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Excess Capacity and Pricing in Bertrand-Edgeworth Markets: Experimental Evidence*

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Abstract

We conduct experiments testing the relationship between excess capacity and pricing in repeated Bertrand-Edgeworth duopolies and triopolies. We systematically vary the experimental markets between low excess capacity (suggesting monopoly) and no capacity constraints (suggesting perfect competition). Controlling for the number of firms, higher production capacity leads to lower prices. However, the decline in prices as industry capacity rises is less pronounced than predicted by Nash equilibrium, and a model of myopic price adjustments has greater predictive power. With higher capacities, Edgeworth-cycle behavior becomes less pronounced, causing lower prices. Evidence for tacit collusion is limited and restricted to low-capacity duopolies.

JEL – classification numbers: C72, C90, D43

Keywords: tacit collusion, excess capacity, Edgeworth cycles.

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1 Introduction

The Bertrand-Edgeworth model of price-setting firms which operate under capacity constraints (Edgeworth, 1925) is one of the core oligopoly theories. By varying firms' capacities, it addresses the intermediate range between uncontested monopoly and perfect competition which is crucial for research in theoretical industrial organization. If capacities are sufficiently small, competition is ineffective and firms charge the monopoly price, whereas if capacities are not binding, perfect competition emerges. In this way, the model generates market outcomes between monopoly and marginal-cost pricing thought to be intuitive for oligopoly. This is Edgeworth's (1925) main competitive advantage to Bertrand's (1883) approach which is often dismissed as a paradox.

A related theoretical argument is made by Brock and Scheinkman (1985) for the infinitely-repeated game. In a supergame, the strength of a cartel is directly related to the foregone profits if the collusive agreement is broken. Fixing the number of firms, if an industry's production capacity is only marginally higher than monopoly capacity, any cartel would be weak, as the punishment for deviation is insignificant. The larger the excess capacity, the larger the punishment looming over members of the cartel, and thus the lower the discount rate necessary to sustain collusion. However, if excess capacity becomes too large, the required discount rises again until firms reach the point where they are *de facto* in a standard Bertrand game, being constant thereafter.

While the empirical validity of such a frequently applied oligopoly model seems crucial, few experimental tests exist.[1] In their seminal paper, Brown-Kruse et al. (1994) find some moderate evidence for mixed-strategy Nash equilibrium play, and average price declines with capacity as predicted by Nash equilibrium. They also find some evidence for collusion and competitive pricing. However, if one were to choose a single theory to explain the data, the non-rational Edgeworth-cycle theory would perform best.[2] In

[1]There are several Bertrand-Edgeworth experiments, but few have investigated the pricing logic of that model. Following Dufwenberg and Gneezy's (2000) game (which boils down to a Bertrand-Edgeworth setting with inelastic demand and one buyer), there has been a growing number of Bertrand-Edgeworth experiments. See, for example, Muren (2000); Anderhub et al. (2003); Dufwenberg et al. (2007); Abbink and Brandts (2009) and Buchheit and Feltovich (2011). Brandts and Guillén (2007) study homogenous-goods markets in which firms specify their production and then select a price. Ewing and Kruse (2010) run Bertrand-Edgeworth oligopolies with downward sloping demand and various cost functions (decreasing or U-shaped average costs). In terms of empirical studies using field data, various studies have looked at Edgeworth cycles in industries such as retail gasoline markets: Eckert (2002), Noel (2007a,b), Foros and Steen (2008), Wang (2009) and Doyle et al. (2010). See Noel (2011) for an extensive discussion of theory and empirical work on Edgeworth cycles.

[2]Edgeworth-cycles have been rationalized by Maskin and Tirole (1988) in a altogether different theoretical framework.

such a cycle (Edgeworth 1925, p. 116), firms undercut their rivals' prices but undercutting a rival's price is only worthwhile up to a certain price level. Once this level is reached, firms prefer to jump back to the monopoly price.[3] Eventually, firms will arrive at the price vector from which they started and will have thus completed an Edgeworth cycle. Brown-Kruse et al. (1994) find evidence for such cyclical behavior, as do some posted-offer experiments (see, for example, Plott and Smith, 1978; Ketcham, Smith and Williams, 1984; Davis, Holt and Villamil, 2002).[4]

Our study builds on and extends the experimental literature on capacity-constrained pricing markets in several dimensions. Firstly, we systematically explore the effect of excess capacity on behaviour, by exogenously changing aggregate capacity and studying the impact on prices.

Secondly, and as a direct consequence of our design, we are able to explore the equilibrium discontinuity the Bertrand-Edgeworth model exhibits at the boundaries of the capacity domain: with very low levels of aggregate capacity, we get monopoly pricing; at the other end of the domain, the mixed-strategy equilibrium collapses to a pure-strategy equilibrium where price equals marginal cost. What happens at these boundaries is, to our knowledge, unexplored.

Thirdly, our paper also extends the work of Brown-Kruse et al. (1994) by considering the effect of the number of sellers. As experimental evidence on markets attests, a small increase in the number of firms can have drastic effects on behavior, particularly with regards to firms' ability to sustain supra-Nash prices (see Dufwenberg and Gneezy, 2000, for Bertrand markets and Huck et al., 2004, for Cournot markets). We combine within a single framework the impact on pricing of the number of sellers, as well as market capacity. Furthermore, while Brown-Kruse (1994) do vary capacities, they focus on the effect of information provided to sellers, and their study considers a much more complex environment to that of this paper, in that they consider a downward sloping constant

[3]In general, the high point of the Edgeworth cycle is the monopoly price from selling to the *residual* demand leftover after low-price firms have sold their capacity. Unless demand is perfectly inelastic (as in this paper) or proportional rationing is used, this price is not equal to the unconstrained monopoly price.

[4]Posted-offer markets differ from Bertrand-Edgeworth markets in that, firstly, information is incomplete (sellers know only their own cost schedule) and, secondly, sellers have to choose a maximum number of units they wish to sell. See also the recent related studies on price dispersion by Morgan et al. (2006) and Orzen (2008) where the equilibrium is also in mixed strategies, as well as Cason et al. (2003), who study price dispersion dynamics in a posted-offer market. In their setup, a discontinuity of the payoff function at equal prices leads to non-existence of a pure strategy equilibrium. The payoff function in such models of imperfect information with buyer search is so similar to that in the standard Bertrand-Edgeworth game that the authors consider Edgeworth cycles as possible explanations for patterns in their data.

elasticity demand curve, while we opt for a simpler box demand curve.

Our experimental results are as follows. We find that average prices decrease as excess capacity goes up. While this is also predicted by the static Nash equilibrium, the data are better explained by Edgeworth-cycle behavior. Not only are average prices closer to the predicted Edgeworth cycle prices, but we cannot reject the hypothesis that firms are engaging in some form of myopic price adjustment. Like evidence from capacity-unconstrained Bertrand markets, we find some evidence of supra-Nash pricing, but no evidence of tacit collusion, as defined by firms coordinating on sustaining prices at a particular level (e.g, monopoly) for a sustained period.

Our findings suggest some qualifications of the previous findings. We observe that the predictive power of the static Nash equilibrium varies with industry capacities and number of firms. Specifically, the gap between Nash predictions and observed average prices significantly increases alongside the level of excess capacity. We also observe a drop in the frequency of monopoly pricing when we move from duopolies to triopolies. While there are some attempts at collusive behavior in two-firm markets, we find no such evidence in markets with three competitors. Monopoly pricing is significantly and negatively correlated with industry capacity.

Interestingly, the explanatory power of the model of myopic price adjustments depends on the capacity level and the number of firms. The Edgeworth price adjustment process is *stronger* for treatments with *lower* production capacities. As capacities become bigger and eventually not binding, the intensity of Edgeworth-cycle behavior diminishes. Regarding pricing behavior at the boundaries where pure-strategy pricing is predicted, we find that, even in the case where capacities are such that marginal cost pricing is the pure-strategy equilibrium, Edgeworth-cycle theory still describes pricing behavior rather accurately. We find differences between duopolies and triopolies in the persistence of Edgeworth price adjustments. In particular, Edgeworth price adjustments are more persistent for duopolies when individual capacities are binding, but we find the reverse when capacity levels are not binding and where we would expect the Bertrand-Nash equilibrium to hold.

In short, although in theory the Nash equilibrium regime changes from mixed to pure-strategy, we find no corresponding discontinuity in behavior in the experiment. A similar point applies to monopoly pricing: in the treatment with the lowest level of capacity, the share of monopoly prices does not exceed 31 percent overall and, again, much of the data still exhibit cyclical patterns. The following section describes the model under scrutiny. Section 3 describes the experimental design and methodology; section 4 analyzes the results and section 5 concludes the paper.

2 The Model and Equilibrium Analysis

We consider a symmetric Bertrand-Edgeworth oligopoly with n firms. We denote by k a firm's capacity such that nk is industry capacity and $(n-1)k$ is the capacity of a firm's competitors. We assume the firms' production costs up to capacity are zero for simplicity.

There are m buyers, each of whom buys one unit of the good as long as the price does not exceed $\overline{p}$. Buyers buy from the firm with the lowest price first. If this firm's capacity is exhausted, they move on to the second lowest price and so on. If two or more firms charge the same price and if their joint capacity exceeds the (remaining) number of customers, demand is split equally among firms.

We assume

$$nk > m > (n-1)k. \tag{1}$$

These assumptions imply that there is competition, but it is not perfect and static Nash equilibrium profits will be positive. If $m \geq nk$, all firms would charge the maximum price of $\overline{p}$ and there would be no competition at all. If $(n-1)k \geq m$, any subset of $n-1$ firms can serve the entire market so there would be perfect Bertrand competition where price equals marginal cost in equilibrium. Since $m > (n-1)k$, equation (1) ensures the static Nash equilibrium is in mixed strategies. Due to the assumption, only two relevant contingencies exist for each firm. If a firm does not charge the highest price, it sells k units. If a does firm charge the highest price, it sells $m-(n-1)k$ units.

We now derive the symmetric static Nash equilibrium, the minimum discount factor required for collusion in the repeated game and a prediction for markets characterized by myopic Edgeworth-cycle behavior. The proofs of the following three propositions can be found in the appendix. (See the early references by Beckmann, 1965, and Levitan and Shubik, 1972, as well as Holt and Solis-Soberon, 1992).

Proposition 1. *There exists a unique symmetric static Nash equilibrium. The equilibrium is in mixed strategies with support* $[\underline{p}, \overline{p}]$ where

$$\underline{p} = \overline{p}(m-(n-1)k)/k. \tag{2}$$

In equilibrium, the probability that a firm charges a price less than or equal to p is

$$F(p) = \left(\frac{pk - \overline{p}\,(m-(n-1)k)}{p(nk-m)} \right)^{1/(n-1)} \tag{3}$$

Equilibrium profits are $\pi^N = \underline{p}k$ and the expected weighted Nash equilibrium price is $p^N = \underline{p}kn/m$.

This is the standard result for Bertrand-Edgeworth oligopolies with inelastic demand.[5] Firms randomize in equilibrium and choose prices between the reservation price and some lower bound that depends on the excess capacity. Nash equilibrium profits and average prices vary between the monopoly level (for $nk = m$) and the perfectly competitive level (for $k = m$). Note that $F(\underline{p}) = 0$ and $F(\overline{p}) = 1$.

Before we continue, it is worthwhile to note that, whilst our theoretical analysis assumes continuous prices, in our experiment subjects picked prices from a grid. As such, it is important to check that the discrete version of the game has similar equilibrium predictions to its continuous-price counterpart. Solving for the Nash equilibrium of an n-player game in mixed strategies when the action set is discrete implies solving a system of polynomial equations of up to degree $n-1$, subject to inequality constraints (Baye, Kovenock and de Vries, 1994; Datta, 2003). While this is relatively easy when both the number of players and the number of pure, strictly undominated strategies are small, matters dramatically change when the number of strategies increases.[6] To circumvent these issues, we guided the search for the equilibrium of the games using the logit-QRE algorithm of McKelvey and Palfrey (1995), and letting the λ parameter go to infinity, corresponding to full rationality and Nash equilibrium play. We checked the limiting QRE distributions were indeed the Nash equilibria in separate calculations. In the data analysis section, we will compare our findings to the discrete equilibrium.

The equilibrium distributions were qualitatively very similar to the equilibrium predictions in the continuous case, with a curious feature: whenever the number of price actions above $\underline{p}$ was even, some of those prices were picked with probability zero. Capacity configurations where the number of price actions above $\underline{p}$ are odd do not exhibit

[5] If $n > 2$, there may exist asymmetric equilibria. See Baye, Kovenock and de Vries (1992).

[6] When solving for the equilibrium of a two-player Tullock contest with a large discrete strategy set, Baye, Kovenock and de Vries (1994) note (p. 372): "For $Q > 15$ the computational burden increases rapidly and exact solutions take an excessive amount of computer time." This problem persists today. Gambit, the standard software package for the numerical analysis of Nash equilibria of finite games, was unable to compute the Nash equilibria of our game, even when we focused on symmetric equilibria and after we eliminated strictly dominated strategies.

this property. This artefact seems to be a feature equilibria of discretisations of different classes of games, including contests (Baye et al. 1994), patent-race games (Dechenaux et al. 2003) and all-pay auctions (Dechenaux et al. 2006). Nevertheless, in our setup, the probability of playing prices p_j or p_{j+1}, where j is an arbitrary integer greater than $\underline{p}+1$ is lower than the probability of playing p_{j-1} or p_j, which resembles the continuous game prediction.[7]

We now turn to the infinitely repeated game. Time is indexed from $t = 0, ..., \infty$ and firms discount future profits with a factor δ, where $0 \leq \delta < 1$. We look for subgame perfect collusive equilibria with profits higher than those of the static Nash equilibrium. When analysing the repeated game, denote by π_i^c the profit firm i earns when all firms adhere to collusion. Let π_i^d denote the profit when a firm defects, and π_i^p is the profit per period when a punishment path is triggered. We assume that firms revert to the static Nash equilibrium after a defection, thus we have $\pi_i^P = \pi_i^N$. (Note that the static Nash equilibrium payoff is equal to the minimax payoff here. Thus, harsher punishments do not exist.)

Proposition 2. *The minimum discount factor required for collusion in the infinitely repeated game is*

$$\underline{\delta} = \begin{cases} 0 & \text{if } m \geq nk \\ 1/n & \text{if } nk > m > (n-1)k \\ 1 - m/nk & \text{if } (n-1)k \geq m > k \\ 1 - 1/n & \text{if } m \geq k \end{cases}$$

The proposition shows how the minimum discount factor behaves in n. In the first segment, as mentioned, firms would set $\overline{p}$ and there is no incentive deviate, hence $\underline{\delta} = 0$. In the Bertrand-Edgeworth range ($nk > m > (n-1)k$), $\underline{\delta}$ decreases in n. This apparently counter-intuitive result has also been found by Kühn (2012) ("how market fragmentation can facilitate collusion"). The minimum discount factor then increases in n when $m \geq (n-1)k$. Note, however, that there is no discontinuity at $m = (n-1)k$ as $\underline{\delta} = 1/n$ either way.[8] The third segment ($(n-1)k \geq m > k$) is interesting in that static Nash profits are zero but a single firm cannot deliver the the m customers when

[7]It would appear that in the discrete version of the game, there is a strategic substitutability between playing adjacent prices on the grid. If a player picks a particular price p_j, it is more attractive for its rival to play p_{j-1}, *ceteris paribus*. However, too high a probability of playing p_{j-1} makes p_{j-2} more attractive, and so on. We are grateful to Ted Turocy for providing this intuition.

[8]We are grateful to a referee for pointing out an inaccuracy here in a previous version of the paper.

defecting, and so the minimum discount factor is still smaller than in last segment. There is no discontinuity either at $m = k$ and for $m \geq k$, and players are finally in the capacity-unconstrained Bertrand case. Again, in the experiments, the second segment alone is relevant as we assume (1).

The folk theorem, which says that infinitely many outcomes can be sustained in a subgame perfect equilibrium in the infinitely repeated game also holds for this game, of course. If one wanted to select among the collusive equilibria, one could argue as follows. The proof of the proposition (see Appendix) shows that colluding at the reservation price $\overline{p}$ requires a lower discount factor than any colluding at $p < \overline{p}$. Thus, for any $\delta > \underline{\delta}$ payoff dominance would suggest that players may coordinate on $\overline{p}$ whereas, if $\delta = \underline{\delta}$, $\overline{p}$ is the only feasible collusive price.

Finally, we consider Edgeworth-cycle behavior. The idea is that, in multi-period Bertrand-Edgeworth markets, firms may dynamically adjust their prices by best responding, assuming that the other firms keep their prices constant. Firms keep undercutting their rivals' prices until they reach a price level (which coincides with the lower bound of the support of the mixed-strategy equilibrium, $\underline{p}$) where they are better off charging the reservation price even if they do not sell their capacity at that price. In other words, in an Edgeworth cycle firms play the myopic best reply, holding naïve price expectations.

Such a myopic Edgeworth cycle can be formalized as follows. All firms that do not charge the highest price in the market sell k. For these firms, the myopic best reply is to undercut by the smallest amount (ε) the highest price a rival firm charged in the previous period. Formally

$$(4) \qquad p_i^{t+1} = \begin{cases} \max\{p^t_{j\neq i}\} - \varepsilon, & \text{if } \max\{p^t_{j\neq i}\} - \varepsilon \geq \underline{p} \\ \overline{p} & \text{else} \end{cases} .$$

These kind of myopic price choices suggest the following proposition.

Proposition 3. *In an infinitely-repeated pricing game, Edgeworth-cycle pricing behavior implies an average price of* $(\overline{p} + \underline{p})/2$.

Proposition 3 is intuitive. If firms play a complete Edgeworth cycle, they charge each of the prices in $[\overline{p}, \underline{p}]$ exactly once. Thus the average price is the mean of $\overline{p}$ and $\underline{p}$ where $\underline{p}$ is defined in Proposition 1. Note that the proposition is only true asymptotically. If there is a finite endpoint, the average price will only rarely be exactly $(\overline{p} + \underline{p})/2$ but will depend on the industry-specific first-period price. Having said that, for the average price across many industries with uniformly random first-period prices, $(\overline{p} + \underline{p})/2$ is a natural benchmark.

Neither Proposition 1 nor Proposition 3 apply when $m < (n-1)k$ (see (1)). In that case, capacity constraints are not binding any more and the pure strategy Nash equilibrium is where price equals marginal cost. However, since firms make zero profits when price equals marginal cost, starting a new cycle by charging $\overline{p}$ does not reduce profits. As is well known, the Bertrand-Nash equilibrium is in weakly dominated strategies, so there are no cost of deviating from equilibrium and a deviation leads to weakly higher payoffs. For that reason, we will also apply the prediction in Proposition 3 in the treatments where $m \leq (n-1)k$.

3 Experimental Design and Procedures

We ran a series of experimental Bertrand-Edgeworth markets. In all treatments, there were $m = 300$ computer-simulated consumers who demanded one unit of a good at the lowest price, as long as that price did not exceed $\overline{p} = 100$. The choice of a box-demand setup was to keep the experiment as simple as possible. The main treatment variable is industry production capacity, which was always symmetrically distributed, and the number of firms in the market (two or three). The choice of capacity distributions was made such that we had treatments in which the static prediction was the standard Bertrand-Nash equilibrium, all the way to a distribution close to the point where firms had monopoly power. Firms' actions spaces are integers between 0 and 100. Table 1 summarizes the treatments.

[Table 1 about here.]

We implemented the treatments with a fixed-matching scheme, and generated six markets (or groups) for each treatment. Subjects were told they were representing a firm in a market where they would meet with one (or two) other firms. Subjects participated in one treatment only and the capacity distribution was held fixed in each market. Subjects were informed about all features of the market in the trading rules (instructions are reproduced in the Appendix).

Sessions lasted for at least 30 periods. From the 31^{st} period on, a random stopping rule was imposed with a continuation probability of 5/6. All groups in a given session faced the same random move regarding duration. Subjects were fully informed about the minimum number of periods and the details of the termination rule. In each period, subjects were asked to enter their price in a computer terminal. Once all subjects had made their decisions, the round ended and a screen displayed the prices chosen by all firms in the market, as well as the profit of each individual firm. Finally subjects were told their accumulated profit up to that point.

Payments consisted of a show-up fee of £5 plus the sum of the profits over the course of the experiment. For payments, we used an "Experimental Currency Unit (ECU)". In all treatments, 25,000 ECU were worth £1.

The sessions were run in the Finance and Economics Experimental Laboratory at Exeter (F.E.E.L.E.) during the Spring of 2008. The experiment was programmed in z-Tree (Fischbacher, 2007). Participants were undergraduate students from a variety of backgrounds. Sessions lasted for about 60 minutes and the average payment was £17 (roughly $27). We conducted two experimental sessions with nine participants for each of the three-firm markets and one session with 12 participants for each of the duopoly markets. The data for treatments 201-201 and 134-134-134 are taken from Fonseca and Normann (2008). These sessions were run by the same experimenter and using the same protocol at the Economics Experiments Laboratory of Royal Holloway College (University of London) during the Fall of 2004 and 2005. A total of 96 subjects participated in the Exeter sessions plus 30 subjects participated in the 201-201 and 134-134-134 treatments at the Royal Holloway College.

4 The Results

4.1 Overview

Throughout, we consider data from period 11 onwards to allow for learning effects. Using the full data set would not alter the results qualitatively.

[Table 2 about here.]

Table 2 displays average weighted price for each treatment. The average prices of the treatments clearly differ. Counting each group average as one observation, a non-parametric Kruskal-Wallis test on the duopoly data shows a highly significant difference ($\chi^2 = 20.97$, $d.f. = 4$, $p = 0.0008$), as does the test on the three-firm markets ($\chi^2 = 8.84$, $d.f. = 2$, $p = 0.0120$).

Table 2 suggests that industry capacity and prices are negatively correlated. A Spearman correlation coefficient is quantitatively substantial and significant for both the duopolies ($\rho = -0.75$, $p < 0.0001$) and the three-firm markets ($\rho = -0.71$, $p = 0.0010$). If we compare treatments pairwise, we find that a rise in capacity almost always results in significantly lower prices (one-tailed Mann-Whitney U test, all tests $p < 0.05$), the exceptions being the comparisons between treatments 175-175 and 201-201, where prices are still lower, but the difference is not significant.

4.2 Analysis of the Nash equilibrium prediction

The negative correlation of average prices with capacity is predicted by the static Nash equilibrium. So, qualitatively, the Nash prediction is consistent with this trend. It is however clear that the Nash equilibrium does not do well in terms of the quantitative predictions. The rate of decrease in prices is less pronounced compared to what the mixed-strategy equilibrium suggests. It seems that, as excess capacity increases, the difference between predicted Nash prices and average weighted prices also goes up. Figures 1 and 2 show the average market price for each capacity in the duopoly and triopoly conditions respectively, as well as the predicted Nash price and Edgeworth-cycle price. Indeed, a Spearman test for correlation based on the difference between the average price of each market and the Nash prediction confirms that this gap significantly widens with industry capacity for both duopolies (Spearman's $\rho = 0.72$, $p < 0.001$) and three-firm markets (Spearman's $\rho = 0.85$, $p < 0.001$).

[Figure 1 about here]

[Figure 2 about here]

Since the static Nash equilibrium of this game is in mixed strategies, it is useful to look at the distribution of posted prices in each treatment and compare it to the predicted mixed strategy distribution. Figures 3 and 4 display the predicted and observed price distributions for the duopoly and triopoly markets, respectively.

[Figure 3 about here]

[Figure 4 about here]

As is readily observable from the figures, all the observed data distributions significantly differ from their theoretical counterparts using Kolmogorov-Smirnov tests (all $p < 0.01$). This is consistent with evidence from Brown-Kruse et al. (1994), who reported significant differences between predicted mixed strategy distributions and observed price distributions.

Nash equilibrium behavior in a finitely-repeated game means that in every period subjects make an independent draw with replacement from the mixed strategy equilibrium distribution of prices. As such, one would expect there to be no correlation between current and previous prices. To test this hypothesis, we regress the difference between the price posted by firm i at time t and the price posted by the same firm at time $t-1$ on its lag, plus a variable (*1/t*) equal to the inverse of the period number to allow for time trends. We also include dummies for market capacity, as well as the corresponding interaction dummies with number of firms (*tri*).

[Table 3 about here.]

Regression (1) looks at the effect of increasing market capacity and its interaction with the number of firms on price autocorrelation. We find a negative and significant coefficient on $(P_{t-1} - P_{t-2})$ for all duopoly capacity levels.[9] Conditioning on aggregate capacity, we find a significantly lower negative autocorrelation in triopolies than in duopolies for all relevant capacities, though that autocorrelation is still significant.[10]

Regression (1) estimates both the effect of a price change $((P_{t-1} - P_{t-2}))$, as well as the sign of that price change. Regression (2) unpacks the two effects by conditioning on the sign of the price change. To do this, we create a series of interaction dummies of capacity levels with positive price changes $(\max\{0, (P_{t-1} - P_{t-2})\})$, as well as negative price changes $(\min\{0, (P_{t-1} - P_{t-2})\})$; for ease of interpretation of the coefficients, we took the absolute value of the negative price changes.

In the duopolies, for all capacity conditions, the larger the price increase in the previous period, the smaller the price increase in the current period. Behavior in the triopoly conditions is not statistically different for the cases where aggregate capacity is

[9] An F-test rejected the hypothesis of joint equality of $(P_{t-1} - P_{t-2})$ and the interaction dummies with capacity in duopolies at the 1% level ($F(3, 47) = 5.75, p = 0.002$).

[10] $(P_{t-1} - P_{t-2}) \times k350 + (P_{t-1} - P_{t-2}) \times k350 \times tri = 0 : F(1, 47) = 72.16, p < 0.001$; $(P_{t-1} - P_{t-2}) \times k402 + (P_{t-1} - P_{t-2}) \times k402 \times tri = 0 : F(1, 47) = 11.39, p = 0.002$; $(P_{t-1} - P_{t-2}) \times k450 + (P_{t-1} - P_{t-2}) \times k450 \times tri = 0 : F(1, 47) = 38.57, p < 0.001$.

350 or 402. In the case where aggregate capacity is 450 (the case where the predicted Nash price equals marginal cost), we see a significantly lesser negative autocorrelation in prices, although we still observe a statistically significant autocorrelation in that case ($\max\{0, (P_{t-1} - P_{t-2})\} \times k350 + \max\{0, (P_{t-1} - P_{t-2})\} \times k350 \times tri = 0 : F(1, 47) = 40.97, p < 0.001$.) In other words, a large increase in prices in the previous period leads to a smaller price increase today in the triopoly condition than in the duopoly case.

When we look at the impact of a price drop in the previous period, the larger this drop is, the larger the price increase in the current period. However, the latter effect is only significant for duopolies with low levels of excess capacity, in particular $K = 350$ and $K = 402$. Again, this effect is much lower in the triopoly cases, and in the case of the lowest capacity conditon, no longer significant.[11]

In other words, this pattern of behavior is consistent with the difference in price levels between duopolies and triopolies: in the former, a price drop is correlated with a subsequent increase in prices, while in the latter it is not. It also suggests that behavior in the duopolies is more consistent with Edgeworth cycles, in that the sign of a price change in the previous period is negatively correlated with the magnitude of the price change in the current period in both directions, while in the triopoly cases, that relationship only seems to work to drive prices down.

To conclude, the static mixed-strategy equilibrium captures the negative correlation between average prices and industry capacity well. On the other hand, it is obvious that subjects do not randomize in the way the theory stipulates. Central for our research question is the finding that, with higher capacities, the gap between the expected Nash prices and average observed prices gets bigger.

4.3 Tacit Collusion

We now address the issue of collusion. One can see in Figures 3 and 4 that there is some mass on the reservation price in all treatments. As discussed in the theory section, while many possible prices may sustain collusion in equilibrium, the maximum price, $\overline{p} = 100$, is a natural candidate for firms to coordinate because it is payoff dominant.[12] When

[11] $\min\{0, (P_{t-1} - P_{t-2})\} \times k350 + \min\{0, (P_{t-1} - P_{t-2})\} \times k350 \times tri = 0 : F(1, 47) = 0.28, p = 0.602$; $\min\{0, (P_{t-1} - P_{t-2})\} \times k402 + \min\{0, (P_{t-1} - P_{t-2})\} \times k302 \times tri = 0 : F(1, 47) = 5.28, p = 0.026$.

[12] In fact, out of all instances in which all firms in a duopoly charged the same price, $p = 100$ was the modal price accounting for 53% (33 out of 62) of all cases. All other cases where both firms picked the same price in a given period individually accounted for less than 5% of observations, and ranged from $p = 99$ to $p = 30$. We did not find an instance in which all firms in a triopoly picked the same price in a given period. As such, we feel our focus on the case where all firms pick $p = 100$ in a given period as the main measure of collusion is justified.

looking at the aggregate data across treatments in Table 4 we find very limited evidence of tacit collusion: 13% of posted prices are equal to 100 in the duopoly treatments and 5% in the triopoly condition. When we look at the proportion of cases where all subjects in a market posted $p = 100$ in a given period, the percentage drops to 3% in the duopoly conditions and 0% in the triopoly conditions. The majority of cases of collusion in this sense can be traced to one market in the 175-175 treatment – see group 3 in Figure 7.

[Table 4 about here.]

However, these averages mask the variation that exists across different capacity configurations. We find that in the duopoly case, the share of $p = 100$ prices goes significantly up as total capacity goes down. Using each market as one independent observation, the Spearman correlation coefficient between share of $p = 100$ and capacity is high and significant ($\rho = -0.51$, $p = 0.004$).

When we turn to the triopoly data, we find very little evidence of collusion. The relative frequency of $p = 100$ is constant at 5% across all treatments, and the relative frequency of three firms simultaneously posting prices equal to 100 is zero. We can therefore reject any relationship between capacity and share of $p = 100$ prices (Spearman's $\rho = 0.01$, $p = 0.958$). Previous studies of Bertrand markets (Dufwenberg and Gneezy, 2000) found that the degree of competition increased dramatically when the number of firms went from two to three (and four). In their paper, firms were not capacity constrained and were thus able to serve the entire market. Our evidence suggests that even when capacities are binding, so that no firm is able to serve all consumers, cooperation is too difficult to sustain once the number of firms goes beyond a simple duopoly. Table 4 summarizes the results.

One possible explanation for the frequency of $p = 100$ observations is that subjects may have attempted to signal the intention to collude by repeatedly posting the maximum price over a number of periods, even when such actions are not reciprocated by the other subjects. We see in the case of duopolies (last column of Table 4) that the frequency of unsuccessful collusive attempts diminishes with excess capacity for duopolies (Spearman's $\rho = -0.47, p = 0.008$.) In the case of triopolies, there is no relationship between excess capacity and failed collusion attempts (Spearman's $\rho = 0.01, p = 0.958$.)

Although a natural candidate for collusion, $p = 100$ is still an *ad hoc* measure of analysis and we therefore need to consider other measures as robustness checks to our result. We constructed an index of collusion equal to $(100 - p)/(100 - p^N)$, where 100 is the monopoly price, p^N is the average Nash price and p is the observed price. This index takes a value of one if the average price is equal to the average Nash price and zero if the average price equals the monopoly price. We find a negative correlation between market capacity and the index for both duopolies (Spearman's $\rho = -0.32$, $p = 0.087$) and triopolies (Spearman's $\rho = -0.49$, $p = 0.041$.)

4.4 Analysis of the EC prediction

As argued before, it is possible that subjects' behavior may be consistent with Edgeworth cycles. Table 2 seems to support this, to the extent that the average observed prices are closer to the average Edgeworth price than to the predicted Nash price, although neither theory manages to accurately predict behavior. Edgeworth cycles seem to overestimate prices while the Nash equilibrium underestimates prices. Figures 1 and 2 suggest that, at least at the aggregate level, Edgeworth cycles are a much better predictor of behavior than the Nash equilibrium in both the duopoly and triopoly conditions. Furthermore, looking at individual timelines of selling prices in selected markets suggests Edgeworth pricing may be occurring, as figures 5 and 6 demonstrate.

[Figure 5 about here]

[Figure 6 about here]

In order to construct a formal test of Edgeworth cycle pricing, we follow Brown-Kruse et al. (1994) in running OLS estimations of individual price adjustments across periods in all treatments. We estimated the following equation:

$$P_{i,t} - P_{i,t-1} = \beta_0 + \beta_1(P^E_{i,t} - P_{i,t-1}) + \beta_2(P^E_{i,t-1} - P_{i,t-2}) + \epsilon_{i,t}.$$

The dependent variable is the change in prices from period $t-1$ to t; the independent variables are the predicted Edgeworth adjustment and its lag. Based on this estimation, we are able to formulate a number of hypotheses. The first hypothesis is that there is no price adjustment process; that is, $\beta_1 = \beta_2 = 0$. The second hypothesis is that firms make an immediate and perfect Edgeworth adjustment, which implies $\beta_0 = 0$, $\beta_1 = 1$ and $\beta_2 = 0$. The third hypothesis, $\beta_1 = 0$, is that any adjustment is not immediate; finally, the fourth test is that there is no lag in the adjustment process, $\beta_2 = 0$.

Tables 5 and 6 show the results from estimating the equation treatment by treatment in both the duopoly and triopoly conditions. Table 5 quantifies the extent to which duopolists make myopic adjustments to their rival's actions in the previous period. The coefficient of β_1 is positive and significant in all individual treatment regressions, as well as the pooled regression. The coefficient of β_2 is only significantly different from zero in treatments 175-175 and 225-225, as well as for the pooled data. The findings are similar for the triopoly conditions. This indicates that firms, on average, are making immediate, if only partial, adjustments to rivals' previous period prices.[13]

[Table 5 about here.]

[Table 6 about here.]

[Table 7 about here.]

Table 7 reports the results of regressions comparing behavior between duopolies and triopolies conditional on whether Nash equilibrium is marginal cost, in regression (1), or it is a mixed strategy, in regression (2). In other words, regression (1) analyses the 300-300 and 150-150-150 data and regressions (2) the rest. In regression (1) we see no significant difference between duopolies and triopolies in terms of immediate adjustment, but the negative and significant coefficient on $\beta_2 \times tri$ indicates that the extent to which subjects in the 150-150-150 adjust prices in an Edgeworth fashion diminishes over time. If we focus on the cases where the Nash equilibrium prediction is in mixed strategies (regression 2), we see the opposite effect: we see a negative and significant coefficient on β_2 and a positive and significant coefficient on $\beta_2 \times tri$. In other words, the extent to which subjects adjust prices a la Edgeworth diminishes over time, while that is not the case with triopolies ($\beta_2 + \beta_2 \times tri = 0 : F(1, 35) = 0.81, p = 0.374$.)

It seems that the key difference between duopolies and triopolies does not rest with the immediate price adjustments, but rather with their persistence over time. Furthermore, this difference in persistence of behavior is very different depending on whether or not the degree of excess capacity leads to (predicted) pure Bertrand-Nash competition. In the case where it does, Edgeworth price adjustments are less persistent in triopolies

[13]Feedback from post-experimental questionnaires reinforces this belief. We transcribe a representative description by a subject of her behavior in the experiment: "Initially, I tried to set a price that would undercut the price set by company A by a small amount so as to maximise profit. However, when the price set by company A got around 30, I predicted that the next round it would be lower, something like 20-25 and so I set my price at 100. By forgetting about setting the lowest price and selling 75 units at 100 I was guaranteed a profit of 7,500. If instead I had tried to undercut company A by setting my price at, say 20, I would only have made 5,550 profit and this was less than 7,500."

than in duopolies. The reverse is true for the case where the Nash equilibrium is in mixed strategies. This is consistent with the lower prices observed in triopolies as well as with the fact that one observes a lower extent of autocorrelation in prices.

Estimating the Edgeworth price adjustment equation at the subject level and performing the aforementioned tests broadly lead us to reject the hypothesis that the observed price adjustments are either immediate or perfect. It confirms the picture that the Edgeworth adjustment process is only partial. This is consistent across duopolies and triopolies and it is qualitatively similar to the evidence presented by Brown-Kruse et al. (1994). The noticeable discrepancy is that we report a higher rejection rate for the third hypothesis, which may indicate a better performance of Edgeworth cycle behavior in our data set. This evidence is summarized in Table 8.

[Table 8 about here.]

A closer look at the price distributions in Figure 3 also suggests discrepancies with the Edgeworth cycle theory. First, we see in a number of treatments that there is mass at $p = 100$ (this is clearest in the case of 175-175), which may be indicative of collusion. Second, in almost all treatments, we also see that the lower bound of the pricing distribution is below the theoretical lower bound, which is the same value in the Edgeworth cycle.

We now turn our attention to how treatments impact Edgeworth cycles (noting that Brown-Kruse et al., 1994 only consider the pooled data set containing all their treatments for the previous analysis). Going back to Table 8, we can also see the frequency with which our null hypotheses are rejected treatment by treatment. The first thing to notice is that the percentage of rejections of hypothesis (1) (no Edgeworth adjustment) is quite high across all treatments. Furthermore, the fraction of rejections of hypothesis (4) is quite low across all treatments.

Focusing our attention on hypothesis (2), we see a rise in the rejection frequency as the industry production capacity goes up (it would be perfectly monotonic if not for treatment 201-201). This indicates that the higher total capacity is, the less likely it is that firms are making price adjustments that are close to Edgeworth. The rejection rates of treatments 250-250 and 300-300 are already close to 100%, meaning that almost no subject in that treatment is doing Edgeworth-type price adjustments. This is consistent with the evidence presented in Table 2. The difference between the average expected Edgeworth cycle prices and the observed prices increases as we move from the low excess capacity treatment (175-175) to the the high excess capacity treatment (300-300).

However, the same pattern is not repeated in the triopoly data. The frequency of rejection of hypothesis (2) appears to follow a U-shape: it is lowest for intermediate capacities, rather than for the highest capacity configuration. This pattern is also consistent with average prices.

A potential reason for the lack of predictive power by Edgeworth cycles in the high capacity treatments is that being the high price firm is very costly when there is large excess capacity in the market. In that sense, it may pay to be unpredictable, and therefore introduce more noise in one's pricing strategy. To test for this, we conducted a squared rank test, which tests for the hypothesis that k populations have identical variances, but possibly different means (Conover, 1980). For the duopoly treatments, the hypothesis that all five duopoly treatment price distributions had the same variance was rejected at the 1% level (squared rank test, $T^2 = 28.67$, $p < 0.01$).[14] With regards to the triopoly condition, we could not reject the hypothesis that all three price distributions had the same variance (squared rank test, $T^2 = 4.10$, $p > 0.10$). One speculative explanation for the difference in patterns between duopolies and triopolies is that Edgeworth cycles are a form of tacit collusion which only prevails in duopoly (see below).

The results also suggest some level of heterogeneity in behaviour across markets within the same treatment. Figure 7 displays price histograms for treatment 175-175, which was the treatment in which Edgeworth price adjustments were most salient. We see a high level of heterogeneity across different groups; group 3 appears to be quite collusive, with a very high frequency of observations close to or including $p = 100$, while group 6 has a distribution of prices which includes price levels significantly below the lowest predicted price (75). A similar conclusion can be drawn from the other treatments. The complete set of histograms for all treatments is available upon request. In short, average prices are consistent with Edgeworth cycles, even though when we estimate individual-level pricing behaviour, we find (perhaps not unexpectedly) that subjects make at best incomplete price adjustments.

[Figure 7 about here]

[14]Performing pair-wise tests, we could reject the null of equal variance for all but four comparisons at the 10% level (175-175 vs. 201-201; 225-225 vs. 250-250 and 250-250 vs. 300-300). For all other comparisons, the variance of the price distribution of the low-capacity market was always lower than its counterpart.

4.5 Discussion

Our main research question is how variations in industry capacity affect pricing behavior in Bertrand-Edgeworth oligopolies. Essentially, we found the following effects, which are most pronounced in the duopoly conditions. Firstly, the larger the capacities, the bigger the gap between average static Nash equilibrium prices and observed prices. Secondly, with larger capacities the monopoly price is charged less frequently. Thirdly, the predictive power of myopic Edgeworth cycles declines as the industry capacity increases.

Given that subjects are not playing the static mixed-strategy Nash equilibrium, the second and the third finding constitute a puzzle. The puzzle is that lower capacities are associated with both more pronounced Edgeworth-cycle behavior and more monopoly pricing. After all, Edgeworth-cycle behavior is based on playing a (myopic) best reply which is non-cooperative behavior, whereas setting the monopoly price should be considered as tacit collusion (the frequency with which subjects play the p=100 is often more than 10 times higher than predicted by the mixed strategy equilibrium, which rules out the argument that we may be observing equilibrium play in the static sense).

Our explanation is as follows. Suppose there is no excess capacity at all. Then participants would surely charge the monopoly price almost all the time. All our predictions (static Nash, tacit collusion and Edgeworth cycles) converge to the monopoly price as $nk \rightarrow m$. With a positive amount of excess capacity, subjects play Edgeworth cycles. As capacities get bigger, the high-price firm earns relatively less money. Thus, the larger the industry capacity, the more "expensive" it becomes to be the high-price firm, and the more random subjects' price choices become as a result.

What this reasoning boils down to is that playing the Edgeworth cycle is an (imperfect) form of tacit collusion. Subjects do not always charge the monopoly price, nor do they take regular turns in being the high-price firm. However, subjects can afford to play relatively predictable pricing patterns when excess capacity is low. Thus, with higher capacities Edgeworth cycles lose some of their predictive power. Subjects still do not play the static Nash equilibrium, but they do fall further below the Edgeworth-cycle prediction with higher capacities. Their behavior becomes more, not less, competitive.

Accepting the notion of Edgeworth cycle as a form of tacit collusion, it seems less puzzling that monopoly pricing and the intensity of the Edgeworth cycles are both negatively correlated with industry capacity. Note also that, with smaller capacities, the monopoly price will be played more frequently because the numbers of periods required for a complete cycle is smaller. Finally, we saw the number of markets where all firms charge the monopoly price (and these few markets are not consistent with Edgeworth cycles) is rather small. Thus, even if some industries charge the monopoly price most of the time, Edgeworth cycles still accurately describe the treatments with low capacities.

Finally, we discuss our findings regarding the discontinuities of the Bertrand-Edgeworth model when capacities become non-binding, or when there is no excess capacity at all such that pure-strategy equilibria emerge. We found no comparable discontinuity in the data. Indeed, our treatments with "large" excess capacity suggesting perfect competition exhibited, to a large extent, cyclical behavior even though capacities were not binding at all. The perhaps provocative conclusion from this is that Bertrand experiments (or at least those Bertrand experiments with inelastic demand like Dufwenberg and Gneezy, 2000; Brandts and Guillén, 2004; Dufwenberg et al., 2007; Abbink and Brandts, 2009) may consider the Bertrand-Edgeworth outcome as a plausible prediction. At marginal cost pricing, profits are zero. As a result, players then choose to switch to the maximum price without losing profits (marginal cost pricing is not a strict Nash equilibrium). Doing so also gives them zero profit but it starts a new cycle. This is clearly boundedly rational behavior. Dufwenberg et al. (2007) indeed show that, in Bertrand-Edgeworth experiments, agents have little incentive to stick to the equilibrium. Specifically, they show that the introduction of a price floor actually leads to lower prices because the floor increases the cost of deviating from equilibrium. With "small" levels of excess capacity, we also found evidence for cyclical behavior. Here, however, behavior seems more in line with the theory. Average Nash equilibrium prices and the support of the mixed strategy converge to the monopoly price when excess capacities are small. This is what is occurring in the data.

5 Conclusion

This paper examines pricing behavior in Bertrand-Edgeworth markets. In particular, we are interested in studying the effect on prices of increasing total production capacity. The game-theoretical analysis of this class of games predicts that a Nash equilibrium in pure strategies does not exist if the total production capacity in the market is higher than demand, but any subset of firms cannot serve the market by themselves. The only Nash equilibrium is in mixed strategies, where firms randomly select from a unique distribution. Originally, Edgeworth (1925) proposed an alternative approach. He claimed that firms would engage in successive price adjustments relative to their rivals' prices in the previous period. Firms would undercut each other up to the point where it would be more profitable to charge the monopoly price, thus creating a cycle.

When considering data at the aggregate level, our findings confirm the results of the seminal Bertrand-Edgeworth experiments by Brown-Kruse et al. (1994). Static Nash theory predicts the subjects' pricing behavior only partially and only qualitatively well. Observed weighted average prices move in the direction predicted by static Nash equilibrium: the higher the total production capacity is, the lower prices are. This occurs in both duopoly and triopoly conditions. However, the rate of decrease in prices is much lower than predicted. When we focus on pricing distributions, we find significant differences between predicted Nash price distributions and the observed price distributions. We also find some evidence of attempts at collusive behavior. The proportion of posted prices equal to the maximum price is negatively correlated with total capacity. However, with the exception of one group, those attempts are largely unsuccessful.

By contrast, a model of myopic price adjustments provides a better fit of the data. Not only are average weighted prices closer to the predicted Edgeworth cycle prices, but we cannot reject the hypothesis that firms are engaging in some form of myopic price adjustment. Crucially, (and perhaps counter-intuitively) the Edgeworth price adjustment process is stronger for treatments with lower production capacities. As we move closer to the perfectly competitive case, the intensity of Edgeworth cycle behavior diminishes. As a result, the difference between expected average Edgeworth-cycle prices and observed prices also increases.

In our data prices are significantly above predicted Nash prices – also in the case where Nash equilibrium prices are equal to marginal cost. It appears that capacity unconstrained duopolies are, at least to some extent, also driven by Edgeworth-cycle behavior. The tendency for Bertrand markets to deviate from equilibrium where price equals marginal cost is not new. Dufwenberg and Gneezy (2000) found Bertrand duopolies consistently priced above marginal cost. One reason may be (Kreps, 1990, p. 446) that the static Nash equilibrium is in weakly dominated strategies, deviating from equilibrium yields weakly higher payoffs. Hence, Edgeworth cycles explain rather well capacity *un*constrained Bertrand markets.

Appendix A: Proofs

Proof of Proposition 1. If firm i charges p, the probability that firm i is the firm with the highest price is $(F(p))^{n-1}$, and $1-(F(p))^{n-1}$ is the probability that firm i does not charge the highest price. In equilibrium, the expected profit of all prices contained in the support must be the one given in the Proposition, $\overline{p}(m-(n-1)k)$, that is,

$$p\left[(F(p))^{n-1}(m-(n-1)k)+(1-(F(p))^{n-1})k\right]=\overline{p}(m-(n-1)k). \tag{5}$$

Manipulating (5) yields

$$p\left[(F(p))^{n-1}(m-nk)+k\right] = \overline{p}(m-(n-1)k) \tag{6}$$

$$(F(p))^{n-1} = \frac{\overline{p}(m-(n-1)k)-pk}{p(m-nk)} \tag{7}$$

This verifies that a firm earns π^N for any price in the support provided the other firms randomize according to $F(p)$.

The sales-weighted average Nash price is derived as follows. If q_i denotes the number of units sold by firm i, the weighted average price is $\sum_{i=1}^n p_i q_i / \sum_{i=1}^n q_i$. From $\sum_{i=1}^n q_i = m$ and since $\sum_{i=1}^n p_i q_i = \sum_{i=1}^n \pi_i^N$ in Nash equilibrium, we obtain $p^N = \sum_{i=1}^n \pi_i^N / m = \underline{p}kn/m$ as claimed.□

Proof of Proposition 2. If $nk \leq m$, capacity constraints are binding, that is, industry capacity is insufficient to serve the monopoly output. No firm could profitably deviate when all firms charge $\overline{p}$. Hence, the minimum discount factor is zero.

If $nk > m > (n-1)k$, we are in the range relevant to the experiment. Suppose first that firms successfully collude by tacitly agreeing to charge a price of $p \leq \overline{p}$. Then collusive profits are $\pi_i^c = pmk/(nk) = pm/n$ (that is, each firm gets its symmetric share of industry profit). Defecting with a price marginally smaller than p, firm i can get $\pi^d = pk > \pi_i^c$. Finally, $\pi_i^p = \overline{p}(m-(n-1)k)$. Collusion is a subgame perfect Nash equilibrium only if $\pi^c/(1-\delta) \geq \pi^d + \pi^p\delta/(1-\delta)$ or

$$\delta \geq \frac{\pi^d-\pi^c}{\pi^d-\pi^p} = \frac{p-pm/(nk)}{p-\overline{p}(m-(n-1)k)/k} \tag{8}$$

From $\partial\delta/\partial p < 0$, colluding with a price smaller than $\overline{p}$ not only decreases profits but also requires a higher discount factor. Therefore, we analyze perfect collusion where firms charge the reservation price $\overline{p}$ when colluding. With $p = \overline{p}$, (8) simplifies to $\delta \geq 1/n$. That is, the minimum discount factor decreases in n.

If $(n-1)k \geq m > k$, static Nash profits are zero: since $n-1$ competitors can competitors can serve all m customers, charging a price of zero is the static Nash equilibrium. Collusive profits are $\pi_i^c = \overline{p}m/n$ as above. Because one firm alone cannot serve

m customers, its defection payoffs are $\overline{p}k$. We obtain

$$\delta \geq \frac{\overline{p}k - \overline{p}m/n}{\overline{p}k} = 1 - \frac{m}{nk} \tag{9}$$

The minimum discount factor increases here in n here.

Finally, for $k > m$, we are in the standard Bertrand setting without capacity constraints. In this case, the minimum discount factor is $\delta \geq 1 - 1/n$, which is increasing in n as in the previous segment.□

Proof of Proposition 3. Let ε denote the smallest amount of money by which one firm can undercut another firm's price. First, note what the notion of a myopic best reply implies in our setting. When myopically best responding, the $n-1$ firms that do not charge the highest price will actually increase their price to the highest price minus ε (selling k as before but at a higher price). The high-price firm will charge the second highest price minus ε. Thus, all firms charge $\max\{p_{j\neq i}\} - \varepsilon$, as in (4).

This best response implies that prices are chosen from the interval $[\underline{p}, \overline{p}]$ (which coincides with the support of the mixed-strategy equilibrium). To prove the proposition, we need to show that prices are uniformly distributed over the interval.

Suppose first that there are $n > 2$ firms and let $p_1 \geq p_2$ denote the two (weakly) highest prices charged in $t = 0$. If $p_1 > p_2$ strictly, the high-price firm will charge $p_2 - \varepsilon$ in $t = 1$ and all other firms will set $p_1 - \varepsilon$ in $t = 1$. Then $\max\{p_{j\neq i}^{t=1}\} = p_1 - \varepsilon$ for all firms and thus *all* firms will charge $p_1 - 2\varepsilon$ in $t = 2$. But then all firms will charge $p_1 - 3\varepsilon$ in $t = 3$, $p_1 - 4\varepsilon$ in $t = 4$ and so on until the firms switch to $\overline{p}$. Eventually they charge $p_1 - 2\varepsilon$ again and a new Edgeworth cycle begin. Hence, all prices in $[\underline{p}, \overline{p}]$ are chosen exactly once by all firms in a cycle (except for the first two periods) and thus prices are uniformly distributed. The same holds if $p_1 = p_2 \geq p_3 ...$ in $t = 0$. All firms set the same price starting from period $t = 1$ on and then play the Edgeworth cycle.

With $n = 2$ firms, the pattern is slightly different. As there is only one rival for each firm, $\max\{p_{j\neq i}^t\}$ is always the price of the other firm. This trivially leads to Edgeworth cycles where all prices are played and are thus uniformly distributed. To see this, suppose that in $t = 0$ firms choose $p_1 = \widehat{p}$ and $p_2 = \widetilde{p}$. As long as prices are above the lower bound, firms will set $p_1 = \widetilde{p} - t \cdot \varepsilon$ and $p_2 = \widehat{p} - t \cdot \varepsilon$ in odd numbered periods; whereas, in even numbered periods, firms will set $p_1 = \widehat{p} - t \cdot \varepsilon$ and $p_2 = \widetilde{p} - t \cdot \varepsilon$. Whenever $p_j = \underline{p}$ in period t, firm i will switch to $\overline{p}$ in $t + 1$, resulting in the same pattern of firms undercutting their rival's $t - 1$ price. As prices are played exactly once over an Edgeworth cycle, they are thus uniformly distributed.□

Appendix B: Sample Duopoly Instructions

Instructions

Hello and welcome to our experiment. Please read this instruction set very carefully, since through your decisions and the decisions of other participants, you may stand to gain a significant amount of money. We ask you to remain silent during the entire experiment; if at any point in time you require assistance, please raise your hand.

In this experiment you will be in the role of a firm, which is in a market with another firm. The firms produce some good and there are no costs of producing this good.

This market is made up of 300 identical consumers, each of whom wants to purchase one unit of the good at the lowest price. The consumers will pay as much as 100 Experimental Currency Units (ECU) for a unit of the good.

In each market there will be 2 firms, A and B. You can find your type written on the top right-hand corner of this instruction set. Each firm will be able to supply 300 consumers.

The market will operate as follows. In the beginning of each period, all firms will set their selling prices. Then the firm who set the lowest price will sell its capacity at the selected price. The firm who set the second lowest price will not have any customers left to supply.

If more than one firm set the same price and if the number of consumers firms can supply is higher than the number of consumers who haven't bought the good, then they will split the available consumers proportionally to their capacity. In order to fix ideas, let us go over a couple of illustrative examples:

Example A:

Suppose that the two firms choose the following prices: Firm A sets a price of 85 and firm B chooses a price of 75. Firm B set the lowest price and therefore sells its 300 units first at a price of 75, making a profit of 22,500 ECU. Firm A set the highest price and therefore will not supply any customers, therefore making 0 ECU.

Example B: Suppose that the two firms choose the following prices: Firm A and firm B both set a price of 70. Given that they set the same price and also given that their combined capacity (600 units) is larger than the number of customers, they will have to share the available customers. Since their capacities are equal, so will their share of the sales. Hence, both firms will sell 150 units at a price of 70 each unit, therefore making a profit of 10,500 ECU.

At the end of each period, all the firms are informed of the chosen prices by all firms and their own profits. There will be at least 30 periods in this experiment once the 30th period is over, the computer will throw a "virtual" dice that will determine whether the experiment continues. If a value of 6 is shown, the experiment is over. If any other value is shown, the experiment continues.

You will be matched with the same participants in every period.

At the end of the experiment, you will be told of the sum of profits made during the experiment, which will be your payment. You will receive £1 for every 25,000 ECU you earn during the experiment. Additionally you will receive £5 for participating.

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$n = 2$	treatment	175-175	201-201	225-225	250-250	300-300
	total capacity	350	402	450	500	600
$n = 3$	treatment	116-116-116	134-134-134	150-150-150		
	total capacity	348	402	450		

Table 1: Treatments

Treatment	Total Capacity	Predictions Edgwth. Cycles	Nash Eq.	Data p
175-175	350	85.71	84.34	84.96
				(9.70)
201-201	402	75.63	69.08	78.44
				(11.93)
225-225	450	66.67	55.21	60.50
				(19.57)
250-250	500	60.00	40.23	54.04
				(23.62)
300-300	600	50.00	0.00	40.48
				(22.20)
116-116-116	348	79.63	70.00	73.51
				(9.46)
134-134-134	402	61.94	37.03	64.69
				(20.19)
150-150-150	450	50.00	0.00	41.73
				(18.10)

Standard deviations in parenthesis

Table 2: Predicted and observed average weighted prices.

dep var: $(P_t - P_{t-1})$	(1)		(2)	
$k350$	0.864	(0.721)	0.470	(1.362)
$k402$	0.172	(0.684)	-2.775**	(1.331)
$k450$	0.270	(0.620)	7.898**	(3.038)
$k500$	0.747	(0.631)	6.950***	(2.122)
$k600$	0.083	(0.689)	2.740**	(1.083)
$(P_{t-1} - P_{t-2}) \times k350$	-0.571***	(0.037)		()
$(P_{t-1} - P_{t-2}) \times k402$	-0.560***	(0.068)		()
$(P_{t-1} - P_{t-2}) \times k450$	-0.431***	(0.035)		()
$(P_{t-1} - P_{t-2}) \times k500$	-0.384***	(0.034)		()
$(P_{t-1} - P_{t-2}) \times k600$	-0.288***	(0.058)		()
$k350 \times tri$	-0.610**	(0.248)	2.336	(1.604)
$k402 \times tri$	0.441	(0.530)	5.086***	(1.474)
$k450 \times tri$	0.403	(0.637)	-4.918	(2.964)
$(P_{t-1} - P_{t-2}) \times k350 \times tri$	0.223***	(0.069)		()
$(P_{t-1} - P_{t-2}) \times k402 \times tri$	0.350***	(0.092)		()
$(P_{t-1} - P_{t-2}) \times k450 \times tri$	0.210***	(0.050)		()
$\max\{0, (P_{t-1} - P_{t-2})\} \times k350$			-0.467***	(0.118)
$\max\{0, (P_{t-1} - P_{t-2})\} \times k402$			-0.340***	(0.071)
$\max\{0, (P_{t-1} - P_{t-2})\} \times k450$			-0.692***	(0.106)
$\max\{0, (P_{t-1} - P_{t-2})\} \times k500$			-0.612***	(0.067)
$\max\{0, (P_{t-1} - P_{t-2})\} \times k600$			-0.392***	(0.047)
$\min\{0, (P_{t-1} - P_{t-2})\} \times k350$			0.702***	(0.131)
$\min\{0, (P_{t-1} - P_{t-2})\} \times k402$			0.831***	(0.010)
$\min\{0, (P_{t-1} - P_{t-2})\} \times k450$			0.054	(0.118)
$\min\{0, (P_{t-1} - P_{t-2})\} \times k500$			0.054	(0.068)
$\min\{0, (P_{t-1} - P_{t-2})\} \times k600$			0.100	(0.104)
$\max\{0, (P_{t-1} - P_{t-2})\} \times k350 \times tri$			-0.118	(0.206)
$\max\{0, (P_{t-1} - P_{t-2})\} \times k402 \times tri$			0.082	(0.126)
$\max\{0, (P_{t-1} - P_{t-2})\} \times k450 \times tri$			0.397***	(0.120)
$\min\{0, (P_{t-1} - P_{t-2})\} \times k350 \times tri$			-0.696***	(0.167)
$\min\{0, (P_{t-1} - P_{t-2})\} \times k402 \times tri$			-0.751***	(0.127)
$\min\{0, (P_{t-1} - P_{t-2})\} \times k450 \times tri$			-0.025	(0.179)
$1/t$	-7.608	(13.573)	-21.361	(15.156)
N	1,584		2,754	
R-squared	0.145		0.171	

Clustered standard errors at group level in parenthesis

Significance level: ***: 1%; **: 5%; *: 10%.

Table 3: Autocorrelation of prices

Treatment	$p = 100$	Successful collusion	Failed collusion
175-175	0.31	0.16	0.15
201-201	0.10	0.01	0.09
225-225	0.13	0.02	0.11
250-250	0.12	0.02	0.09
300-300	0.04	0.01	0.03
Total	0.13	0.03	0.09
116-116-116	0.05	0.00	0.05
134-134-134	0.05	0.00	0.05
150-150-150	0.05	0.00	0.05
Total	0.05	0.00	0.05

Table 4: Relative frequency of attempted and successful collusion

	(175-175)	(201-201)	(225-225)	(250-250)	(300-300)	All
β_1	0.521**	0.499**	0.485**	0.454**	0.465**	0.465**
	(0.088)	(0.046)	(0.052)	(0.034)	(0.024)	(0.020)
β_2	-0.248*	-0.043	-0.0892	-0.105*	0.041	-0.079**
	(0.090)	(0.069)	(0.053)	(0.040)	(0.042)	(0.029)
β_0	-0.829	0.074	-1.422	-1.908	0.154	-0.994
	(0.558)	(0.124)	(1.068)	(1.851)	(0.246)	(0.503)
Obs.	240	300	384	348	312	1584
R-squared	0.29	0.23	0.22	0.25	0.29	0.24

Estimated equation: $P_{i,t} - P_{i,t-1} = \beta_0 + \beta_1(P^E_{i,t} - P_{i,t-1}) + \beta_2(P^E_{i,t-1} - P_{i,t-2}) + \epsilon_{i,t}$
Clustered standard errors at group level in parenthesis
Significance level: ***- 1%; **- 5%; *- 10%.

Table 5: Edgeworth-cycle estimates at treatment level: duopolies

	(116-116-116)	(134-134-134)	(150-150-150)	All
β_1	0.467**	0.412**	0.388**	0.398**
	(0.024)	(0.076)	(0.095)	(0.064)
β_2	0.014	-0.046	-0.131**	-0.093*
	(0.052)	(0.035)	(0.031)	(0.033)
β_0	-1.342*	-1.241	-1.481	-1.224**
	(0.417)	(0.559)	(0.775)	(0.393)
Obs.	414	360	396	1170
R-squared	0.31	0.17	0.24	0.22

Estimated equation: $P_{i,t} - P_{i,t-1} = \beta_0 + \beta_1(P^E_{i,t} - P_{i,t-1}) + \beta_2(P^E_{i,t-1} - P_{i,t-2}) + \epsilon_{i,t}$
Clustered standard errors at group level in parenthesis
Significance level: ***- 1%; **- 5%; *- 10%.

Table 6: Edgeworth-cycle estimates at treatment level: triopolies

	(1)	(2)
β_1	0.466***	0.469***
	(0.023)	(0.023)
β_2	0.041	-0.103***
	(0.040)	(0.028)
$\beta_1 \times tri$	-0.078	-0.039
	(0.094)	(0.052)
$\beta_2 \times tri$	-0.171***	0.078*
	(0.050)	(0.040)
tri	-1.634*	-0.084
	(0.776)	(0.650)
constant	0.154	-1.178**
	(0.234)	(0.574)
Obs.	708	2,046
R-squared	0.264	0.229

Clustered standard errors at group level in parenthesis
Significance level: ***- 1%; **- 5%; *- 10%.

Table 7: Edgeworth-cycle estimates: treatments with pure-strategy equilibrium (1) vs. treatments with mixed strategy equilibrium (2).

Treatment	(1)	(2)	(3)	(4)
	$\beta_1 = 0, \beta_2 = 0$	$\beta_0 = 0, \beta_1 = 1, \beta_2 = 0$	$\beta_1 = 0$	$\beta_2 = 0$
175-175	0.58	0.42	0.58	0.00
201-201	0.75	0.75	0.75	0.17
225-225	0.67	0.67	0.83	0.08
250-250	0.67	0.92	0.75	0.17
300-300	0.67	0.92	0.83	0.08
Duopolies	0.83	0.82	0.88	0.08
116-116-116	0.61	0.94	0.78	0.11
134-134-134	0.67	0.61	0.67	0.06
150-150-150	0.72	0.72	0.72	0.17
Triopolies	0.78	0.80	0.80	0.09

Table 8: Fraction of rejection of null hypotheses at the 5% level by treatment

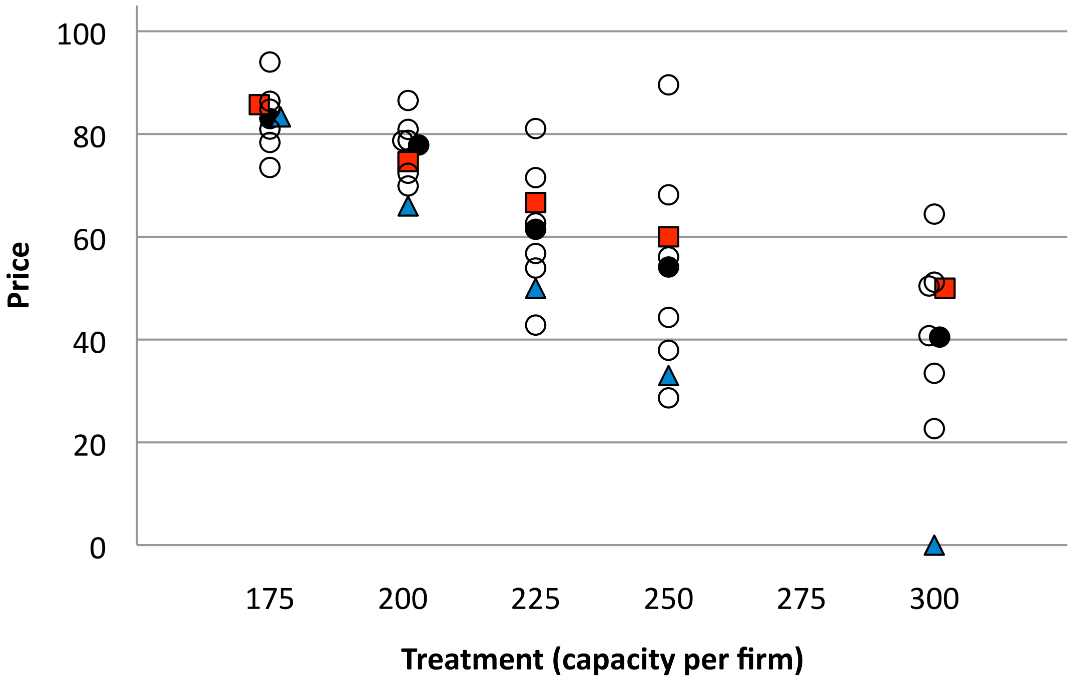


Figure 1. Average prices and predictions in the duopoly treatments. Blank circles are the average price of a group (six per treatment). Filled circles are the average price per treatment across all groups. Triangles and squares indicate the expected Nash price and the expected Edgeworth-cycle price, respectively.

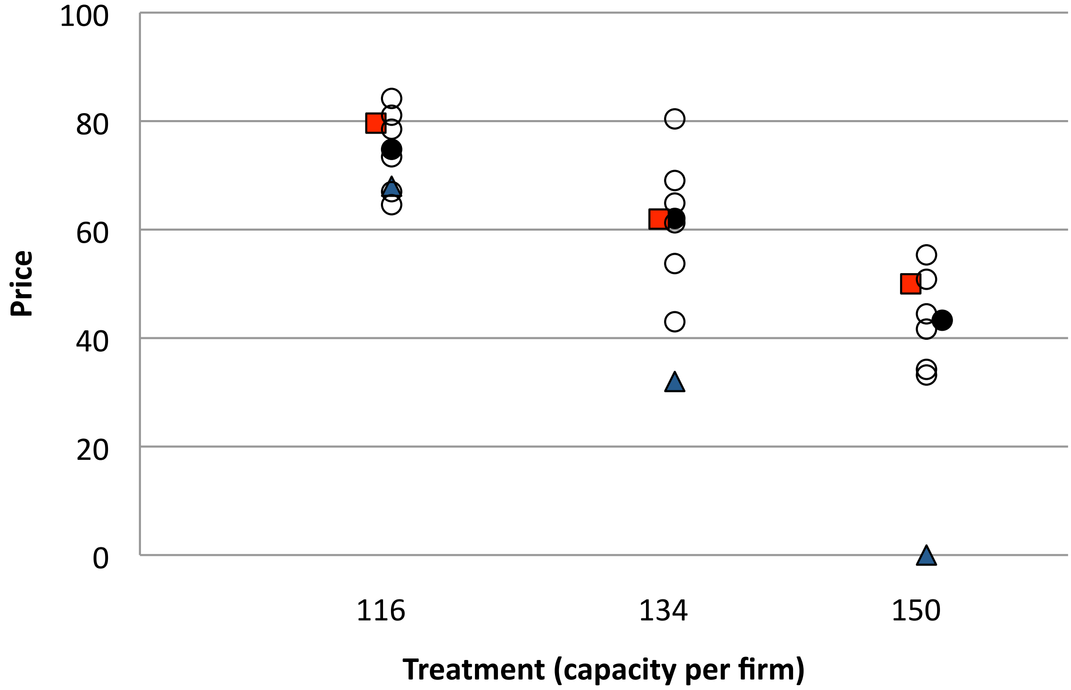


Figure 2. Average prices and predictions in the triopoly treatments. Blank circles are the average price of a group (six per treatment). Filled circles are the average price per treatment across all groups. Triangles and squares indicate the expected Nash price and the expected Edgeworth-cycle price, respectively.

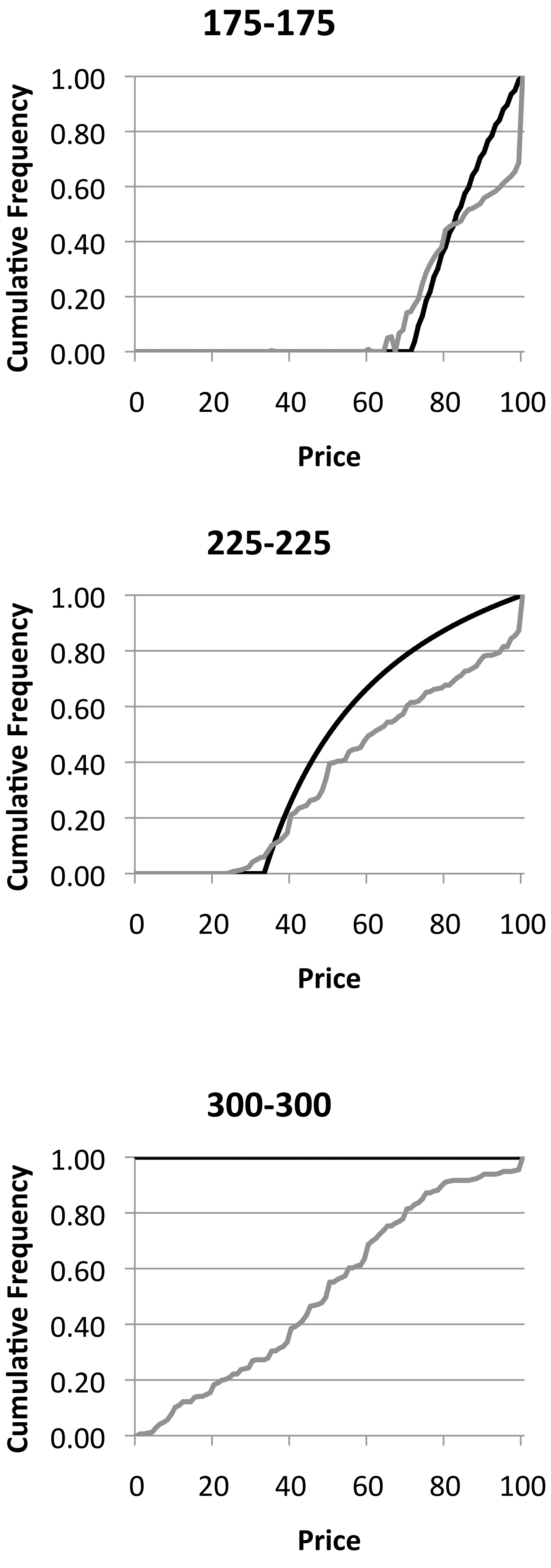


Figure 3. Predicted (black) and observed (grey) cumulative price distributions – duopoly treatments.

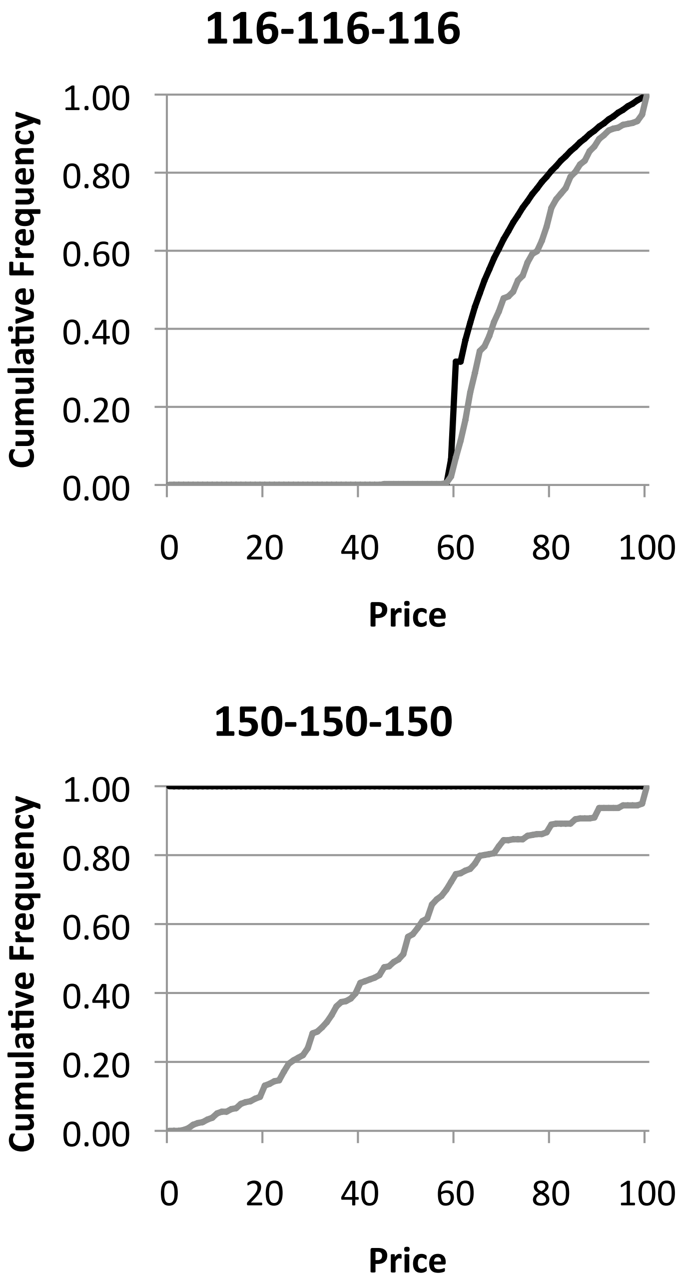


Figure 4. Predicted (black) and observed (grey) cumulative price distributions – triopoly treatments.

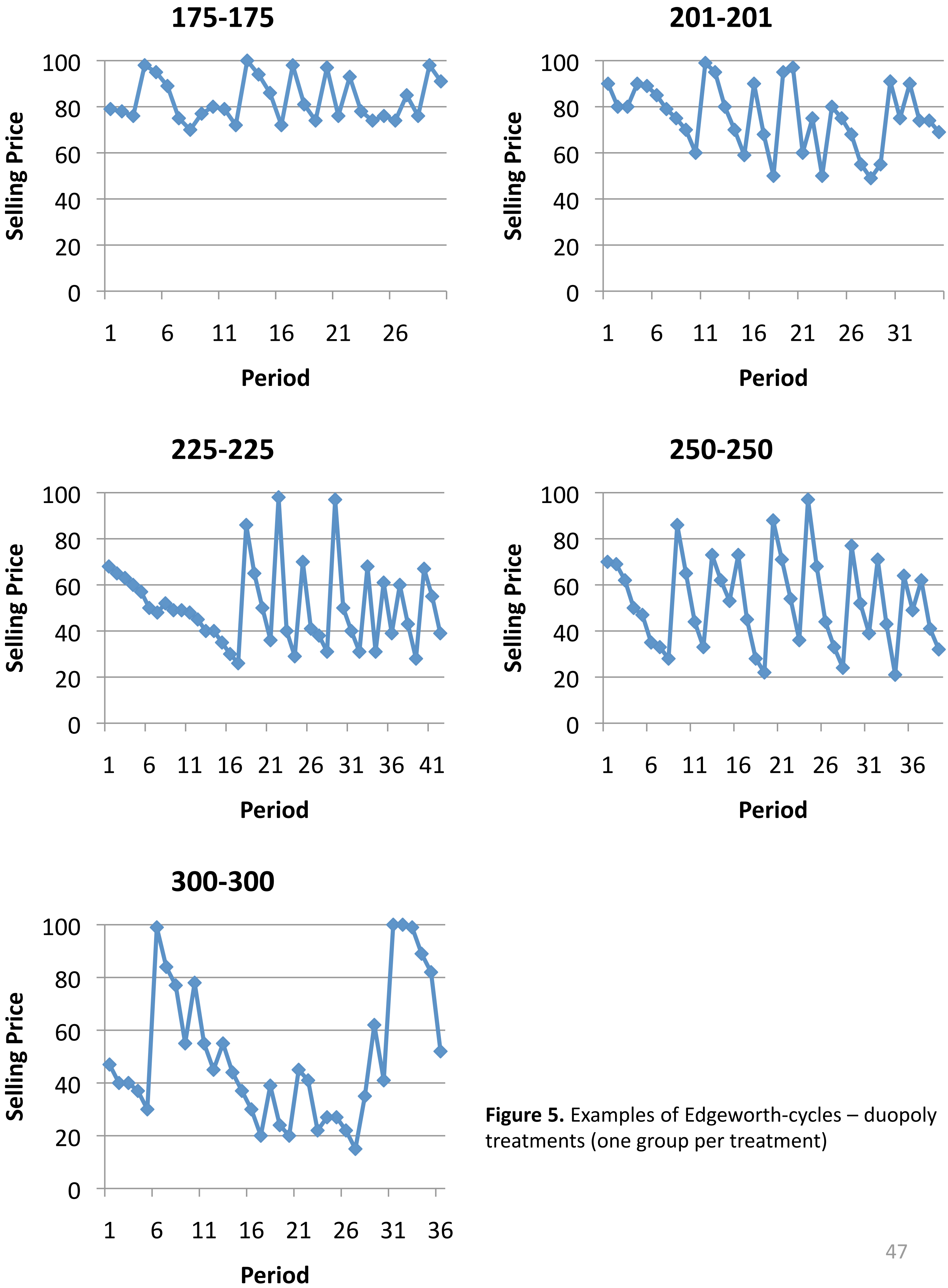
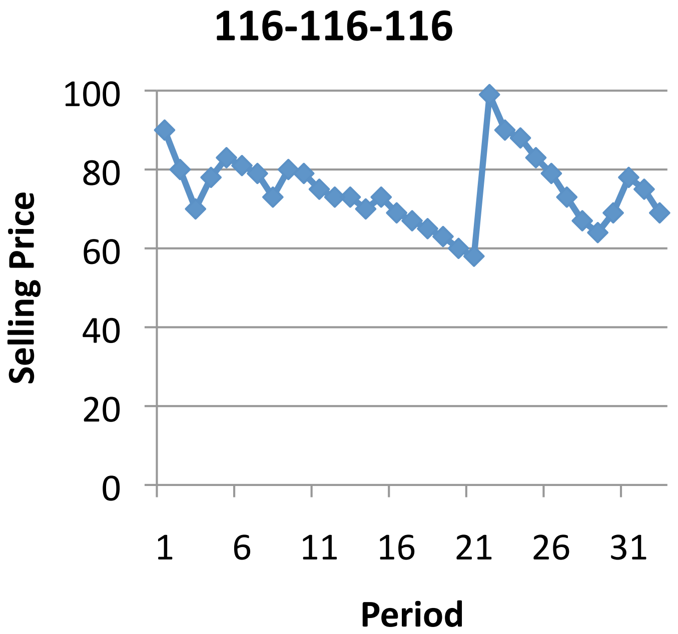
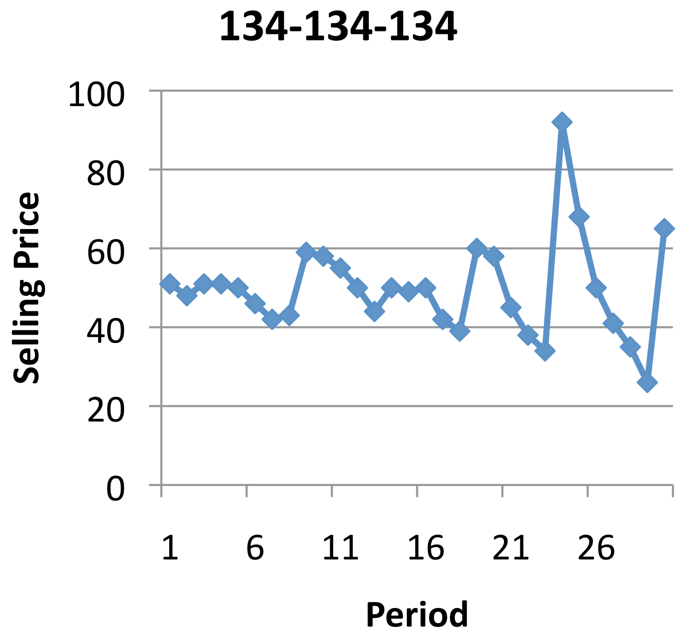


Figure 5. Examples of Edgeworth-cycles – duopoly treatments (one group per treatment)





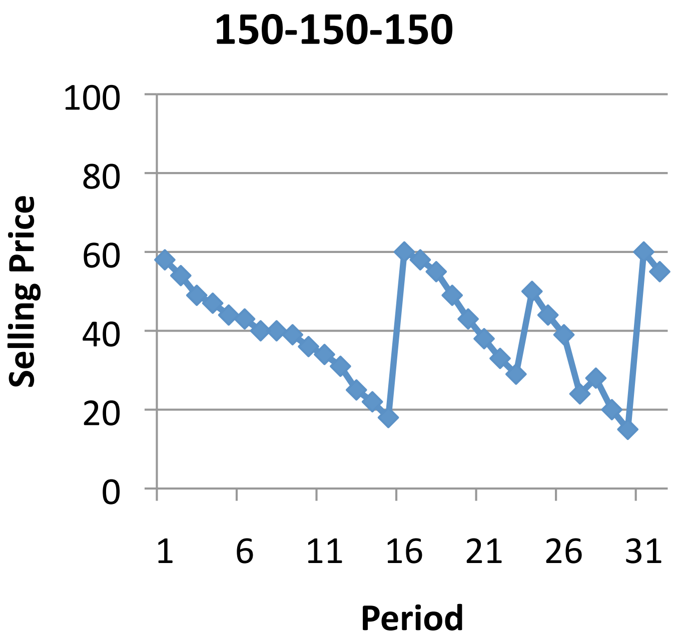


Figure 6. Examples of Edgeworth-cycles – triopoly treatments (one group per treatment)

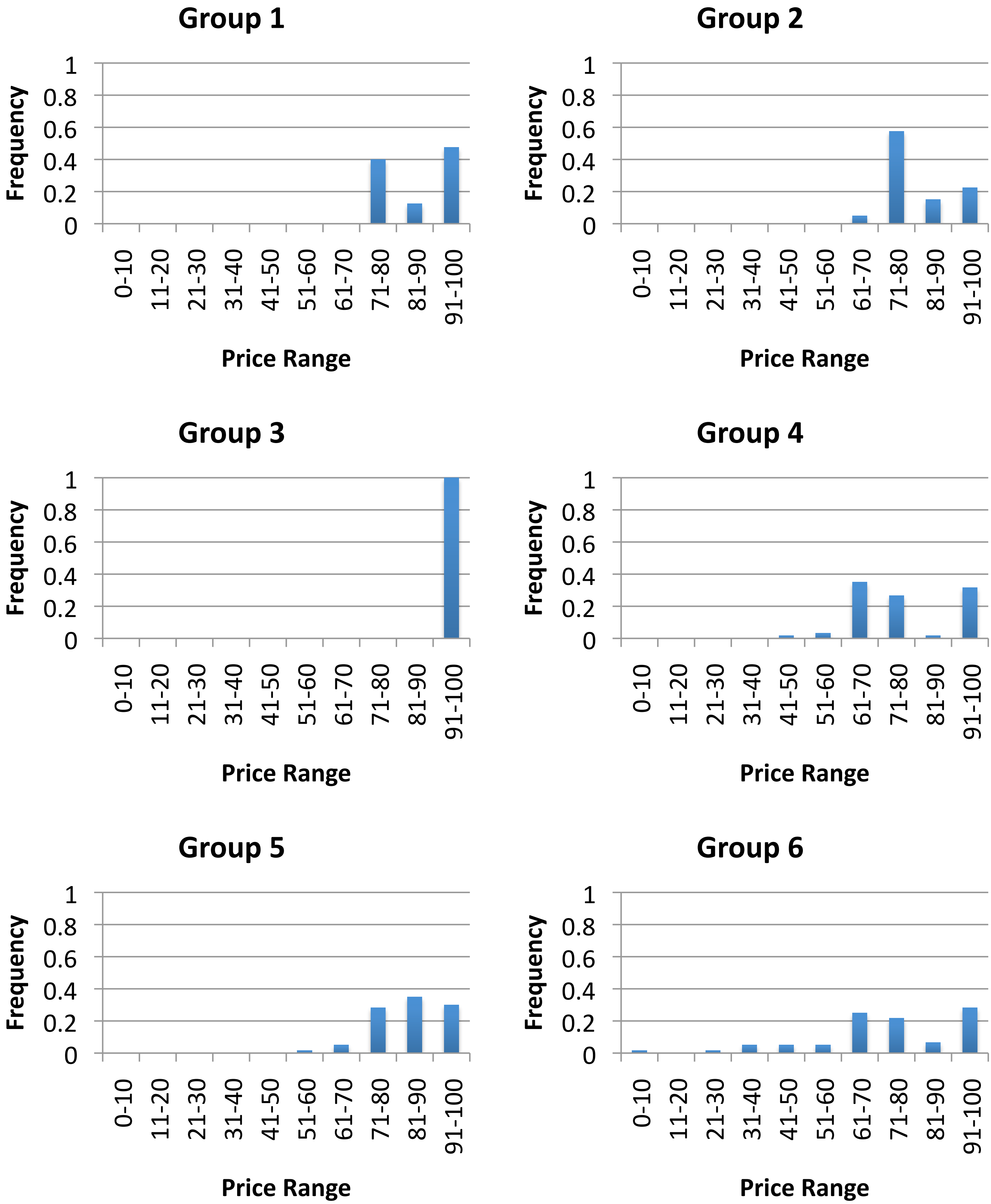


Figure 7. Histograms of pricing decisions by group, treatment 175-175

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