments make use of the forward market as predicted? The data indicate that the discrepancies between theory and data, analyzed separately for the forward and the spot stage, are more severe in AV2 than in AV4. While deviations in the four-seller markets do not seem to be systematic, we find that in seven of the eight AV2 groups the forward quantities are lower, and the spot quantities higher, than predicted (p-value: 0.070). The observation that markets characterized by relatively low forward quantities tend

[14] As explained above, the quantities reported in this subsection are not "truncated". One consequence of this is that some markets in Figure 2 yield average production levels above 1000 units. This does not imply that these markets are fully efficient or produce outcomes that are more efficient than in other markets, however. The averages are driven up by relatively few periods with a very high excessive supply.

[15] See Huck et al. (2001) for an overview.

Number of markets with	average quantities are below prediction	above prediction	p-value*	average market prices are below prediction	above prediction	p-value**
Overall						
C2	5	3	0.727	3	5	0.727
C4	1	7	0.070	6	2	0.289
AV2	6	2	0.289	1	7	0.070
AV4	2	6	0.289	5	3	0.727
Forward stage						
AV2	7	1	0.070	1	7	0.070
AV4	3	5	0.727	5	3	0.727
Spot stage						
AV2	1	7	0.070	1	7	0.070
AV4	5	3	0.727	5	3	0.727

Table 7: Predicted vs. observed average quantities and prices

to produce high spot quantities and vice versa indicates that subjects respond to different levels of residual demand on the spot market (generated by different levels of forward market supply). This is in a sense consistent with theory, which predicts Cournot outcomes on the spot market for any given forward market choice. To illustrate in more detail how choices in the second stage correlate with the outcomes in the first stage, we have plotted the total spot quantities against the total forward quantities in Figures 3a and 3b, for all markets and periods. The figures also contain relevant theoretical benchmarks: first, the "ex ante" point prediction for both stages ("equilibrium prediction"), and second, the "ex post" prediction (i.e. after observing the empirical forward stage results) for the spot market ("Spot stage Cournot path").

[FIGURE 3 HERE]

Figures 3a and 3b reveal that the exact point predictions do not deliver a very accurate description of actual behavior. On the other hand, the data points are clearly scattered around the spot stage Cournot paths, which all but approximate the actual linear trend lines for the data. Futhermore, the point predictions seem to satisfactorily describe average behavior, in particular in the four-seller markets.[16]

[16] The predicted total quantities in AV4 are 706 units and 235 units for the forward and the spot market respectively. The corresponding empirical averages are 768 and 239.

The determination of the forward market price in the model as well as in our experiment is based on the expectation of equilibrium play in the spot stage (ex post prediction). If firms do choose Cournot quantities on the spot market, forward prices and spot prices are identical in every forward market contingency and not only along the equilibrium path.[17] Figure 4 compares the theoretical with the empirical forward and spot prices and illustrates some distinctive differences between the two-seller and the four-seller markets. The pattern in the AV2 time series indicates that, on average, the duopolists choose (a) lower than ex ante predicted quantities in the forward stage (forward prices above theoretical level) and (b) lower than ex post predicted quantities in the spot stage (spot prices above forward prices). These outcomes are consistent with partly collusive behavior in both stages. In contrast, average prices in AV4 are relatively close to the theoretical levels as well as each other.

[FIGURE 4 HERE]

An interesting question is whether the discrepancies between point predictions and data decrease over time. We have little evidence of this; in fact, behavior is remarkably stable over the thirty periods. For example, while the production levels in four of the eight AV4 markets move closer to the prediction in the second half of the experiment, the opposite is the case for the other four markets. This is true for forward quantities, spot quantities and total quantities, and we get similar results for the other treatments, when comparing the outcomes of the second to the outcomes of the first half of the sessions.

5 Conclusions

In this paper, we report the results of a laboratory test of Allaz and Vila's (1993) model of quantity competition in two-stage markets. Treatments with two and four sellers per market were conducted and compared with results from benchmark conditions of two and four competitors in standard Cournot markets. Our subjects respond strongly to the treatment variables with quantity changes in the predicted

[17] See Ferreira (2001) for a detailed discussion.

directions leading to the corresponding price changes. Furthermore, our data supports Allaz and Vila's hypothesis that forward markets promote competition. However, the predicted equivalence of introducing a forward market and increasing the number of sellers from two to four is strongly rejected. Our findings indicate that this is due to the AV2 markets being less competitive than predicted by theory as well as the C4 markets being more competitive than predicted. In this sense the competition-enhancing effect of the forward market is weaker, and the effect of adding more competitors stronger, than predicted by the theoretical comparative analysis.

An obvious candidate for an explanation of the differences between the two-seller and the four-seller conditions that we observe is the notion that implicit collusive agreements are easier to achieve with two than with four competitors. Thus, as suspected by Harvey and Hogan (2000), it seems that repeated play in a duopoly makes a tendency towards collusive outcomes likely. However, despite this our data also suggest that forward trading does have a clear and substantial positive effect on competition, even in two-seller markets.

Experiments may play a significant role in the empirical research on forward trading because they can disentangle different reasons for forward transactions, which may all be relevant in the field at the same time. In particular, risk-hedging motives are undeniably relevant in real forward markets and may conceal or overlap with strategic motives. Furthermore, there is a literature (e.g. Newbery, 1997, and Lien, 2000) that considers the possibility that the forward market effect may help incumbent firms deter entry. In the laboratory the motives for forward trading and their interactions can be systematically studied in a controlled environment. Experiments can also be used to evaluate the importance of particular factors relevant for the applicability of AV's theory to real markets which have been identified in recent theoretical developments. For example, Hughes and Kao (1997) and Ferreira (2001) re-examine the model and discuss the role of observability in AV's approach, showing that the improvement in efficiency may break down if firms cannot observe each other's forward positions. On the other hand, Ferreira also finds that the competition-enhancing effect may be even stronger than in AV if observability is partial. Experimental investigations can help assess the importance of these and other theoretical arguments. Thus, the present study should only be viewed as a first step in experimentally investigating how serious market designers should take forward trading institutions as a building block for improving the efficiency on real-world markets.

Instructions

{...}:Two-seller conditions only
* *: Cournot conditions only

[...]:Four-seller conditions only
#...#: AV conditions only

Welcome! This session is part of an experiment in the economics of decision making. If you follow the instructions carefully and make good decisions, you can earn a consider-able amount of money. At the end of the session you will be paid, in private and in cash, an amount that will depend on your decisions.

General Rules

The session will consist of 30 periods, in each of which you can earn "experimental dollars" (e$). At the end of the session you will be paid £2 plus an additional amount based on your total e$ earnings from all 30 periods. Your e$ earnings will be converted to cash using an exchange rate of *{60e$}[20e$]*#{20e$}[4e$]# = 1p. Notice that the higher your e$ earnings are, the more cash you will receive at the end of the session.

There are sixteen people in this room who are participating in this session. It is important that you do not talk to any of the other people until the session is over.

In this experiment each person in the room represents a firm. During the session [four]{eight} different markets will operate and at the beginning of the session the computer will randomly allocate you to one of these. Similarly, the other firms will be randomly allocated to markets. In your market there will be you and {one}[three] other firm[s]. Your e$ earnings will depend on your decisions and those of the other [three] firm{'s}[s']. The firm[s] you are matched with will be the same throughout this session but you will not learn the identity of the person[s] representing [these]{this} firm[s].

Description of a period

#Each of the 30 periods consists of two successive stages. The first of these is called Stage A and the second is called Stage B. We will first describe Stage A, then Stage B.

Stage A#

At the beginning of *each of the 30 periods* #Stage A# you have to decide how many units of a good to produce. You make your decision by entering a number (any whole number between 0 and 1000) on your terminal. After all firms have made their decisions, the computer will calculate your profits for *that period* #Stage A#.

Your profits will be equal to the number of units you produce times the market price.

The market price will depend on how many units you and the other firm[s] in your market have produced in total. We will call the total number of units produced in your market "Total Production". The computer will calculate the market price in *a period* #Stage A# using the following formula.

$$\text{Price} = 1000 - \text{Total Production}$$

$$\# \quad \left\{\text{Price A} = \tfrac{1000\ -\ \text{Total Production in A}}{3}\right\}$$

$$\left\{\text{Price A} = \tfrac{1000\ -\ \text{Total Production in A}}{5}\right\} \quad \#$$

This formula gives you the market price in eCents (and 1e$ is worth 100 eCents). Thus, if Total Production were zero (that is, if neither you nor the other firm[s] in your market produced anything at all), then the market price would be *1000 eCents (equals 10 e$)*#{333 eCents (equals 3.33 e$)}[200 eCents (equals 2 e$)]#. But note that the higher is Total Production, the lower the market price will be.

If Total Production is equal to or above 1000 units, then the market price is 0. The market price cannot become negative.

At the end of *each period*#Stage A# you will see a "Results Screen". The Results Screen will show how many units you have produced and how many units the other firm[s] in your market {has} [have] produced [in total]. It will further display the Total Production in your market, the market price*,* #and# the profits you have made in #Stage A#*that period and your accumulated profits from all periods. After the Results Screen, and before you enter the next period, your terminal will furthermore display a "History Screen" showing the results from all previous periods in a summarized form.*

#Stage B

Stage B is, in principle, identical to Stage A, but with one important exception. The way the market price is computed in Stage B differs from the way it was computed in Stage A. The market price in Stage B is calculated as (this is again in eCents)

$$\text{Price B} = 1000 - \text{Total Production in A} - \text{Total Production in B}$$

That is, the market price in Stage B depends on both Total Production in Stage A and Total Production in Stage B. As before, the higher Total Production is, the lower the market price will be. Also as before, the market price cannot become negative: if Total Production in Stage B is so high that the formula for Price B would yield a negative result, then the computer sets Price B to zero.

Please also note the following additional rule. If Total Production in the first stage (Stage A) is already equal to or above 1000 units, then there will be no second stage and neither you nor the other firm[s] in your market will be able to produce in Stage B! If this happens your profits for that period are set to zero, and instead of entering Stage B, you and the other firm[s] in your market will be automatically redirected to the next period.

Otherwise, your total profits in a period are computed as the sum of your profits from both stages.

$$
\begin{array}{rc}
 & \text{(Price A)} \times \text{(Number of units you produce in A)} \\
+ & \underline{\text{(Price B)} \times \text{(Number of units you produce in B)}} \\
= & \text{Your Total Earning in a period}
\end{array}
$$

At the end of Stage B, you will again see a Results Screen showing similar information as the Results Screen described above. In addition, it will display your total earnings for that period and your accumulated earnings from all periods. After the Results Screen for Stage B, and before you enter the next period, your terminal will furthermore display a "History Screen" that shows the results from all previous periods in a summarised form.#

Further Instructions

Before you make a decision in *a period*#either Stage A or Stage B# you can experiment with different hypothetical choices by using the "Results Calculator". You can activate the Results Calculator by clicking on a button on the "Decision Making Screen". The Results Calculator is easy to use. You simply enter arbitrary numbers for your own production and the production of the other firm[s]. When you press the Enter key, the Results Calculator will show you the resulting market price#s# and your profits for the hypothetical choices.

#When you are in Stage A, the Results Calculator will allow you to enter hypothetical numbers for both stages. When you are in Stage B, the Results Calculator will only allow you to enter hypothetical numbers for Stage B, and it will take the results from the real Stage A as given when calculating Price B.#

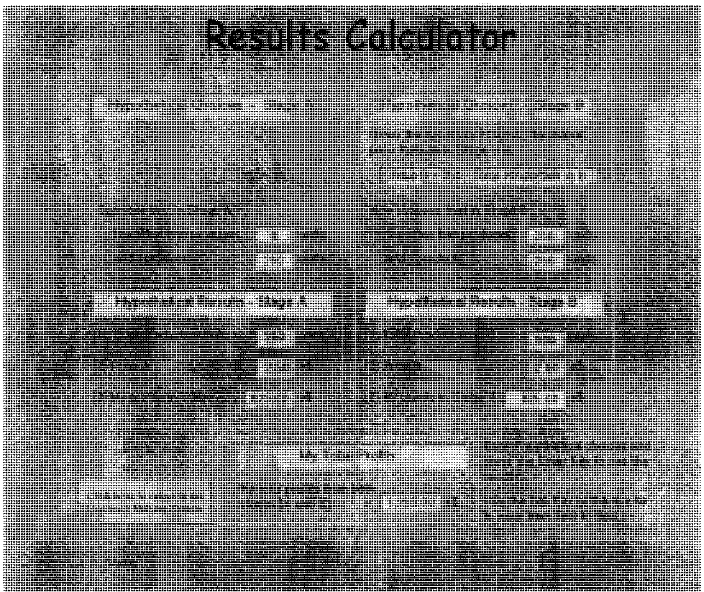
A The results calculator

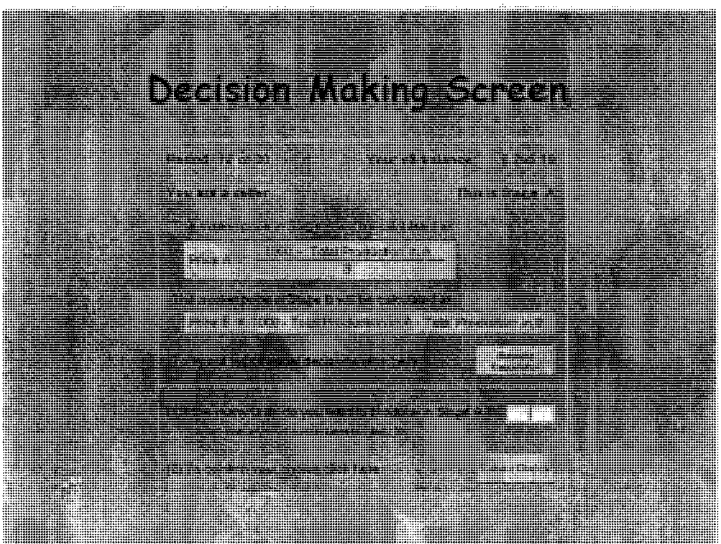
When using the calculator subjects were not constrained by any time restrictions. The basic function of the calculator is similar to the profit calculator used in various experiments (see for example Huck et al., 1999). A difference is that our calculator does not provide a "Max" button computing the best response for given hypothetical choices of other firms. The way the results calculator could be used differed slightly between the Cournot and the AV treatments. The following gives a description of the variant we programmed for the AV sessions; the result calculator used for the Cournot condition is just a simplified version of this. A screen-shot is provided in Appendix C.

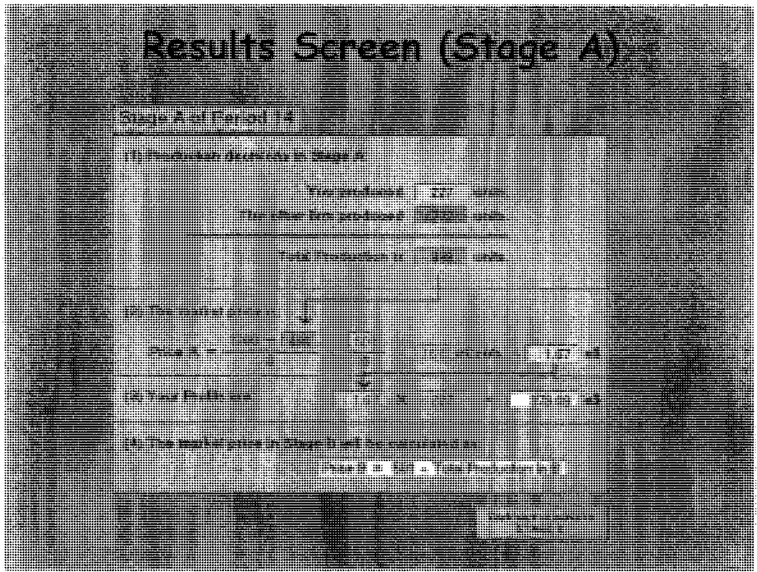
In the forward stage of a period the results calculator worked as follows. First, the participant could enter a hypothetical own quantity and a hypothetical (total) quantity chosen by the other firm(s) in his or her market. After hitting the Enter key, the screen displayed the resulting forward market price and the hypothetical forward profit for the subject. Then, a new window opened, allowing the subject to enter further hypothetical quantities for the second stage (spot market), where the spot price, spot profits and total profits were calculated according to the hypothetical choices of both the forward and the spot stage.

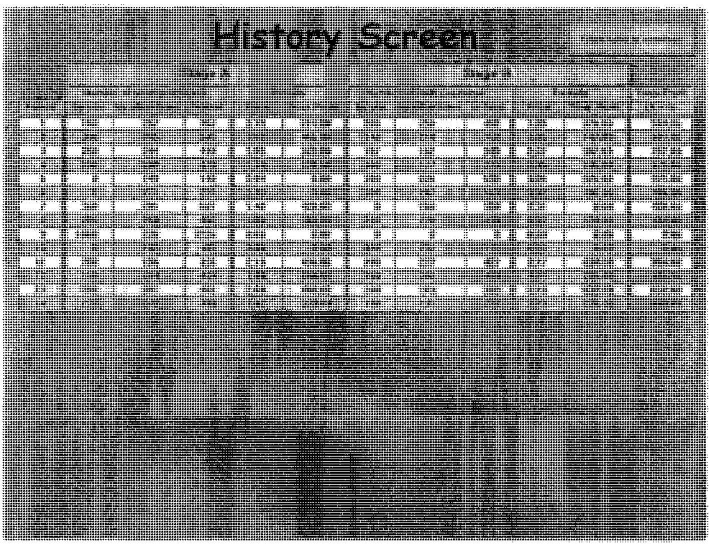
When the experiment was in the spot market stage of a period the subjects were only able to feed the results calculator with hypothetical spot quantities, and computations were then based on these hypothetical decisions and the real forward quantities.

B Screenshots






Results Screen (Stage A)
Stage A of Period 14


History Screen

C Figures and Table

Figure 1: Theoretical and empirical average prices over time

3-period moving averages

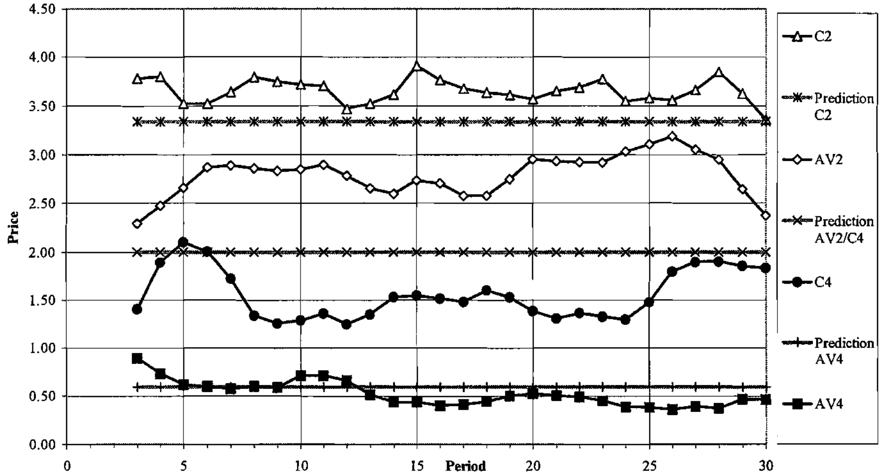


Figure 2: Average total production in all 32 markets

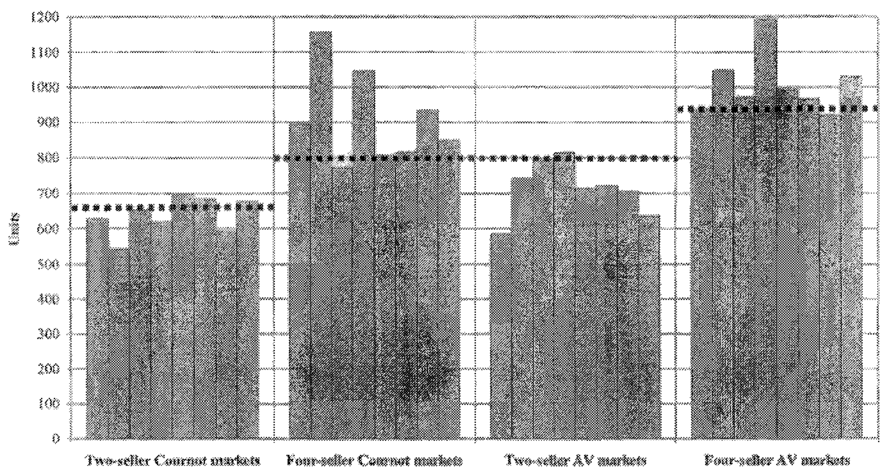


Figure 3a: Forward against Spot Market Quantities

- Two-seller Treatment -

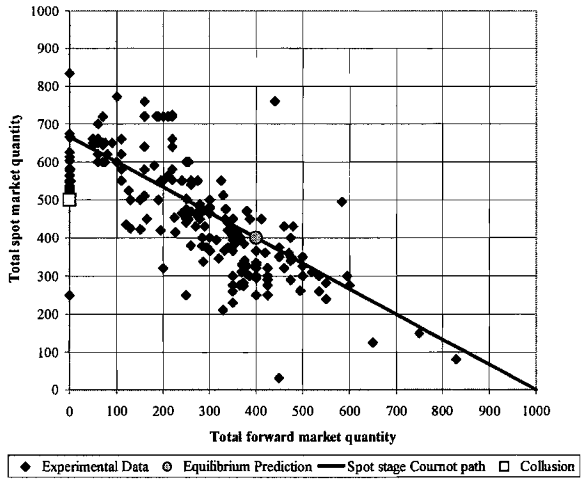


Figure 3b: Forward against Spot Market Quantities

- Four-seller Treatment -

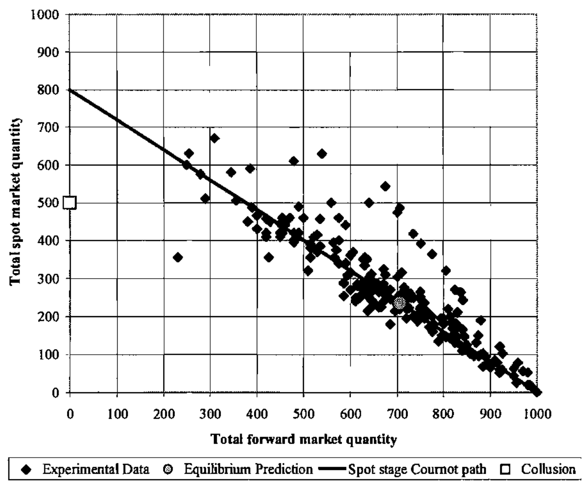
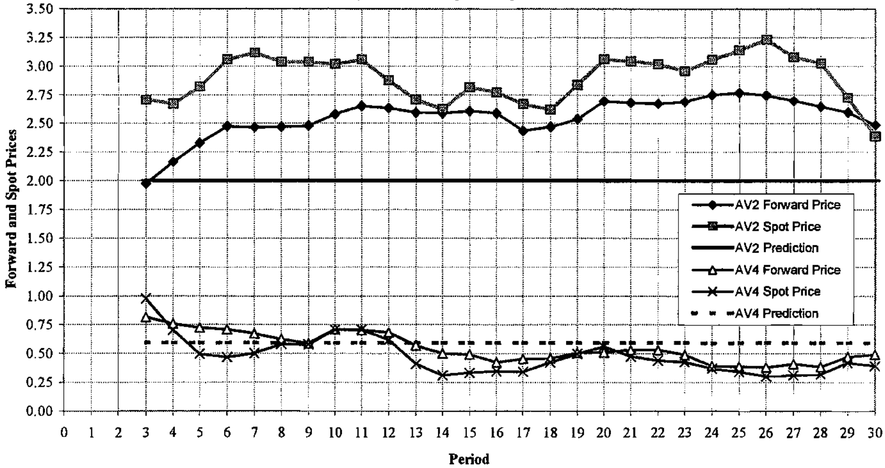


Figure 4: Forward and Spot Market Prices Over Time

(3-period moving averages)



	C2	C4	AV2	AV4
Average forward quantity	_	_	242.34	768.31
			(122.40)	(237.59)
Average spot quantity			472.15	239.08
			(102.02)	(141.41)
Average total quantity	636.73	909.22	714.48	1007.39
	(93.78)	(189.22)	(95.93)	(132.63)
Median total quantity	647	827.5	720	965
Average forward price	_	_	2.52	0.56
			(0.41)	(0.33)
Average spot price	_	_	2.87	0.50
			(0.91)	(0.50)
Average price	3.63	1.54	2.75	0.54
	(0.94)	(0.98)	(0.75)	(0.36)
Average total profits	2198.12	1184.25	1843.75	490.35
	(332.44)	(677.87)	(314.75)	(296.79)
Average consumer surplus	2084.59	3638.64	2676.97	4481.98
	(623.03)	(824.54)	(536.32)	(335.01)
Average total welfare	4282.70	4822.90	4520.72	4972.33
	(328.35)	(161.52)	(269.83)	(48.05)

Table 8: Summary statistics (standard deviation in parentheses)

Chapter IV

Long-term Supply Contracts and Collusion in the Electricity Market[1]

1 Introduction

There are essentially two ways of selling power in deregulated electricity markets; either firms sell power through long-term contracts, or they sell it on the spot (day-ahead) market. Empirical evidence indicates that firms exercise market power on the spot market (see Wolak and Patrick (1997), Wolfram (1998, 1999), Borestein and Bushnell (1999), among others). Some observers argue that this market power could be reduced if more transactions were taking take place through contracts (Wolak, 2000). In the process of redesigning domestic electricity markets, many countries have in fact decided to facilitate the access to contract markets. In March 2001, the New Electricity Trading Arrangements (NETA), which allow bilateral contracts between producers and retail companies, were introduced in England and Wales (Ofgem, 1999). Following the energy crisis in the State of California during the summer of 2000, the Market Surveillance Committee (MSC) recommended an unrestricted ability for utility distribution companies to contract. According to the MSC, such a measure would limit the ability of generators to exercise market power (MSC, 2000, p.15).[2] Regulators thus seem to believe that the market power of generators would be reduced by an enhanced opportunity for firms to contract.

4

[1] I would like to thank Tore Ellingsen, Maria Saez-Marti and seminar participants at the Stockholm School of Economics for valuable comments.

[2] This issue is still under debate in the process of redesigning the Californian electricity market (CAISO, 2002).

Some formal arguments support the view that generators may have less incentive to exercise market power, if they have large contract positions. Intuitively, a firm may obtain a leadership position by selling contracts before going on the spot market. Motivated by this opportunity, all players participate in the contract market and as a consequence compete more aggressively overall. Access to contract markets prior to the spot market may thus decrease the market price (Allaz and Vila, 1993). Several authors have confirmed this result for the wholesale electricity market (von der Fehr and Harbord, 1992; Powell, 1993; Newbery, 1998; Green, 1999; Wolak, 2000).

A central feature of the analysis of Allaz and Vila is that it is based on a framework with a finite horizon. As a result, the access to a contract market gives rise to a situation reminiscent of the prisoners' dilemma; each producer has an incentive to offer a contract, but when all producers do so, everyone is worse off. The repeated nature of electricity markets raises the question of whether Allaz's and Vila's result is applicable to that market (Borestein and Bushnell, 1999 or Harvey and Hogan, 2000).[3]

The purpose of this paper is to check the robustness of the argument that access to contract markets reduces the market power of generators. In particular, it investigates the sensitivity of this result with respect to the assumption of a finite horizon. We consider a model where two firms initially offer a long-term supply contract before repeatedly interacting on the spot market by choosing prices. Both firms offer retailers the opportunity to sign a contract, which stipulates a quantity of electricity to be bought in every future period at a ceiling spot price. That is, in every period, the retailers commit to buy the contracted quantity at the prevailing spot market price, unless this price is higher than a threshold level specified in the contract; if so, the retailers buy the contracted quantity at a price equal to the threshold level.[4]

In this setup, firms enforce price collusion even though they have signed

[3] Electricity prices have decreased in England since 2001, that is, after the introduction of NETA. The empirical study of Bower (2002) suggests, however, that the price reduction was due to changes in market structure rather than increased contracting opportunities.

[4] Such a forward contract, which in the UK is called a one-way Contract for Difference, is used in many electricity markets, mainly as an insurance against events such as spot prices above \$300/MWh. In contrast, the generators bear the risk if the spot price falls below the ceiling spot price; they are not compensated for downward shocks.

contracts stipulating that they will supply large amounts of electricity in the future.[5] In fact, the contract market enables collusion on the spot market when firms would compete in the absence of such a market. The reason is twofold. First, the incentives to deviate are smaller than in classical repeated price games. Indeed, a firm undercutting the monopoly price will earn less than the monopoly profits during the deviation phase, since the rival firm still sells the quantity stipulated in its long-term contract. Second, firms' ability to punish deviators is not reduced relative to classical repeated price games. This is due to the ceiling spot price which implies that the contracted quantities will be sold at the spot market price, if sufficiently low. By pricing at marginal cost on the spot market, a firm thus ensures that its rival earns profits equal to zero in the punishment phase.

The above result is related to the work by Schnitzer (1994) who considers a finitely repeated price game with best-price clauses. She shows that sellers can sustain monopoly profits with a meet or release (MOR) clause, that is a clause according to which the seller promises a rebate to its customers if the purchase price is undercut by competing sellers in the future. The mechanism driving this result is different from the mechanism in the present paper due to the assumption that consumers are strategic. If one seller deviates by undercutting the monopoly price, it triggers a price war in the following period. Anticipating the price war, all consumers buy from the seller offering the MOR clause, since this clause guarantees them a rebate in the future due to the price war. In turn, the initial deviation becomes unprofitable. The analysis in the present paper differs from that by Schnitzer in several respects. First, we consider a game with an infinite horizon and analyze equilibria sustained by irreversible punishments (trigger strategies). Second, we analyze contracts that constituting a combination of the MOR clause and a most favored customer clause.[6] Third, consumers are non-strategic.

A few other papers have analyzed the interaction between contract and spot markets in a dynamic setup. A common feature of these studies is that the contract market is infinitely repeated, while the spot market takes place

[5] See Toro and Fabra (2002) for evidence of collusion on the electricity market.

[6] The most favored customer clause stipulates that buyers are offered a rebate if a seller undercuts its own price in the future. Schnitzer (1994) shows that such a clause is insufficient to enable firms to collude on the monopoly price.

in one period only. Anderson and Brianza (1991) show that firms are able to sustain collusion if they take long positions and corner the market of their opponents. In effect, each firm nominally commits itself to purchase the whole of its rival's output in each contract period. This result is also valid in a model of a price-setting duopoly with differentiated products (Mahenc and Salanié, 2002). In contrast, we consider a setup where the contract is offered once while the spot market is infinitely repeated. This model can be viewed as a version of a repeated game with capacity constraints (Benoit and Krishna, 1987 or Davidson and Deneckere, 1990). Unlike the case with capacity constraints, the contracted quantity must, however, be fulfilled in each spot period.

The paper is organized as follows. Section 2 presents the model. Section 3 solves for equilibria in the repeated price game, taking contracted quantities as given, and Section 4 analyzes the contracting stage. The paper ends with some concluding remarks.

2 The model

Consider two firms (generators), 1 and 2, who produce an homogeneous good (electricity) with identical constant marginal costs c and no capacity constraints. They sell the good to retailers on two successive wholesale markets, namely a contract market (taking place in period $t = 0$) and an infinitely repeated spot market (taking place in all periods $t = 1, 2, 3, ...$). We consider n regional retailers, which, at the national level, have relatively small market shares. For this reason, retailers are assumed to be price takers, i.e. to be non-strategic players. In each period $t \geq 1$, the demand of each retailer is given by $D(p)$, which is a decreasing and continuous function of the price p. Aggregate profits in each regional market are given by $\pi(p) \equiv (p - c) D(p)$ and are assumed to be single peaked with an unique maximum at $p^M \equiv \arg\max_p \pi(p)$. To eliminate the variable n from the analysis, the total demand facing the firms is summarized by the demand $D(p)$ of a single representative retailer.

The timing of the game is illustrated in Figure 1. The spot market takes place in all periods $t \geq 1$. In this market, the firms repeatedly compete for

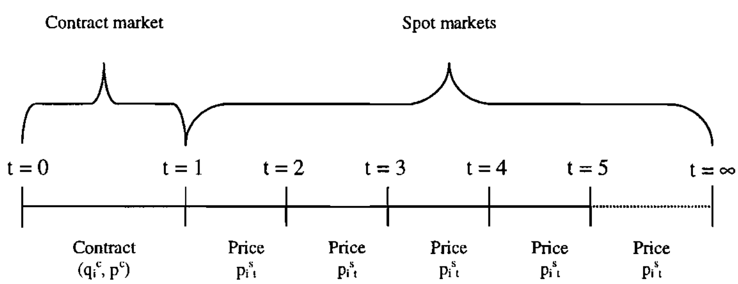


Figure 1: The timing of the game

sales of short duration. More precisely, each firm i $(i = 1, 2)$ posts a price p^s_{it} in each period $t \geq 1$. As a result, the spot price prevailing in period t is determined as $p^s_t \equiv \min\{p^s_{1t}, p^s_{2t}\}$. (Henceforth, the superscript s stands for spot market.)

In period $t = 0$, the contract market opens and the generators simultaneously propose a binding and observable long term supply contract to the retailers. A supply contract between firm i $(i = 1, 2)$ and a retailer specifies a pair (q^c_i, p^c_i), whereby the retailer commits to buy and firm i commits to supply the fixed quantity q^c_i in every subsequent period $t \geq 1$. The price p^c_i constitutes a ceiling spot price whereby the retailer, in each period t, pays the spot price p^s_t for the quantity q^c_i; if $p^s_t > p^c_i$, the generator, however, compensates the retailer for the difference $p^s_t - p^c_i$. (Henceforth, the superscript c stands for contract market.)

The analysis will focus on collusive equilibria such that the firms offer the same ceiling spot price, that is equilibria such that $p^c_1 = p^c_2 = p^c$. We assume that a retailer is willing to sign two contracts (q^c_1, p^c) and (q^c_2, p^c) as long as $q^c_1 + q^c_2 \leq D(p^c)$.[7] In fact, we will focus on equilibrium contracts such that $q^c_1 + q^c_2 = D(p^c)$.

Stage-games: A stage-game consists of a single spot market period where each firm i is already committed to the contract (q^c_i, p^c). Its outcome is

[7]Both generators and retailers are assumed to be risk neutral and hence, there are no risk sharing benefits in signing long-term contracts.

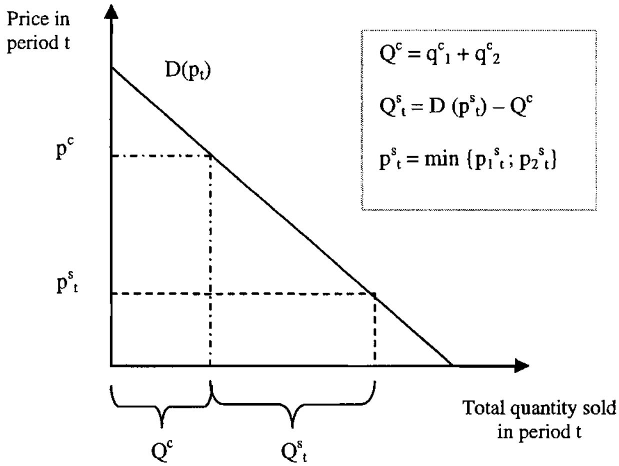


Figure 2: An outcome in a spot-market period

illustrated in Figure 2, assuming that $p_t^s \leq p^c$. $D\left(p_t^s\right)$ is the total quantity sold given the spot price p_t^s. In addition of the contracted quantities $q_1^c + q_2^c = Q^c$, the firms thus supply $Q_t^s = D\left(p_t^s\right) - Q^c$ in period t, that is the residual demand evaluated at p_t^s. For this residual demand, firms compete in prices and retailers buy from the cheaper supplier.

In each stage game a firm earns profits, which are decomposed in two parts, namely the profits derived from the contracted quantity q_i^c and the additional profits derived from the residual demand. These profits depend on the contract positions $\left(\left(q_1^c, p^c\right), \left(q_2^c, p^c\right)\right)$ and on the pair of prices $\left(p_{1t}^s, p_{2t}^s\right)$ chosen by the firms in period t. Below, we provide expressions for these profits assuming that $\max\left\{p_{1t}^s, p_{2t}^s\right\} \leq p^c$. Our focus will be on equilibria in the repeated spot market, which satisfy this inequality. Subsequently, we will check that the firms do not have an incentive to deviate from the proposed equilibrium by choosing a price in period t which exceeds p^c.

Consider the profits earned by firm i in a single stage game, that is the sum of the profits derived from the contracted quantity and the residual demand. If $p_{it}^s = p_{jt}^s \leq p^c$ (where $i, j = 1, 2$ and $j \neq i$), firm i shares the residual demand on the spot market with firm j. Firm i's stage game profits are then given by

$$\begin{aligned}\pi_{it} &= \left(p_{it}^s - c\right) q_i^c + \tfrac{1}{2}\left(p_{it}^s - c\right)\left(D\left(p_{it}^s\right) - q_i^c - q_j^c\right) \\ &= \tfrac{1}{2}\left[\pi\left(p_{it}^s\right) + \left(p_{it}^s - c\right)\left(q_i^c - q_j^c\right)\right]\end{aligned} \qquad \text{if } p_{it}^s = p_{jt}^s \leq p^c. \quad (1)$$

If instead $p_{it}^s < p_{jt}^s \leq p^c$, firm i supplies all the residual demand in addition of its contracted quantity. Its stage game profits are then given by

$$\begin{aligned}\pi_{it} &= \left(p_{it}^s - c\right) q_i^c + \left(p_{it}^s - c\right)\left(D\left(p_{it}^s\right) - q_i^c - q_j^c\right) \\ &= \pi\left(p_{it}^s\right) - \left(p_{it}^s - c\right) q_j^c\end{aligned} \qquad \text{if } p_{it}^s < p_{jt}^s \leq p^c. \quad (2)$$

Finally, if $p_{jt}^s < p_{it}^s \leq p^c$, firm i only sells its contracted quantity q_i^c. Its stage game profits are then given by

$$\begin{aligned}\pi_{it} &= \left(p_{jt}^s - c\right) q_i^c \\ &= \pi\left(p_{jt}^s\right) - \left(p_{jt}^s - c\right)\left(D\left(p_{jt}^s\right) - q_i^c\right)\end{aligned} \qquad \text{if } p_{jt}^s < p_{it}^s \leq p^c. \quad (3)$$

Unlike the traditional repeated Bertrand game, the firm posting the highest price thus earns strictly positive profits as long as $q_i^c > 0$ and $p_{jt}^s > c$. Note also that in equations (1)-(3), the contracted quantity q_i^c is sold for the spot price $p_t^s = \min\left\{p_{1t}^s, p_{2t}^s\right\}$ rather than for the ceiling spot price p^c. This is due to the definition of the ceiling spot price and to the fact that in equations (1)-(3), it is assumed that $\max\left\{p_{1t}^s, p_{2t}^s\right\} \leq p^c$.

Trigger strategies: We restrict our attention to stationary collusive agreements supported by trigger strategies, that is, firms remain at the collusive price unless someone cheats.[8] If at any point time anyone is detected cheating, players revert to the static Nash equilibrium and remain there forever (Friedman, 1971). This greatly simplifies the analysis as well as the exposition and does not restrict the scope of the results.[9] Let π_i^N denote firm i's per period profits on the spot market when the firms post the one period Nash equilibrium price vector $p^N = \left(p_i^N, p_j^N\right)$. Let π_i^A denote firm i's static payoff when the firms stick to the stationary tacit agreement A, that is when

[8] I assume that renegociation and side payment are not possible.

[9] Exactly as in a repeated Bertrand competition, unrelenting trigger strategies are "optimal punishments" in our setting, since the players are at their security levels. Expressed differently, no complex punishment mechanism can enlarge the set of supportable equlibria (Abreu, 1986).

the firms post the collusive price vector $p^A = \left(p_i^A, p_j^A\right)$. Let π_i^D denote firms i's static payoff from unilaterally deviating from A by setting the static best response price $p_i^D\left(p_j^A\right)$.

Given the common discount factor δ and using the one-stage deviation principle for infinite-horizon games (Fudenberg and Tirole, 1991, p.110), a collusive agreement A is sustainable as a subgame-perfect equilibrium as long as neither firm has an incentive to defect unilaterally from the collusive agreement. For firm i, this condition is equivalent to

$$\frac{\pi_i^A}{1-\delta} \geq \pi_i^D + \frac{\delta}{1-\delta}\pi_i^N.$$

This Inequality can be rewritten in terms of the minimum level of the discount factor, $\underline{\delta}_i$, such that firm i has no incentive to deviate from the A, that is,

$$\delta \geq \underline{\delta}_i \equiv \frac{\pi_i^D - \pi_i^A}{\pi_i^D - \pi_i^N}. \tag{4}$$

The agreement A is sustainable if, and only if, neither firm has an incentive to deviate, that is if, and only if, $\delta \geq \underline{\delta} \equiv \max\left\{\underline{\delta}_1, \underline{\delta}_2\right\}$.

3 Equilibrium in the repeated spot markets

Throughout this section, we take the contract positions $\left(\left(q_1^c, p^c\right), \left(q_2^c, p^c\right)\right)$ as given and analyze collusive equilibria in the repeated spot market. As a preliminary, we introduce a benchmark, namely the case when no contract market is available or, equivalently, when contracted quantities are equal to 0. This case corresponds to the classical repeated (Bertrand) price game. The purpose is to define the minimum discount factor $\underline{\delta}^B$ at which the firms can sustain collusion in the absence of a contract market. (Henceforth, the superscript B stands for the Bertrand case.)

Benchmark (Repeated spot market without a contract market): Assume that the firms are able to sustain a collusive price $p^A \in \left(c, p^M\right]$. In equilibrium, aggregate profits in a stage game are then given by $\pi\left(p^A\right)$. If firm i sticks to the agreement, it shares the market with firm j and thus earns $\pi_i^{AB} = \pi\left(p^A\right)/2$. If firm i deviates unilaterally by undercutting p^A, it earns at most $\pi_i^{DB} = \pi\left(p^A\right)$ during the deviation period. In all future periods, the unilateral deviation triggers a retaliation by firm j. As a result, firm i earns the static Nash equilibrium profits in all future periods, that is $\pi_i^{NB} = \pi(c)/2 = 0$. By equation (4), $\underline{\delta}_1^B = \underline{\delta}_2^B = 1/2$ and consequently collusion is sustainable if $\delta \geq 1/2$.

Remark 1 *In the absence of a contract market, $\underline{\delta}^B = 1/2$ is the lowest discount factor that sustains collusion on the spot market (Friedman, 1971).*

We now turn to the more interesting case when the firms attempt to sustain collusion given the contract positions $\left(\left(q_1^c, p^c\right), \left(q_2^c, p^c\right)\right)$ where $q_1^c + q_2^c = D\left(p^c\right)$ and $p^c > c$. The purpose is to find an expression for $\underline{\delta}^C$, that is the lowest discount factor enabling the firms to sustain collusion, and to compare $\underline{\delta}^C$ with $\underline{\delta}^B$.

Assume that the firms are able to sustain the collusive price $p^A \in \left(c, \min\left\{p^c, p^M\right\}\right]$. By equation (4), we need to define firm i's profits by sticking to the agreement (π_i^{AC}), by deviating unilaterally (π_i^{DC}) and its profits in the punishment phase (π_i^{NC}). (Henceforth, the superscript C indicates the value of a variable when the contract positions $\left(\left(q_1^c, p^c\right), \left(q_2^c, p^c\right)\right)$ are given.)

First, consider firm i's payoffs by sticking to the collusive price p^A. By equation (1), we have that

$$\pi_i^{AC} = \frac{1}{2}\left[\pi\left(p^A\right) + \left(p^A - c\right)\left(q_i^c - q_j^c\right)\right] \tag{5}$$

Second, consider firm i's payoffs in the punishment phase. Note that pricing at marginal cost constitutes a Nash equilibrium of the stage game for any pair of contracts $\left\{\left(q_1^c, p^c\right), \left(q_2^c, p^c\right)\right\}$ such that $q_1^c + q_2^c = D\left(p^c\right)$ and $p^c > c$.[10] Consequently, playing the pair of prices $\left(p_{1t}^s, p_{2t}^s\right) = (c, c)$ in all periods of the subgame starting in the beginning of the punishment phase constitutes an equilibrium. By equation (1), we thus have that

$$\pi_i^{NC} = 0. \tag{6}$$

[10]To see this, assume that $p_{jt}^s = c$. If firm i posts a price $p_{it}^s \geq c$, it makes 0 profits. If it posts a price $p_{it}^s < c$, it makes negative profits. Consequently, the price $p_{it}^s = c$ constitutes a best reply to $p_{jt}^s = c$.

Third, consider firm i's payoffs by deviating unilaterally from the collusive price p^A. Let $p_i^D \equiv \arg\max_p \pi_{it|p_{it}^s=p,\, p_{jt}^s=p^A}$ denote the optimal price associated with a unilateral deviation. Clearly $p_i^D < p^A$.[11] By equation (2), it follows immediately that

$$\pi_i^{DC} = \pi\left(p_i^D\right) - \left(p_i^D - c\right) q_j^c. \tag{7}$$

Next, we derive an expression for $\underline{\delta}_i^C$. Insert into equation (4) the expressions for π_i^{AC}, π_i^{NC} and π_i^{DC} in equations (5)-(7) and rearrange:

$$\underline{\delta}_i^C = 1 - \frac{1}{2}\frac{\pi\left(p^A\right) + \left(p^A - c\right)\left(q_i^c - q_j^c\right)}{\pi\left(p_i^D\right) - \left(p_i^D - c\right) q_j^c}. \tag{8}$$

We are now ready to establish the main result of this section.

Proposition 1 *Assume that $q_1^c = q_2^c > 0$. Then firms are able to sustain collusion on the spot market even when $\delta < \underline{\delta}^B$.*

Proof: The proof establishes that $\underline{\delta}^C < \underline{\delta}^B$. Note that $p_1^D = p_2^D$, since $q_1^c = q_2^c$. By equation (8), it follows immediately that $\underline{\delta}_1^C = \underline{\delta}_2^C = \underline{\delta}^C$. Consequently $\underline{\delta}^C < \underline{\delta}^B = 1/2$ if, and only if,

$$\pi\left(p^A\right) / \left[\pi\left(p_i^D\right) - \left(p_i^D - c\right) q_j^c\right] > 1.$$

First, note that $-\left(p_i^D - c\right) q_j^c < 0$, since $q_j^c > 0$ and $p_i^D - c > 0$. Second, note that $\pi\left(p^A\right) > \pi\left(p_i^D\right)$, since $\pi(p)$ is single peaked and $p_i^D \leq p^A \leq p^M$. Consequently the above inequality is fulfilled. ■

A contract market with a ceiling spot price helps to sustain collusion for three reasons. First, when a firm deviates, it only "steals" market shares

[11] To see this, assume that $p_{jt}^s = p^A$ and note that deviating to a price $p > p^A$ does not increase the profits of the deviating firm. Indeed, by sticking to the price p^A, firm i's static profits are equal to $\pi_i^{AC} = \left(p^A - c\right) q_i^c + \frac{1}{2}\left(p^A - c\right)\left(D\left(p^A\right) - q_i^c - q_j^c\right)$ (by equation (1)). If firm i deviates unilaterally to the price $p \in \left(p^A, p^c\right]$, firm i's static profits are equal to $\left(p^A - c\right) q_i^c$ (by equation (3)). Note that $D\left(p^A\right) - q_i^c - q_j^c \geq D\left(p^c\right) - q_i^c - q_j^c = 0$, since $p^A < p^c$. Consequently $\left(p^A - c\right) q_i^c \leq \pi_i^{AC}$. If firm i deviates unilaterally to the price $p > p^c$, firm i only sells its contracted quantity q_i^c at the spot price $p_i^s = p_{jt}^s = p^A$. Consequently firm i's profits are once more given by $\left(p^A - c\right) q_i^c$ and we already know that $\left(p^A - c\right) q_i^c \leq \pi_i^{AC}$.

on the spot market. Indeed, the opponent still sells it contracted quantity. Therefore, the deviation profits are smaller when firms have committed to sell positive quantities through the contract market (that is $\pi_i^{DC} < \pi_i^{DB}$). Second, the fact that the contract specifies a ceiling spot price implies that the firms' ability of punishing deviators is not reduced (that is $\pi_i^{NC} = \pi_i^{NB}$). Third, by focusing on equilibria where $q_1^c = q_2^c$, it follows that the profits from sticking to the collusive agreement are not affected by long term contracts (that is $\pi_i^{AC} = \pi_i^{AB}$). Consequently, long term contracts with a ceiling spot price help to sustain collusion, since their only effect is to reduce the incentives to deviate from the collusive agreement.

The above analysis has also the following interesting implications.

Remark 2 *The larger the quantities specified in the long term contracts, the easier it is to sustain collusion on a given price p^A.*

Recall that the deviation profit is decreasing with the contracted quantities of the opponent. As an immediate consequence if the contracted quantities of both firms increase, both firms have less incentive to deviate.

Remark 3 *The more asymmetric the contracted quantities are, the more difficult it is to sustain collusion.*

To see this consider an initial situation where $q_1^c = q_2^c$. Increase q_1^c and decrease q_2^c by dq. Such a change, reduces firm 2's incentive to deviate (that is $\underline{\delta}_2^C$ decreases). The change, however, increases firm 1's incentive to deviate (that is $\underline{\delta}_1^C$ increases). Since $\underline{\delta}^C = \max\left\{\underline{\delta}_1^C, \underline{\delta}_2^C\right\}$, it follows that the proposed change makes collusion more difficult.

4 Equilibrium in the contract market

In this section, we analyze the firms' initial choices of contracts (in period $t = 0$), before the repeated spot market game starts (in period $t = 1$). We assume that the firms offer contracts of the form analyzed in the previous section, that is contracts, which define a quantity q_i^c and a ceiling spot price p_i^c. The end of this section provides an informal discussion about this assumption.

Assume that the firms wish to cooperate by choosing the same contract (q^c, p^c) such that $2q^c = D(p^c)$ and $p^c > c$. The next Proposition shows that such a cooperation is possible to implement by means of trigger strategies.

Proposition 2 *Assume that the firms are able to sustain the collusive price $p^A \in (c, p^M]$ in the repeated spot market if both firms firms have signed the contract $(D(p^c)/2, p^c)$. Then there exists a subgame-perfect equilibrium in which both firms offer the contract $(D(p^c)/2, p^c)$ in period $t = 0$ and collude on the price $p^A \in (c, p^M]$ in all periods $t \geq 1$.*

Proof: Consider the following strategy for firm $i = (1, 2)$. Choose the contract $(D(p^c)/2, p^c)$ in period $t = 0$. If firm $j \neq i$ chooses any contract $(q_i^c, p_i^c) \neq (D(p^c)/2, p^c)$ in period $t = 0$, then punish firm j in all future periods by pricing at marginal cost. If instead firm j chooses the contract $(D(p^c)/2, p^c)$ in period $t = 0$, then cooperate in period $t = 1$ by choosing the collusive price p^A. In all periods $t \geq 2$, cooperate by choosing the collusive price p^A unless firm j deviated in period $t - 1$. If so, punish firm j in the current as well as in all future periods by pricing at marginal cost.

Assume that firm j follows the same strategy. The proof establishes that firm i has no incentive to deviate from the proposed strategy, given that firm j follows the same strategy.

If firm j cooperates in period $t = 0$ by choosing the contract $(D(p^c)/2, p^c)$, we know by Proposition 1 that firm i has no incentive to deviate in any period $t \geq 1$, provided that firm j sticks to its strategy in all future periods. If firm j deviates in period $t = 0$, both firms price at marginal costs and thus make 0 profits in all periods $t \geq 1$. This constitutes an equilibrium in the subgame starting after firm j's deviation. The reason is that the price p^c is a ceiling spot price. Therefore, firm i cannot raise its profits by increasing or decreasing its price in any future period. Finally, firm i has no incentive to deviate in period $t = 0$. Indeed, by sticking to the proposed strategy, it makes strictly positive profits. In contrast, by deviating at $t = 0$, it triggers a punishment forever by firm j, implying that firm i will make 0 profits. ■

Like in Allaz and Vila (1993), Proposition 2 shows that when the firms have the choice to sell their output either through long term contracts or on the spot market, both firms may choose the latter solution. In a repeated game setting, this choice does not imply, however, that the spot market becomes more competitive. Moreover, the consequence of such a strategy may be that only a small proportion of total output is sold on the spot market. This is a commonly observed feature of electricity markets; according to Shuttleworth and McKenzie (2002), only 10% of the total output of electricity is bought on the spot market.

To derive the result it was important to assume that firms choose contracts with a ceiling spot price, rather than a contract with a fixed price. One way of motivating this assumption would be to assume that the consumers are strategic. Intuitively, such consumers would refuse to sign such a contract. The reason is that strategic consumers realize that a deviation by a firm triggers a price war in the following periods. Signing a contract with a fixed price prohibits the strategic consumer from benefiting from the price war.

5 Conclusion

It has been argued that having a contract market before the spot market enhances competition on the latter market (Allaz and Vila, 1993). This paper proposes a model of the electricity market where firms sign long-term supply contracts with their retailers. Subsequently, the firms repeatedly interact on the spot market. We show that contract markets help sustain collusion on the spot market.

We do not argue that sustaining collusion is the only motive behind firms' contracting decisions. One important motive might be to hedge risk. Unlike the collusion motive, the hedging motive has beneficial effects. However, we believe that the pro-collusive motive is one important reason behind the large amount of contracted quantity. Of course it would be desirable to check this belief empirically. An interesting research project would be to analyze the outcomes of the new market designs in the UK and the State of California where access to contract markets are encouraged by regulators.

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