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bertrand-edgeworth markets with increasing marginal costs and voluntary trading: experimental evidence

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Bertrand-Edgeworth Markets with Increasing Marginal Costs and Voluntary Trading: Experimental Evidence^{*}

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Abstract: Price competition with increasing marginal costs, though relevant for many markets, appears as an under-researched field in the experimental oligopoly literature. We provide results from an experiment that varies the number of firms as well as the demand rationing and matching schemes in Bertrand-Edgeworth markets with increasing marginal costs and voluntary trading. We find that prices and profits are substantially higher in duopoly than in triopoly and with proportional compared to efficient demand rationing. The matching rule has little effect on prices and profits. Nash equilibrium predictions do not capture observed behavior. Neither the mixed-strategy Nash equilibria of the underlying one-shot game nor, for the fixed matching condition, the symmetric stationary outcome pure-strategy Nash equilibria of the infinitely repeated game are supported by the data. In contrast to results from related experiments, behavior is largely more competitive than predicted by Nash equilibrium theory. Individual pricing decisions can predominantly be explained by either myopic best responses (Edgeworth cycles) or simple imitative behavior, where the complexity of the decision situation plays a crucial role in which behavioral pattern applies.

JEL classification: C72, C90, D43, L13.

Key words: Bertrand-Edgeworth, demand rationing, increasing marginal costs, Edgeworth cycles, oligopoly, laboratory experiment.

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1 Introduction

In his "Papers Relating to Political Economy", Edgeworth (1925) advanced oligopoly theory by his critique of the Bertrand model. He suggested abandoning Bertrand's assumption that firms can produce any quantity at constant marginal costs and assuming instead capacity restrictions or increasing marginal costs. The Bertrand (1883) model predicts that price competition leads to marginal cost pricing and zero profits whenever there is more than one firm in the market. Edgeworth's modifications abandon that prediction and thus make the model more realistic. In this study, we concentrate our attention on Edgeworth's second alternative supposition, that of increasing marginal costs. Note that strictly convex production costs, or, put differently, decreasing returns to scale, are also a key ingredient of the neoclassical model of perfect competition. However, the modification also complicates analysis tremendously. The Bertrand-Edgeworth model has no pure-strategy Nash equilibrium. Edgeworth himself suggested that firms will react myopically to their competitors' price choices, thus giving rise to the price cycles that were later named after him. Advances in game theory later allowed for a more extensive analysis. Existence of Nash equilibrium in mixed strategies has been proven. It has been shown that equilibrium predictions can be heavily influenced by seemingly minor changes in the model design, notably by the rule according to which demand is rationed.

A considerable part of experimental economics has been concerned with conduct in oligopolies. The experimental investigation of the Bertrand-Edgeworth model, however, stands out as an under-researched topic. Compared to the wealth of experiments that study behavior in Bertrand and Cournot markets with diverse variations, experimental studies in the more realistic Bertrand-Edgeworth setting are relatively scarce. Additionally, most of the few existing studies deal with the case of fixed capacities instead of increasing marginal costs. We are aware of only three studies that consider price competition with increasing marginal costs in an experimental setting. Two of them - Abbink and Brandts (2008) and Argenton and Müller (2012) - assume, contrary to Edgeworth, that firms are obliged to cover the entire market demand at the price they choose. That assumption, while considerably simplifying the analysis, does not reflect reality in most cases where suppliers are free to limit the quantity they wish to bring to the market. The assumption pertains only to a minority of heavily state-regulated markets, notably for utilities. The third study by Kruse (1993) is, to the best of our knowledge, the only former experiment of price competition with increasing marginal costs and voluntary trading. In this study, however, only demand rationing is varied and behavior on the individual level is hardly analyzed.

Further experiments based on the Bertrand-Edgeworth model appear fruitful to us for at least two reasons. Firstly, since the model's assumptions are more realistic than those made by Cournot and Bertrand, experimental results may more easily be transferred to real oligopolies. Secondly, as game-theoretic analysis has revealed that the model's outcome is highly sensitive to seemingly minor modifications in design, the question arises whether subjects in experiments and actual firms will in fact react to such inconspicuous changes.

In this study, we present an experiment of price oligopoly with linear demand and a quadratic cost function. We investigate both duopoly and triopoly markets. Furthermore, we vary the demand rationing rule and the matching scheme. We find substantially higher prices and profits in duopoly compared to triopoly and under proportional compared to efficient demand rationing. In contrast, it has only a small positive effect on prices and profits when subjects repeatedly interact within fixed groups instead of being re-matched after every round of the game. Analysis of individual price choices does not support the static Nash equilibrium prediction. In contrast to results from related experiments, behavior is largely more competitive than predicted by the Nash equilibrium. We observe both myopic best response and imitation behavior. While myopic best responses are the main driving factor in duopoly, subjects seem to resort to the simpler strategy of imitation in the more complex triopoly. Furthermore, subjects are more prone to stable pricing, i.e. set the same price in successive periods, under random matching. That stands in contrast to theory since a Nash equilibrium supporting such pricing patterns exists only in the infinitely repeated game. Our finding can be explained by the observation that stable pricing is hardly an indication of collusion in our data; rather, most subjects exhibiting stable behavior constantly set low prices following a risk averse maximin strategy.

The remainder of this study is structured as follows. Section 2 discusses Edgeworth's model of price competition and later studies in game theory that ensued from it. Section 3 reviews the related experimental literature. Sections 4 and 5 introduce the setup of the model that underlies our experiment and the experimental procedures. Section 6 presents the rather complex Nash equilibrium predictions of the calibrated model. We present and discuss our experimental results in section 7. Section 8 concludes.

2 Theory

The model of simultaneous price oligopoly by Bertrand (1883) assumes that firms can produce any quantity of a homogenous product at constant marginal costs and therefore suggests perfect competition leading to marginal cost pricing and zero profits whenever there

is more than one firm in the market. To overcome this unrealistic result, Edgeworth (1925) proposed to either introduce production capacity constraints for firms or substitute strictly convex for linear production costs. In the latter case, self-imposed capacity constraints emerge implicitly since each firm is willing to produce only as long as its marginal production costs are no higher than the sales price it has set. Trading is voluntary, so firms are free to turn customers away when further supply becomes unprofitable. As in the Bertrand model, productions are made to order after demands have been revealed. Production costs are therefore incurred only for units that can be sold in the market.

The thus modified model turned out to be very intricate. It has no Nash equilibrium in pure strategies. The existence of equilibrium in mixed strategies was proven only many decades after Edgeworth's proposal (Dixon, 1984; Dasgupta and Maskin, 1986; Maskin, 1986). While equilibrium strategies have been characterized for special cases of the model with fixed capacity constraints (Beckmann, 1967; Levitan and Shubik, 1972; Osborne and Pitchik, 1986; Vives, 1986; Allen and Hellwig, 1993; Hirata, 2009; De Francesco and Salvadori, 2010; 2013), an equilibrium characterization for the model with strictly convex costs still is unavailable. Instead, further model modifications have been suggested in order to restore existence of pure-strategy Nash equilibrium. Those suggestions comprise weakening the voluntary trading constraint (Dixon, 1990; 1992; Dastidar, 1995) and allowing only discrete pricing (Dixon, 1993; Roy Chowdhury, 2008).

The complexity of Bertrand-Edgeworth models is in part due to the fact that their outcomes depend on the assumption made about demand rationing. Customers first try to buy the good from the firm offering at the lowest price. Due to the capacity constraints, that firm may well be unable to satisfy the entire market demand. Some residual demand will then be left for the other firms offering at higher prices. To determine residual demands, an assumption about how demand is rationed is necessary. Two rationing schemes are prominent in the literature. The one, proportional rationing, assumes that customers are served in random order. According to the other scheme, efficient rationing, customers are served in order of their willingness to pay for the product. Those customers with the highest willingness to pay are served first, thus leaving the least residual demand among all possible rationing schemes. The effect of different rationing schemes on residual demand is illustrated in Figure 1 for a triopoly with linear total demand $D(p) = 1000 - p$. In the figure, the bold line represents the remaining demand for firm 3 with given capacities ($q_1 = 300$, $q_2 = 200$) and prices ($p_1 = 200$, $p_2 = 400$) of firms 1 and 2. While under proportional rationing residual demand is

obtained by rotating the demand curve around the reservation price, under efficient rationing the demand curve is shifted leftwards in parallel.

- Figure 1 about here -

Whereas a full characterization of the equilibrium is unavailable, some results about its properties have been obtained. Allen and Hellwig (1986a; 1986b) show that, as the number of competitors increases, the probability mass of the equilibrium strategies moves towards the competitive price. However, under proportional rationing, there is no convergence in the supports. A strictly positive, albeit declining, probability for a high price near the monopoly price always remains. An intuition for this result may be provided by the fact that if all firms but one set the competitive price, the last firm maximizes its profit by acting as a monopolist vis-à-vis its residual demand. Under proportional rationing, a random portion of customers is left for that firm and it pays off to set a high price. Under efficient rationing, in contrast, there is no point for the last firm in setting a high price since all customers with a high willingness to pay have already been served by others. In that case, also the supports of the equilibrium strategies converge (Vives, 1986).¹

Further studies consider repeated interaction of firms, thus allowing for supergame effects. If there is a sufficiently high probability for the firms to interact again, threats of future punishment can deter them from uncooperative conduct. In repeated price competition with exogenous capacities, Brock and Scheinkman (1985) find two opposing effects of an increasing number of firms in the market. On the one hand, as the number of firms grows, each firm in a cartel receives a declining share of the cartel profit, which makes defection more attractive. On the other hand, with more firms there is more total capacity in the market, which allows for a fiercer retaliation against a defector. As it turns out, the effect is non-monotonic; cartel power attains a maximum for some intermediate number of firms.

Moreover, as shown by Abreu (1988), infinitely repeated games possess subgame perfect Nash equilibria in pure strategies which follow a rather simple stick-and-carrot approach. Whenever a player deviates from collusion, a predefined phase of punishment is executed. In the Bertrand-Edgeworth framework, such equilibria are characterized by Lambson (1987) for the case with fixed capacities and by Requate (1994) for the case with increasing marginal costs.

¹ Börgers (1992) shows that this result can also be arrived at if one deploys iterated elimination of dominated strategies instead of the Nash equilibrium concept.

3 Related experiments

Compared to the plenty of experiments investigating oligopolies in standard Cournot or Bertrand markets, the number of studies concerned with Bertrand-Edgeworth markets is relatively small. In a seminal study, Kruse et al. (1994) consider the effect of capacity and information conditions on pricing in a four-player Bertrand-Edgeworth game with exogenously given capacities and proportional demand rationing. They find that higher capacities go along with lower prices whereas the information condition entails no significant effect. Moreover, prices are higher than predicted by the static Nash equilibrium and there is evidence that subjects to some extent adjust their prices according to a myopic best response rationale as put forward by Edgeworth. A closely related experiment is conducted by Fonseca and Normann (2013) who vary capacities and the number of firms in the market.² They also observe falling prices with increasing capacities and dynamic pricing patterns which are more in accordance with Edgeworth cycles than with the static Nash equilibrium. The explanatory power of Edgeworth cycle theory decreases with increasing market capacity and is lower in triopoly than in duopoly. Fonseca and Normann (2008) investigate duopolies and triopolies with symmetric and asymmetric firms. They observe that symmetric firms and a market with fewer firms lead to higher prices. Heymann et al. (2014) find that their experimental data fit a simple heuristic model according to which a subject increments her price as long as her sales hit the capacity constraint and lowers her price by a certain amount if she is unable to sell up to her capacity.

All experiments mentioned in the above paragraph pertain to a setting with constant marginal costs up to a fixed exogenous cap. A Bertrand-Edgeworth setting with strictly convex costs is investigated by Abbink and Brandts (2008). However, they abandon the voluntary trading constraint. In their experiment, the firm offering at the lowest price is obliged to satisfy the entire demand at its price. Residual demand for the other firms thus equals zero. Varying the number of firms in the market between two, three and four, Abbink and Brandts observe that a market with more firms yields lower prices. Yet, prices remain substantially above the competitive level. Moreover, price choices concentrate on a focal price not predicted by any benchmark result, which the authors rationalize by employing an imitation model. In a similar framework, Argenton and Müller (2012) study cost asymmetry in duopolies and find that asymmetry can be conducive to collusion.

² Fonseca and Normann employ a model with box demand, so an assumption about demand rationing is superfluous.

Few experiments have studied the effect of demand rationing. Kruse (1993) compares proportional and efficient rationing in posted-offer markets with two sellers and U-shaped average costs. She finds that prices are higher with proportional rationing. That effect as well as the observed price levels are in accordance with the Nash prediction for the underlying one-shot game, though in the experiment repeated play was executed. Jacobs and Requate (2016) obtain a similar effect of rationing in price competition with fixed exogenous capacities. In contrast to Kruse, they observe that prices largely are higher than predicted by the Nash equilibrium of the one-shot game. Lepore and Shafran (2013) and Jacobs (2016) vary demand rationing in a two-stage quantity setting and pricing experiment resembling the model by Kreps and Scheinkman (1983). Both studies find that while rationing has no significant effect on capacity choices at the first stage, prices at the second stage are higher with proportional rationing. Contrary to the aforementioned experiments, prices are considerably lower than the Nash prediction in that setting. Another study in which several different rationing schemes are employed is by Buchheit and Feltovich (2011). However, they aim at investigating a sunk cost effect and do not use demand rationing as a treatment variable; rather, in their experiment the effective rationing scheme is determined randomly.

4 The model

The underlying model of our experiment is a price-setting oligopoly market in which n identical firms offer a single homogenous good. Firms are confronted with a linear market demand function

$$D(p) = \frac{\alpha - p}{\beta}, \alpha, \beta > 0,$$

representing the total volume of the good that can be sold in the market at a certain price in each period. Each firm i has a quadratic cost function

$$C_i(q_i) = \frac{\gamma}{2} q_i^2, \gamma > 0, i = 1, \dots, n.$$

There are no fixed costs. As productions are made to order, q_i represents both the produced and the sold quantity of firm i . A firm will stop producing and selling when its marginal production cost reaches its marginal revenue which is equal to the price it has set. Each firm therefore has an implicit capacity constraint K_i depending on its individual price p_i :

$$K_i(p_i) = \frac{p_i}{\gamma}, i = 1, \dots, n.$$

If demand is not enough for all firms to exhaust their capacities, firms with lower prices will sell first and demand will be rationed according to the effective rationing scheme. We employ

both proportional and efficient rationing. The quantity of firm i thus is the minimum of its implicit capacity and its residual demand $d_i(\mathbf{p})$ which depends on the price vector \mathbf{p} :

$$q_i(\mathbf{p}) = \min\{d_i(\mathbf{p}), K_i(p_i)\}, i = 1, \dots, n.$$

The residual demand of firm i varies with the rationing scheme and is given by

$$d_i(\mathbf{p}) = \begin{cases} \max\left\{0, \frac{D(p_i)}{m} \left(1 - \sum_{j|p_j < p_i} \frac{K_j(p_j)}{D(p_j)}\right)\right\} & \text{for proportional rationing} \\ \max\left\{0, \frac{1}{m} \left(D(p_i) - \sum_{j|p_j < p_i} K_j(p_j)\right)\right\} & \text{for efficient rationing} \end{cases},$$

$$i = 1, \dots, n,$$

where m is the number of firms in the market charging the same price as i (including i itself). We assume demand to be divided equally among firms in case of price ties.³ Lastly, profits are given by

$$\Pi_i(\mathbf{p}) = p_i q_i(\mathbf{p}) - C_i(q_i(\mathbf{p})), i = 1, \dots, n.$$

We calculate three benchmark outcomes. First consider the outcome in the competitive benchmark case which is characterized by marginal cost pricing. Since all firms have identical cost schedules, the marginal cost pricing rationale leads to identical price choices of all firms and to symmetric quantities. Quantities can therefore be expressed by $q_i(p) = D(p)/n$, $i = 1, \dots, n$. Equating price and marginal cost then yields firms' quantities $q_i^W = \alpha/(n\beta + \gamma)$, $i = 1, \dots, n$, and the competitive (Walrasian) benchmark price

$$p^W = \frac{\alpha\gamma}{n\beta + \gamma}.$$

The corresponding profit for each firm is

$$\Pi_i^W = \frac{\gamma}{2} \left(\frac{\alpha}{n\beta + \gamma}\right)^2, i = 1, \dots, n.$$

The second benchmark is the Cournot outcome which obtains when firms choose quantities rather than prices. Though there is no rationale for the Cournot outcome in our specific setting, it is the equilibrium prediction in the related Kreps-Scheinkman model of two-stage capacity setting and price competition under efficient demand rationing. Choosing simultaneously their quantities q_i , firms maximize $\Pi_i = q_i \left(\alpha - \beta(q_i + \sum_{j \neq i} q_j)\right) - \gamma q_i^2/2$,

³ As it is common in the literature on demand rationing, residual demand under proportional rationing is defined by the expectation of all possible customer reservation price orderings, and we do not actually model the order of such prices as a random variable. Zouhar (2015) notes that this difference as well as the exact tie-breaking rule (when several firms set the same price) affects quantities and profits in some cases when firms are to choose both prices and quantities simultaneously. Yet, his arguments do not apply to our setting in which, by construction, the produced quantity of each firm cannot be larger than its residual demand.

which yields $q_i^Q = \alpha / ((n + 1)\beta + \gamma)$, $i = 1, \dots, n$. The corresponding endogenous Cournot price is

$$p^Q = \frac{\alpha(\beta + \gamma)}{(n + 1)\beta + \gamma}.$$

Profits are

$$\Pi_i^Q = \frac{\alpha^2(2\beta + \gamma)}{2((n + 1)\beta + \gamma)^2}, i = 1, \dots, n.$$

The third benchmark is full collusion maximizing industry profit which is denoted by Π without subscript. As costs are strictly convex, maximization of joint profit demands symmetric quantities and thus symmetric pricing. The collusive price then is the argument that maximizes $\Pi = \sum_{i=1}^n \Pi_i = pD(p) - nC(D(p)/n)$, which is

$$p^C = \frac{\alpha(n\beta + \gamma)}{2n\beta + \gamma}.$$

Firms' profits under full collusion are given by

$$\Pi_i^C = \frac{\alpha^2}{4n\beta + 2\gamma}, i = 1, \dots, n.$$

Due to symmetric pricing, all benchmark outcomes are independent of the effective rationing scheme.

5 Experimental setup

In our experiment, we investigate the model described in the last section for the duopoly and triopoly ($n = 2, 3$) with parameterization $\alpha = 1000$, $\beta = 1$, $\gamma = 1$. Subjects could choose integers from the interval $[0, 1000]$ as prices. Price is the only choice variable as quantities are determined endogenously. Table 1 shows the benchmark prices and profits for the one-shot version of the game with our parameterization.⁴

- Table 1 about here -

Subjects chose prices repeatedly over several periods. Each experiment lasted at least 20 periods. From the 20th period on, the probability for the experiment to continue for another period was $5/6$. In order to enhance the comparability of our data, the total number of periods was equalized for all sessions as it was determined in advance by one random draw; it turned out that 24 periods were to be played.⁵

⁴ Where applicable, prices were rounded to the nearest integer. Integer prices were used to calculate profits.

⁵ A similar procedure is applied by Fonseca and Normann (2013).

We conducted treatments with both fixed matching, where the same subjects interacted in one market throughout all periods, and random matching, where subjects were randomly assigned to markets anew in each period. While the fixed matching condition is clearly more in accordance with real oligopolies, random matching allows for a strict test of the static Nash equilibrium predictions of the game. On the whole, our experiment consists of eight treatments in a 2x2x2-design with the number of firms in a market ($n = 2, 3$), the rationing scheme (proportional, efficient), and the matching scheme (fixed, random) as treatment variables.

The experiment was conducted in the economics experimental labs at the Universities of Kiel and Heidelberg in June/July and November/December 2013. We usually conducted two sessions per treatment, one at each lab, yielding data of 9 to 11 markets for each treatment.⁶ Subjects from all fields of study were recruited and each subject participated only once.⁷ The sessions proceeded as follows. Upon their arrival, the subjects were randomly seated at computer terminals in the lab. They could not infer with whom of the other subjects they would interact in the experiment. Printed instructions provided complete information about the setup of the experiment, including cost and demand,⁸ and about how their payoff would be determined. The instructions did not state any of the benchmark outcomes calculated in the last section. When reading was finished, the experimenter gave a short presentation highlighting the experiment's main features. Then, the computerized experiment – using Fischbacher's (2007) z-tree software - started. First, subjects had to correctly answer a set of yes-no questions checking the understanding of the experimental procedures and setup before they could proceed. Three unpaid trial periods were played before the 24 paid periods started.⁹ Throughout all periods, subjects could use a profit calculator implemented on their screens. When a subject entered a vector of hypothetical prices - one for each firm -, the profit calculator returned the subject's sales quantity and profit resulting from the chosen price combination.¹⁰ After each period, subjects were informed about the price choices in their market and about their individual sales quantity and profit. While information on the quantities and profits of other players was not stated explicitly, due to the symmetry of

⁶ In the duopoly treatment with efficient rationing and fixed matching, no-shows necessitated a third session which was conducted at Kiel University.

⁷ Subjects were recruited in lectures in Kiel. In Heidelberg the ORSEE recruitment software (Greiner, 2015) was used.

⁸ As students from all fields participated, cost and demand were described verbally rather than algebraically.

⁹ In the fixed matching treatments, subjects were re-matched after the trial periods. The new matching was then effective in all paid periods.

¹⁰ Instructions for an exemplary treatment, including a screenshot of the profit calculator, can be found in Appendix A.

players, subjects could easily calculate those numbers using the profit calculator. In the end, subjects were paid the sum of their earnings from all paid periods at a predefined exchange rate in private.¹¹ An average session lasted about 105 minutes; average earnings per subject were 15.0 Euro.

6 Equilibrium predictions

Figures 2 and 3 show the best response correspondences with our parameterization in the oligopoly with two and three firms, respectively, each for proportional and efficient rationing. The best response functions for the duopoly in Figure 2 consist of three sections. In the leftmost section, the other firm sets such a low price p that the best response $BR(p)$ is to set a high price and thus act as a monopolist vis-à-vis residual demand. In the middle section, underbidding the other price by one unit is the best response. In the rightmost section, the best response price is the monopoly price, which happens whenever the other firm sets a price higher than the monopoly price. Comparing the best response functions for the two rationing schemes, it can be seen that proportional rationing supports higher best response prices in the leftmost section since it leaves more residual demand to the firm with the higher price. Moreover, under proportional rationing the discrete jump in the best response price between the leftmost and the middle section occurs at a somewhat higher price of the other firm (at $p = 391$ as compared to $p = 367$ under efficient rationing) and is considerably larger (the best response price jumps from 576 to 390 under proportional and from 423 to 366 under efficient rationing).

Figure 3 illustrates the best response correspondences for the triopoly in the form of three-dimensional plots. The two horizontal axes correspond to the two prices p_1 and p_2 set by the two other firms. The vertical axis displays the best response price $BR(p_1, p_2)$. Regarding all possible combinations of p_1 and p_2 , best response prices range from 290 to 667 under proportional and from 268 to 667 under efficient rationing. A better understanding of what is going on may be obtained if one looks at the density plots in Figure 4. This figure depicts best response *strategies*. The five regions of different brightness in the figure show the five strategies which can be distinguished, each of which takes the form of either underbidding or monopolizing some residual demand. First consider region (iii) in the lower left corner. In that region, the best response is characterized by setting the highest price and monopolizing residual demand since both other prices are low. When the prices of the other firms rise,

¹¹ Throughout the experiment, money was accounted in experimental currency units (ECU). The exchange rates were 120,000 ECU per Euro in the duopoly treatments and 60,000 ECU per Euro in the triopoly treatments.

underbidding becomes the best response at some point. Regions (i) and (ii) correspond to underbidding strategies. In region (i) the best response is to underbid the lower of the two other prices by one unit. If one of the other prices is sufficiently low, it can pay to only underbid the higher of the two other prices. This is the case in region (ii). The two strategies left again describe monopolistic behavior. In region (iv) sprawling from the upper left and lower right corners, one of the two other prices is so high and the other so low that the best response is to monopolize residual demand after the lowest-price firm has sold up to its implicit capacity, which leads to a best response price lower than the higher other price. The last strategy is monopolistic behavior vis-à-vis entire market demand; it obtains in region (v) when both other firms charge prices higher than the monopoly price.

- Figure 2 about here -

- Figure 3 about here -

- Figure 4 about here -

The discretization of the pricing model with strictly convex costs can in general give rise to Nash equilibria in pure strategies (Dixon, 1993). However, the price grid we employ is sufficiently dense that there is no such equilibrium. We calculated the mixed-strategy one-shot Nash equilibria under efficient and proportional rationing, each for duopoly and triopoly, using the Gambit game theory software tool (McKelvey et al., 2014). Under proportional rationing, the set of rationalizable prices is very large, which makes the computation of the equilibria complex. Having been unable to have the equilibria calculated on a 2.1 GHz processor within ten days computation time, we slightly changed the input for the games with proportional rationing. Allowing only even integers as permissible prices proved successful. The densities of the calculated equilibria are displayed in Figure 5.¹² All equilibria have full support on the respective set of rationalizable prices. Under efficient rationing, those price intervals are relatively short: [366, 423] in duopoly and [268, 309] in triopoly. Under proportional rationing, the supports of the mixed-strategy equilibria are [390, 576] in duopoly and [290, 542] in triopoly. The equilibrium densities exhibit a U-shaped pattern which is much more pronounced under efficient rationing. Table 2 shows the expected mean individual prices and profits with their standard errors as well as the median prices and profits in Nash equilibrium. Note that uniqueness of the equilibria we calculated is not guaranteed.

- Figure 5 about here -

- Table 2 about here -

¹² The class width in all histograms in the figure is 2 ECU. So, for efficient rationing, the bars show averaged densities over two prices.

All analysis so far pertains to the one-shot game. Requate (1994) analyzes infinitely repeated price competition with increasing marginal costs. He finds that the repeated game possesses subgame perfect Nash equilibria of a simple form. In such a symmetric stationary outcome equilibrium, a unique price is set by all firms throughout the entire game as long as no one deviates from that path. In case of a deviation, the severest credible punishment is executed from the next period on forever. The set of prices which can be sustained in equilibrium depends on both the number of firms in the market and the discount factor. For our parameterization and for discount factors we consider reasonable, the sets of sustainable equilibrium prices are large,¹³ i.e. there is a large multitude of pure-strategy Nash equilibria. The issue then becomes coordination on one equilibrium. Since the collusive benchmark price that maximizes industry profit can be sustained, it appears as a prime candidate for coordination.¹⁴ For a fixed discount factor, interestingly, the set of sustainable prices in pure-strategy Nash equilibrium is smaller under proportional than under efficient rationing, which contrasts with the larger supports of the mixed-strategy equilibria under proportional rationing in the one-shot game.

7 Results

We divide the presentation of our results into two parts. First, data on the market level are presented to compare the results to the benchmark outcomes and to elicit treatment effects. We then turn to the analysis of individual pricing decisions and inquire accordance of behavior with Nash predictions, its stability, and incidence of Edgeworth cycles or imitation. Within this section we also motivate and state our hypotheses and discuss our results.

7.1 Market performance

Summary statistics of the observed market data are provided in Table 3. Each treatment is denoted according to the scheme "number of firms per market, demand rationing scheme, matching rule"; for example, the duopoly treatment with efficient rationing and random

¹³ Since subjects are paid off their earnings from all periods at one point in time at the end of the experiment, one may assume that earnings are not discounted at all. In that case, the intervals of sustainable equilibrium prices are [405, 795] in duopoly with proportional rationing, [370, 830] in duopoly with efficient rationing, [296, 846] in triopoly with proportional rationing, and [269, 873] in triopoly with efficient rationing. Taking instead $5/6$, the continuation probability from the 20th period on, as discount factor, the respective intervals are [410, 718], [371, 762], [298, 720], and [269, 759].

¹⁴ The other way round, we can check how large the discount factors need to be in order to make the collusive benchmark outcome sustainable in equilibrium. Those critical discount factors are 0.716 in duopoly with proportional rationing, 0.645 in duopoly with efficient rationing, 0.735 in triopoly with proportional rationing, and 0.697 in triopoly with efficient rationing.

matching is named " $n = 2$, efficient, random". The price measure we employ is the average price in a market, weighted by the quantities the firms were able to sell at their respective prices.¹⁵ Profit is measured as the sum of firms' profits in a market. We will refer to these measures as "price" and "profit" throughout this subsection. Table 3 for each treatment displays the average price and profit together with their standard deviations as well as the median price and profit for all (1-24) and for the last ten (15-24) periods.

The evolution of prices and profits over the periods of the experiment is depicted in Figures 6 and 7. The data points in the figures refer to averages over all markets in the respective period and treatment.¹⁶ In all treatments prices first decline and then mostly tend to stabilize in the later periods. The time trend is less clear for profits. Whereas profits rise and then tend to stabilize in the duopoly, there is no trend, or, if at all, a small decline, in the triopoly. Comparing the data to the benchmarks from Table 1, it can be seen that both prices and profits lie above the competitive and below the Cournot benchmark for all treatments and in all periods.

As to the effects of the three treatment variables, we set up the following hypotheses:

Hypothesis 1a: Prices and profits will be higher in duopoly than in triopoly.

Hypothesis 1b: Market conduct will be more collusive in duopoly than in triopoly.

We state Hypothesis 1 in two different versions since the benchmark prices and profits in Table 1 vary with the number of firms in the market. Therefore, one cannot simply infer from higher prices and profits in the duopoly that duopoly markets are more collusive. To investigate collusiveness, we set up a measure that normalizes prices and profits using the benchmark outcomes. That measure is elaborated on at the presentation of the results below.

Hypothesis 2: Prices and profits will be higher with proportional than with efficient demand rationing.

Hypothesis 3: Prices and profits will be higher with fixed than with random subject matching.

For Hypotheses 2 and 3, a case discrimination is not needed as the benchmark prices and profits are not affected by the rationing or matching condition. Higher collusiveness thus is equivalent to higher prices and profits.

- Table 3 about here –

- Figure 6 about here -

¹⁵ In this we follow Fonseca and Normann (2008; 2013).

¹⁶ Graphs for the evolution of prices in single markets with fixed matching can be found in Appendix B.

Hypotheses 1 and 2 accord with both theory predictions and evidence from earlier related experiments. As the analysis in section 6 has shown, the expected Nash equilibrium price is higher in duopoly than in triopoly and higher with proportional than with efficient rationing.¹⁷ The same relations hold true for the equilibrium predictions for profits. Furthermore, one can infer from the best response correspondences in section 6 that setting higher prices under proportional than under efficient rationing is in a sense dominant: For every given other price (in duopoly) or vector of other prices (in triopoly), the best response price under proportional rationing is at least as high as the best response price under efficient rationing. In the repeated game, however, there is no unambiguous theory prediction for the rationing effect. One may argue that efficient rationing allows for punishing deviant behavior in an implicit cartel more effectively as less residual demand is left. Consequently, the threat of more severe punishment may sustain more collusion in the first place. Yet, for reasonable discount factors, full collusion can be sustained under either rationing rule. The experimental results by Kruse (1993) let us expect that proportional rationing goes along with higher prices also when fixed matching is employed. As to the procollusive effect of fewer firms, our hypothesis is in accordance with the results by Abbink and Brandts (2008) and by Fonseca and Normann (2008).

- Figure 7 about here -

As regards Hypothesis 3, we cannot produce evidence from related experiments since those do not vary the matching scheme. From the theoretical viewpoint, however, we expect higher prices and profits with fixed matching from the fact that full collusion is supported by a Nash equilibrium only in the infinitely repeated game which the fixed matching condition resembles.

We start to investigate the effect of the treatment variables with a visual analysis of Figures 6 and 7. In every of the 24 periods we compare the averaged prices and profits pairwise between treatments. For such a pairwise comparison, we use two treatments which differ only with respect to the relevant treatment variable while the two other variables are held constant. Each of the two other variables can take two states. Therefore, $2 * 2 = 4$ pairwise comparisons apply for each treatment variable.¹⁸ Multiplying the number of pairwise comparisons with the number of periods yields $4 * 24 = 96$ instances of comparison. When

¹⁷ While the equilibrium price predictions presented in Table 2 pertain to individual and not market level prices, adding quantity weights leaves the qualitative relationships unaffected.

¹⁸ For example, when investigating the effect of the rationing scheme, the following four pairwise treatment comparisons apply: " $n = 2$, efficient, random" vs. " $n = 2$, proportional, random", " $n = 2$, efficient, fixed" vs. " $n = 2$, proportional, fixed", " $n = 3$, efficient, random" vs. " $n = 3$, proportional, random", and " $n = 3$, efficient, fixed" vs. " $n = 3$, proportional, fixed".

we compare the duopoly data to those from the triopoly, we find that both prices and profits are higher in duopoly in every single of those 96 instances. An analogous comparison of treatments with different demand rationing schemes yields that prices (profits) are higher with proportional than with efficient rationing in 90 (94) of 96 instances. Fixed as compared to random matching also a predominantly positive effect on prices and profits, as well, although the picture is not as clear-cut as with the other two treatment variables. Prices (profits) are higher with fixed matching in 78 (66) of 96 cases.

We now turn to a formal analysis and perform nonparametric significance tests of subsamples within single periods. For the sake of conciseness, we restrict our attention to the last ten periods. Our results remain qualitatively unchanged if we consider all 24 periods. To formally test for treatment effects, we repeat the pairwise comparison of treatments, holding all but one variable constant, and perform Mann-Whitney tests. The significance test results are summarized in Table 4.¹⁹ The observed difference between duopoly and triopoly is highly significant for both prices and profits. In every single test, we find that prices and profits are significantly higher in the duopoly at the one percent level.²⁰ The results for the effect of demand rationing are somewhat less overwhelming, but still powerful. Both prices and profits are significantly higher under proportional rationing at least at the five percent level in 38 out of 40 cases. By contrast, the visual impression of higher prices and profits under fixed than under random matching is not supported by significance test results. The difference between the two matching conditions is mostly insignificant. We find significance in the expected direction at the five percent level in only one case for prices and no such instances for profits - even less than what would be expected by coincidence, given that there is no difference between the two matching conditions.

- Table 4 about here -

In order to compare collusiveness between duopoly and triopoly, we define collusiveness indices that normalize the absolute data. The price collusiveness index is defined as

$$pcoll = \frac{p - p^W}{p^C - p^W},$$

where p is the observed price in a given market and period, and p^W and p^C are the benchmark prices as defined in section 4. A value of the collusiveness index of one (zero) thus corresponds to the fully collusive (competitive) outcome. An analogous index is defined for

¹⁹ Since we consider only the last ten periods, now 40 instances of comparison (four pairwise treatment comparisons multiplied by ten periods) apply.

²⁰ All p -values refer to two-tailed tests.

profits.²¹ Performing Mann-Whitney tests on the collusiveness indices, we find that pricing in the duopoly is significantly more collusive and that this conduct yields to profits significantly closer to the collusive benchmark. The collusiveness index is significantly higher in duopoly at least at the five percent level in 37 (39) of 40 cases for prices (profits).

Rather than to rely only on pairwise comparisons, we can make use of our full data set by multivariate regression analysis. Since there is heavy positive autocorrelation within markets in our data, we perform generalized least squares (GLS) regressions that correct the standard errors for effects of autocorrelation and heteroskedasticity on the market level. We investigate regressions with price as well as profit as dependent variable. Independent variables comprise three dummy variables, " $n = 3$ ", "proportional", and "fixed", related to the three dimensions of the treatment variable space. Each dummy equals one in those treatments for which the condition mentioned in the caption holds true and zero otherwise. Time trends are captured by the variable " $1/\text{period}$ ", the inverse of the period. Additional specifications furthermore include interaction terms of the treatment space dummies.

The regression results are presented in Table 5. All specifications indicate that the three treatment space dummy variables have the expected signs. The effects of the number of firms and of demand rationing are strongly significant.²² Contrary to the results of the pairwise significance tests, also the matching entails a statistically significant effect in three of the four regressions. In the fourth, regression (2), the effect of matching approaches significance ($p = 0.1126$). Nevertheless, the economic significance of the matching effect remains doubtful. Consider for example regression (1). The estimated price increase with fixed matching by 7.4 ECU corresponds to an increase of no more than approximately two percentage points of the price collusiveness index. The effects of the other treatment variables are much more sizable: Prices are about 32 ECU higher with proportional than with efficient rationing and about 113 ECU higher in duopoly than in triopoly. The same pattern can be found in the other regressions.

- Table 5 about here -

The variable " $1/\text{period}$ " is positive and significant in the price regressions whereas it is insignificant in the profit regressions, i.e. there is a significant downward time trend for prices, but no time trend for profits. The coefficient of the constant shows the level to which prices or, respectively, profits converge in the long run in treatment " $n = 2$, efficient,

²¹ Engel (2007) uses a similar collusiveness measure in his meta-study of oligopoly experiments.

²² In order to be able to analyze Hypothesis 1b by means of multivariate regressions, we also ran regressions (1) to (4) with the above-defined price or profit collusiveness measures as dependent variable. The " $n = 3$ " dummy variable is negative and significant at the one percent level in all four regressions.

random" when "1/period" approaches and all dummy variables are zero. Adding the coefficients of the suitable treatment space dummies (and, in regressions (2) and (4), their interactions) yields the convergence levels for the other treatments. The results confirm that both prices and profits converge to levels well above the fully competitive and well below the Cournot outcome.

Combining the evidence regarding the treatment effects, we conclude that Hypothesis 1 (in both its versions) and Hypothesis 2 are strongly supported. In contrast, we have found only limited support for Hypothesis 3, and the observed effect is rather small.

Result 1: Prices and profits are substantially and significantly higher in duopoly than in triopoly. Market conduct is significantly more collusive in duopoly than in triopoly.

Result 2: Prices and profits are substantially and significantly higher under proportional than under efficient demand rationing.

Result 3: Prices and profits are slightly higher under fixed than under random subject matching. The effect is mostly statistically significant in multivariate regressions, but not in pairwise treatment comparisons.

As has been mentioned above, most oligopoly experiments employ only fixed matching because that assumption is closer to real oligopoly markets. Having found that the matching condition does not entail a substantial effect on the collusiveness of our oligopoly markets, we can provide some justification for that approach and for testing also static predictions in a fixed matching setting with repeated interaction.

Aside from treatment effects, we are also interested in the general level of collusiveness in our experimental setting. We again employ the price collusiveness measure to quantify collusiveness. The data in Table 6 indicate that our markets are rather competitive. When zero (one) is defined as the fully competitive (collusive) price, the collusiveness of the mean price, averaged over all treatments, is 0.251. In 93.1 percent of all observations the collusiveness is smaller than 0.5, i.e. the price is closer to the fully competitive than to the fully collusive benchmark price. Only in 0.6 percent of the observations is a price collusiveness of at least 0.75 attained, and there is not a single instance in which the fully collusive benchmark is reached. Moreover, we test for every single treatment and each of the last ten periods whether the median price or profit equals any of the benchmarks in Table 1. We observe that in every of the 80 instances²³ both prices and profits are significantly higher than the fully competitive benchmark (all p 's < 0.01 , Wilcoxon signed rank tests) and significantly lower than the Cournot (all p 's < 0.05 for prices, all p 's < 0.01 for profits) or the fully collusive (all p 's < 0.01) benchmark.

²³ The 80 instances of comparison to the benchmarks result from eight treatments multiplied by ten periods.

- Table 6 about here -

Comparing the competitiveness in our markets to that in related experiments, we find that behavior in our setting is more competitive than in the markets in Abbink and Brandts (2008) who observe pricing at or above the Cournot level when firms have to satisfy all demand at the price they choose. Pricing below the Cournot benchmark is in line with what has been found in experimental tests of the Kreps-Scheinkman model with inexperienced subjects (Davis, 1999; Muren, 2000; Goodwin and Mestelman, 2010; Jacobs, 2016). Furthermore, the overall competitiveness in our markets seems comparable to the results by Dufwenberg and Gneezy (2000) in an experiment of price competition with no costs.

The question of session-specific effects is salient in our procedures because we conducted sessions with participants from two different subject pools at different universities. Subject pool effects may thus have translated into session effects. To test whether subjects' price choices diverge in different sessions, we regress the price on a constant, the time trend variable, and a set of session dummies and then test for equality of those dummy coefficients that refer to the same treatment. We find no significant session effects (all p 's > 0.10 , F -tests).²⁴

7.2 *Individual behavior*

We now turn to the analysis of individual price choices. Figure 8 for each treatment displays the densities of observed individual prices.

7.2.1 *Nash equilibrium predictions*

We first compare the empirical individual price choices to the static Nash equilibrium predictions from section 6, testing our Hypothesis 4:

Hypothesis 4: The distribution of individual price choices in any treatment follows the probability distribution of prices in the respective static mixed-strategy Nash equilibrium.

There are four Nash equilibria to be compared to the data from eight different treatments. Each Nash equilibrium serves as a standard of comparison for two treatments with different matching conditions.

- Figure 8 about here -

²⁴ However, in treatment " $n = 2$, proportional, fixed", the session effect approaches significance ($p = 0.1014$). The values of the coefficients indicate that prices are circa 11 ECU higher in the session conducted at Heidelberg University. All other session effects are smaller and clearly insignificant.

A visual comparison of Figures 5 and 8 already reveals that there is hardly any similarity between the predicted equilibrium densities and the according empirical data. Statistical analysis confirms the visual impression: In each case, a Kolmogorov-Smirnov test at the one percent significance level rejects the hypothesis that the equilibrium and the empirical price distribution are equal. This result remains unchanged if the early periods in which some subjects may still have to learn are disregarded and only the data from the last ten periods are used for the tests. These findings are consistent with those from experiments in the related setting of price competition with fixed exogenous capacities (Kruse et al., 1994; Fonseca and Normann, 2013; Jacobs and Requate, 2016).

Whereas the test results are powerful, it appears unsatisfactory that, due to the lacking uniqueness of equilibrium, there could in principle be other Nash equilibria which fit the empirical data. We tackle this problem with Bernheim's (1984) rationalizability concept. Iterative elimination of prices that are never a best response yields the sets of rationalizable prices. As noted in section 6, one then finds that those sets coincide with the supports of the equilibria we calculated. Since all prices chosen with a strictly positive probability in a mixed-strategy Nash equilibrium must be rationalizable, we know that the cumulative distribution function of any Nash equilibrium strategy must attain the value of zero for all prices lower than the lowest rationalizable price and the value of one for all prices equal to or higher than the highest rationalizable price. Using only this information, Kolmogorov-Smirnov tests reveal that the empirical price distributions (using data from all periods) are significantly different from any possible static Nash equilibrium distribution ($p < 0.01$ in seven out of eight treatments; $p < 0.05$ in the eighth treatment, " $n = 2$, proportional, fixed"). In fact, non-rationalizable price choices are quite common in the data. Pooling the data from all treatments, the share of non-rationalizable price choices is 21.8 percent. Among single treatments, the shares range from 12.9 to 35.4 percent, with no obvious correlation to any treatment variable. Moreover, if only price choices in the last ten periods are considered, the share of non-rationalizable prices is somewhat diminished to 16.9 percent, but is still sizable. Accordingly, we conclude:

Result 4: Empirical price choices do not follow any mixed-strategy static Nash equilibrium. Non-rationalizable prices are chosen frequently.

Although the Nash equilibrium price distributions do not provide a proper description of the empirical data, some properties of the equilibria we calculated might nevertheless be reflected in the data if we consider a higher aggregation level. As a weakened version of Hypothesis 4, we formulate Hypothesis 5:

Hypothesis 5: The average empirical price and profit levels in any treatment accord with the average price and profit levels predicted by the respective static mixed-strategy Nash equilibrium.

To inquire this weaker hypothesis, we compare the predicted Nash equilibrium means and medians for prices and profits from Table 2 with the empirical observations summarized in Table 7.²⁵ Figure 9 provides a graphical illustration of the comparison of mean prices and profits. Nash predictions are depicted as triangles, empirical data as circles. In order to avoid disturbances by outliers from early periods, only empirical data from the last ten periods are considered.

- Table 7 about here -

Inspection of the mean individual prices in Panel A of Table 7 and in the accompanying graphical illustrations in the upper two panels of Figure 9 shows that under proportional rationing the observed prices are considerably lower than their Nash predictions. Deviations from equilibrium predictions are larger in triopoly than in duopoly. In the treatments with efficient rationing, however, mean prices come rather close to the equilibrium levels. Considering only the last ten periods, the largest relative difference between the observed and the predicted mean price in an efficient rationing treatment corresponds to a 3.2 percent deviation from the equilibrium price. That is, while the variation of the rationing scheme entails a sizable effect on prices, the predicted effect is even larger. In the upper two panels of Figure 9 this result is reflected by the larger distance between the orange and the blue triangles than between the orange and the blue circles.

- Figure 9 about here -

A quite similar picture emerges when individual profits in Panel B of Table 7 and in the lower two panels of Figure 9 are considered. Mean profits under efficient rationing are close to equilibrium predictions, diverging from the mean equilibrium profit by no more than two percent in the last ten periods. However, this holds true also in the duopoly treatments with proportional rationing. Profits are clearly lower than predicted by the Nash equilibrium only in the triopoly with proportional rationing.

Since the Nash equilibrium prices and profits are not normally distributed, we resort to medians rather than means for significance tests and perform Wilcoxon signed rank tests.²⁶

²⁵ The numbers in Table 7 differ from those in Table 3 because in Table 7 (i) the individual prices are not weighted by sales quantities and (ii) profits in the same market are not summed up.

²⁶ If we ignore the distributional assumption and perform Gauß's z-tests (using the standard errors predicted for the Nash equilibrium and data from the last ten periods), we receive the following results: Empirical mean prices are significantly lower than the Nash prediction at the one percent level in six treatments. In one treatment (" $n = 3$, efficient, fixed") the price is significantly higher at the one percent level, and in one treatment (" $n = 2$,

The test results are indicated in the columns captioned "comparison to Nash prediction" in Table 7. Whereas the test results are somewhat ambiguous when data from all periods are pooled, confinement to the last ten periods brings about more clarity. In six (five) out of eight treatments, the median price (profit) is significantly lower than the Nash prediction.²⁷ In the remaining instances, equality to the Nash prediction cannot be rejected at the ten percent significance level. This is the case for both price and profit in the two treatments with efficient rationing and fixed matching. The median price or profit is never significantly higher than the Nash prediction. According to these findings, we summarize:

Result 5: The average empirical price and profit levels are mostly lower than the respective static Nash equilibrium predictions. The difference to Nash predictions is much more pronounced in treatments with proportional demand rationing. In the two treatments with efficient demand rationing and fixed subject matching, average prices and profits are close to their Nash predictions.

Consequently, behavior in our setting is quite competitive as measured not only by the average value of the collusiveness index on the market level. Individual pricing is also largely more competitive than predicted by the static mixed-strategy Nash equilibrium. The last result contrasts with evidence from related experiments. Kruse (1993) in the study most closely related to ours observes profits that are not significantly different from the Nash predictions. Kruse et al. (1994), Fonseca and Normann (2013), and Jacobs and Requate (2016) find that prices and profits are rather higher than the Nash prediction in price competition with fixed exogenous capacities.

As to the treatments with fixed matching, another theory prediction is given by the subgame perfect stationary outcome pure-strategy Nash equilibria for the infinitely repeated game as described by Requate (1994). Those are the basis for our next hypothesis:

Hypothesis 6: Individual pricing patterns in the fixed matching treatments follow a stationary outcome pure-strategy Nash equilibrium.

efficient, fixed") there is no significant difference at the ten percent level. Mean profits are significantly lower than the Nash prediction at the one percent level in one treatment (" $n = 3$, proportional, fixed") and at the five percent level in two more (" $n = 2$, efficient, random" and " $n = 3$, proportional, random"). There is no significant difference at the ten percent level in the remaining five treatments.

²⁷ In treatment " $n = 3$, efficient, random" the Wilcoxon signed rank test for the last ten periods indicates a significant difference although the predicted and the empirical median profit are equal. That occurs since the empirical distribution is so asymmetric that a significant difference in the rank sums between the lower and the upper half of the observations ensues. The assumption of a symmetric distribution contained in the Wilcoxon signed rank test may be considered impermissible since the Nash equilibrium profit distributions are not symmetric. Acknowledging this problem, we nevertheless prefer the Wilcoxon signed rank test to the sign test because of the much greater statistical power of the former. Using instead the sign test leads to weaker, but qualitatively similar results: The empirical median profit (using data from the last ten periods) is significantly lower than the Nash prediction at the one percent level in three treatments (" $n = 2$, proportional, random", " $n = 3$, proportional, random", and " $n = 3$, proportional fixed"); in the remaining five treatments there is no significant difference at the ten percent level. For the price data the Wilcoxon signed rank test is unproblematic anyway since the predicted Nash equilibrium price distributions are close to perfect symmetry.

In those equilibria, a uniform price is set by all firms in the market in all periods as long as no firm deviates. Also full collusion is sustainable at reasonable discount factors. However, as is already obvious from the empirical price distributions in Figure 8, subjects do, if at all, only seldom manage to cooperate at or near the fully collusive level. Nevertheless, since a large range of prices is sustainable in equilibrium, one may expect lasting cooperation also at lower price levels. Such cooperation, however, is, on the one hand, difficult to achieve because firms have to coordinate on a price without explicit communication. On the other hand, it is fragile since a single deviation triggers punishment forever after in equilibrium. Acknowledging these difficulties, we look in our data for uniform stationary pricing and count as successful equilibrium cooperation all cases in which all firms in a market choose a uniform price for two successive periods, the shortest time interval for which stationarity can be tested. We find that there is only one single instance of successful cooperation according to our definition. In a duopoly with proportional rationing, the two players manage to coordinate on the Cournot price of 500 in periods 19 and 20 after one player set this price, presumably as a signal, in periods 17 and 18. In period 21, one player deviates to a price of 490 and a phase of underbidding starts. If the assumption of a uniform price is relaxed and asymmetric, but individually stationary pricing is allowed for, there are all in all five instances of cooperation in the data, all in duopoly markets. The conclusion thus is clear-cut:

Result 6: There is no evidence of behavior in the fixed matching treatments that accords with the stationary outcome subgame perfect pure-strategy Nash equilibria of the infinitely repeated game.

7.2.2 *Stable pricing*

Despite the missing evidence for behavior according to the pure-strategy Nash equilibria, one may still presume to find evidence of the different Nash equilibrium predictions under random and fixed matching on the individual level. Whereas in the one-shot game there is only a mixed-strategy equilibrium in which firms have to randomize over prices, the infinitely repeated game also possesses Nash equilibria in pure strategies. Although we have found that players do not achieve to maintain the simple stationary pure-strategy equilibria, attempts to reach them may be reflected by sequences of individual stable pricing as signals to collude. Under random matching, in contrast, it does not make much sense for players to signal to others with whom they will play again in the next period only with minor probability. We therefore hypothesize:

Hypothesis 7: Stable individual pricing is more frequent in fixed matching treatments.

We start to investigate the hypothesis by counting the instances of stable individual pricing in each treatment. An instance of individual price stability occurs whenever a subject does not change her price compared to the last period.²⁸ Table 8 presents the relative frequencies of stable pricing. Contrary to our conjecture, the shares are lower in the fixed matching treatments. Overall, subjects choose the same price as in the last period in 21.7 percent of all cases under random matching, but only in 11.5 percent of all instances in the fixed matching condition. The hypothesis that the share of stable prices is independent of the matching condition is rejected for each pairwise treatment comparison and also for the pooled data (all p 's < 0.01 , chi-square tests). Additionally, we set up a probit regression with a stable pricing dummy as dependent variable. The regression results in Table 9 again show that stable pricing is significantly less probable under fixed matching. As indicated by the significant negative coefficient of "1/period", stable pricing is more probable in later periods.²⁹

- Table 8 about here -

- Table 9 about here -

We thus have a clear negative result:

Result 7: Stable individual pricing is *less* frequent in fixed matching treatments.

What causes this unexpected effect of matching on price stability? Whereas we cannot provide a definite answer, looking at the treatment-specific distributions of stable prices in Figure 10 leads us to a plausible presumption. We expected that instances of stable pricing would mostly arise as attempts to set up collusion. However, there are only few cases of stable pricing in the data that can be regarded as collusive. Instead, we observe clearly right-skewed distributions due to large frequencies of relatively low stable prices. This effect is absent only in the duopoly treatments with fixed matching; in triopoly, the effect is present in all four treatments, but stronger under random matching. Those patterns of constantly setting relatively low prices may be considered to follow the intention to play safe, i.e. to ensure oneself a certain minimum payoff, no matter what the other players will do. A similar phenomenon is observed by Abbink and Brandts (2008) where subjects often chose the lowest possible price assuring a non-negative payoff. An extreme case of such risk averse behavior would be to choose one's price according to the maximin criterion. In our setting, the maximin

²⁸ All results in this paragraph remain qualitatively unchanged if we demand price stability for three consecutive periods instead.

²⁹ Interestingly, when we add demographic variables, we find further significant effects, according to which younger and male subjects are more prone to stable pricing.

prices are 375 or 376 in duopoly and 267 in triopoly.³⁰ Those values match the modes of the distributions in Figure 10 fairly well. Hence, stable pricing does not signify an environment conducive to collusion where players try to cooperate. Contrariwise, it indicates a complex environment in which others' choices appear so unpredictable that many players resort to playing a low-risk near maximin strategy. Consequently, stable pricing occurs more often under random matching where players are more uncertain which prices they will be confronted with next period when they are matched with new competitors. Following this interpretation, for some players the increase in the number of firms in the market from two to three complicates the pricing game that much and makes its outcome so unpredictable that they play a maximin strategy even under fixed matching.

- Figure 10 about here -

7.2.3 *Myopic best response and imitation*

Since pricing does not accord with the Nash equilibrium predictions, we investigate two off-equilibrium behavioral strategies as alternative hypotheses.

Hypothesis 8a: Individual price choices are based on a myopic best response rationale as purported by Edgeworth's price cycling theory.

The figures in Appendix B showing price evolutions in single markets indicate price cycles in some markets. Furthermore, Kruse et al. (1994) and Fonseca and Normann (2013) have found supportive evidence for myopic best response behavior à la Edgeworth in related experiments.

The second alternative hypothesis is imitation:

Hypothesis 8b: Individual price choices are based on imitation of other firms' past prices.

The imitation hypothesis is supported by evidence from the experiment by Abbink and Brandts (2008) who observe price imitation as a driving force in price competition with increasing marginal costs and compulsory trading. Moreover, Heymann et al. (2014) find that pricing in a Bertrand-Edgeworth experiment with fixed exogenous capacities can be explained by simple heuristics. From that point of view, myopic best response behavior may already be too advanced a strategy.

We start with a replication of the regression equation in Kruse et al. (1994). The dependent variable is $p_{i,t} - p_{i,t-1}$, the change of subject i 's individual price choice in period t compared

³⁰ Due to the discretization of the price space, the maximin price can vary with the rationing scheme, although the effect of rationing is tiny. In our setting, 375 (376) is the maximin price in duopoly with efficient (proportional) rationing. In the triopoly, the maximin price is 267 under either rationing rule.

to the last period $t - 1$. $BR_{i,t-1}$ is i 's best response price to the price vector she was confronted with in the last period; it thus equals Edgeworth's theory prediction for i 's current price. Independent variables are the Edgeworth prediction for i 's current price minus i 's actual price in the last period, $BR_{i,t-1} - p_{i,t-1}$, and its lag, $BR_{i,t-2} - p_{i,t-2}$. The independent variables measure the shares of immediate and lagged adjustment to Edgeworth's myopic best response price. A strict interpretation of Edgeworth's theory, i.e. immediate and perfect adjustment to the best response price, translates into the prediction that the coefficient of $BR_{i,t-1} - p_{i,t-1}$ takes a value of one. However, what we expect from the results of related studies and what we indeed observe is only partial adjustment. The results of the regression, presented in column (1) of Table 10, are in line with those by Kruse et al. (1994) and Fonseca and Normann (2013). We find a highly significant positive immediate adjustment effect; the coefficient indicates that an individual on average adjusts her price towards the Edgeworth price prediction by circa 22 percent. Running the regression for single treatments yields highly significant positive adjustment effects, as well (results not reported).

- Table 10 about here -

However, the aim of regression (1) is just to check whether we can reproduce the results by Kruse et al. (1994) and by Fonseca and Normann (2013) in our setting. The regression is not suited to test Hypothesis 8a against Hypothesis 8b since imitation is not contained as an alternative explaining factor in the model. The Edgeworth adjustment effect we have found and that has been found in the earlier studies may obscure the simpler behavioral pattern of imitation. Since for a large set of price vectors the best response is to underbid the price of another firm by one unit, there is considerable collinearity between imitative and myopic best response behavior. What is essentially imitation may thus have strengthened the Edgeworth adjustment effect in regression (1).

In specification (2) we consider both myopic best response and imitation, adding to model (1) variables that measure the adjustment towards the other prices p_{-i} observed by i in the last period. The additional independent variables in regression (2) are $p_{-i,t-1} - p_{i,t-1}$ and its lag, $p_{-i,t-2} - p_{i,t-2}$. In duopoly, $p_{-i,t-1}$ is simply the price of the other firm i was matched with in period $t - 1$; in triopoly, we define $p_{-i,t-1}$ as the arithmetic mean of the two other prices. The results of regression (2) in Table 10 suggest that price changes are due to imitation rather than myopic best response behavior. Inclusion of the additional variables considerably increases the fit of the regression; the share of explained variance of the dependent variable roughly doubles. The coefficients measuring the immediate and lagged Edgeworth adjustment are clearly insignificant and virtually equal to zero. In contrast, the immediate imitation effect

of circa 47 percent is highly significant. The significant negative coefficient of the lagged term indicates that the imitative adjustment towards other prices slows down if those other prices stay constant. At this stage we conclude:

Preliminary Result 8: Individual price choices are based on imitation of other firms' past prices and not on a myopic best response rationale.

Yet, things may be more complicated than that one of our two hypotheses is completely right and the other is completely wrong. One may suppose that the extent to which imitation or myopic best responses explain pricing varies across treatments. Specifically, we conjecture that imitation has more explaining power in triopoly where more sophisticated strategies such as finding the best response to past price vectors are more intricate. This conjecture is corroborated by our above finding that the simple pattern of stable maximin pricing occurs more frequently in triopoly and by the result by Fonseca and Normann (2013) that Edgeworth pricing cycles are more prominent in duopoly than in triopoly. Moreover, myopic best response behavior appears reasonable only within fixed groups of competitors. It does not make sense to adapt to the specific price choice of someone with whom the subject will not interact again in the next period. In contrast, prices of other firms can provide subjects with an orientation of which price range is reasonable independent of the effective matching scheme. Consequently, we set up a third hypothesis:

Hypothesis 8c: The extent to which pricing is based on myopic best response or imitative behavior varies with the treatment conditions. Imitation has more explaining power in triopoly than in duopoly and with random than with fixed subject matching.

Estimations of specification (2) for single treatments are interfered, in one case even precluded, by collinearity. However, the (unreported) results broadly suggest that imitation is indeed more prominent in triopoly. In contrast, we cannot detect a clear effect of matching. As a more viable alternative, we augment specification (2) with interaction terms. We include interactions of both the immediate Edgeworth adjustment variable $BR_{i,t-1} - p_{i,t-1}$ and the immediate imitation variable $p_{-i,t-1} - p_{i,t-1}$ with the three treatment space dummies " $n = 3$ ", "proportional", and "fixed". With respect to the number of firms in the market, our conjecture is confirmed by the regression results presented in column (3) of Table 10. In the baseline treatment " $n = 2$, efficient, random" (where all treatment space dummies are zero), myopic best response behavior and not imitation explains pricing. While the results imply a highly significant immediate Edgeworth adjustment of circa 70 percent for this treatment, the immediate imitation effect is insignificant. In treatments with triopolies and/or proportional rationing, the immediate Edgeworth adjustment effect is significantly and substantially

diminished whereas the immediate imitation effect gains importance. This is indicated by significant negative (positive) coefficients of the interaction terms with myopic best response pricing (imitation). Compared to the baseline, triopoly decreases the coefficient of the Edgeworth adjustment effect by 36 percentage points and increases the coefficient of the imitation effect by 45 percentage points. The effect of proportional rationing, while somewhat smaller, is also substantial: The Edgeworth adjustment coefficient is decreased by 35 percentage points and the imitation coefficient is increased by 32 percentage points. Though we acknowledge that proportional rationing complicates the underlying oligopoly model and thus the identification of the best response to a given price vector, we find the magnitude of the effect entailed by the rationing scheme quite surprising. The matching condition, on the contrary, surprisingly, does not entail a significant effect.³¹

Having found that the number of firms entails the largest effect on which behavioral pattern best explains pricing, we divide the sample according to that dimension and investigate the Edgeworth adjustment and imitation effects separately for duopoly and triopoly markets.³² Regression (4) in Table 10 is a replication of regression (2) on the restricted sample considering only duopoly treatments. The results show a highly significant Edgeworth adjustment effect and no significant imitation effect.³³ Regression (5) in Table 10 estimates the effects for the triopoly. Since only triopoly markets are included, we do not collect the two other prices an individual has observed in one term, but consider both of them with own variables in the regression. $p_{-i,t-1}^L$ denotes the lower of the two prices i has observed in period $t - 1$. Analogously, $p_{-i,t-1}^H$ denotes the higher of the two prices. Thus, $p_{-i,t-1}^L - p_{i,t-1}$ and $p_{-i,t-1}^H - p_{i,t-1}$ measure the adjustment towards the lower and, respectively, the higher

³¹ Additionally, we run a regression of model (3) with further interaction terms pertaining to gender, age, and field of study. The only significant effect (at the five percent level) we find is that subjects who do not study economics or a related field adjust their price to the best response price by seven percentage points less. That appears plausible if one assumes that best response pricing is a rather advanced behavioral pattern that requires some grasp of economics.

³² To recheck our hypothesis that pricing patterns are also influenced by the matching condition, we additionally run regression (2) separately for markets with fixed and random matching. The results of the two regressions on a partitioned sample are largely similar to those of the regression on the full sample. Under fixed as well as under random matching, the immediate imitation effect is highly significant and of magnitude 0.45 to 0.5 while the immediate Edgeworth adjustment effect is insignificant and close to zero. Consequently, we again find no evidence that the matching condition has a substantial influence on the rationale of individual price choices.

³³ While we are still able to receive clear results in regressions (3) and (4), the tremendous increase in the standard errors of the coefficients compared to regression (2) points to the issue of collinearity mentioned above. The variance inflation factors of the coefficients attain values of up to 72 in regression (4) and even up to 444 in regression (3). As collinearity can cause overfitting and make coefficient estimates highly dependent on particular samples, we test the validity of our results by a jackknife resampling approach. We run regressions (3) and (4) with varying subsamples of our data, leaving out observations from one particular period at a time. The coefficient estimates from those regressions with subsamples come close to the estimates with the full sample, which gives us confidence that the coefficient estimates reported for regressions (3) and (4) are not artifacts caused by overfitting to observations of a particular sample.

other price observed in the last period. Again, we also include the first lags of these terms to allow for delayed adjustment. The regression results reveal that both an Edgeworth adjustment effect and imitation of the lower and higher other prices are present in the data. All three effects are highly statistically significant. Yet, imitation of the lower price entails by far the largest effect. The average individual in the triopoly adjusts her price by 53 percent to the lower of the two other prices observed in the last period; the higher price and the best response price, in contrast, each account only for an adjustment of about five percent.

Result 8: The extent to which pricing is based on myopic best response or imitative behavior varies with the number of firms in the market. Myopic best response (imitation) is the main explaining factor in duopolies (triopolies). The matching condition does not influence the rationale of individual price choices.

Thus, we have found partial support for both Edgeworth's hypothesis of myopic best response pricing and the hypothesis of simple imitation. In the duopoly individual pricing is well explained by Edgeworth's theory. In the triopoly, in contrast, imitation of past other prices possesses more explaining power. While playing the mixed-strategy Nash equilibrium is too complicated anyway, subjects can achieve higher profits than under full competition by choosing myopic best response prices. However, subjects seem to resort to the simpler behavioral pattern of imitation when finding the best response price becomes more intricate. This interpretation partly coincides and partly contrasts with Fonseca's and Normann's (2013, p. 220) conjecture. We may agree with them that myopic best responses à la Edgeworth are more common in markets with fewer firms because this kind of behavior constitutes a form of imperfect tacit collusion. Yet, Fonseca and Normann furthermore argue that, as in markets with more firms and thus higher production capacity it is less attractive to be the high-price firm since this results in a relatively larger loss of potential profits, it may pay off for firms to behave unpredictably. We do not agree that behavior in markets with more firms follows such a rationale. After all, we observe that in triopoly subjects substitute myopic best responses for another behavioral pattern which is hardly unpredictable, namely simple imitation of others' prices.

8 Conclusion

This study investigates by means of a laboratory experiment firm conduct in a Bertrand-Edgeworth framework with increasing marginal costs and voluntary trading. While the Bertrand-Edgeworth setting is more realistic than the standard Cournot or Bertrand model, there have so far been relatively few experiments based on the Bertrand-Edgeworth model.

Moreover, virtually all those earlier experiments either research the case with fixed capacity constraints instead of strictly convex costs or, if they do consider strictly convex costs, abandon the voluntary trading constraint, which restricts the applicability of those studies to a small minority of markets. Our study thus closes a relevant gap in the experimental economics literature.

The game-theoretic predictions of our underlying model are sophisticated. For the one-shot game there is only a mixed-strategy Nash equilibrium whose features are influenced tremendously by the rather inconspicuous change of the demand rationing rule. In the infinitely repeated game there is a large multiplicity of equilibria, but the stationary outcome pure-strategy equilibria that follow a simple stick-and-carrot approach and allow for full collusion to be sustained may appear focal. Further off-equilibrium predictions are Edgeworth's supposition that firms optimize myopically, taking into account the past choices of their competitors, thus giving rise to price cycles, and the hypothesis that subjects simply imitate others' prices they have observed in the past.

Our experiment examines the effect of three treatment variables: number of firms in a market, demand rationing, and subject matching. We find that subjects behave considerably and significantly more collusively in duopoly than in triopoly and with proportional than with efficient demand rationing. Whether subjects are re-matched in every period or play in fixed groups repeatedly entails only a small effect. Whereas the former two effects reflect Nash equilibrium predictions qualitatively, the quantitative prognoses mostly do poorly. Conduct is largely more competitive than predicted by the static Nash equilibrium and also than might be expected from the results of related experimental studies. We observe some risk averse near maximin pricing, especially under random matching. The stationary outcome pure-strategy Nash equilibria of the infinitely repeated game we investigate do not possess any explaining power. In contrast, Edgeworth's price cycle theory rationalizes our data partially. Examining also imitation of other firms' past prices as an alternative behavioral pattern, we find that imitation is the main driving force in triopolies while in duopolies myopic best response pricing à la Edgeworth best explains behavior. We hypothesize that the complexity of the decision situation is crucial to what behavioral strategy subjects employ. Whereas play according to the mixed-strategy Nash equilibrium is computationally infeasible anyway, subjects can realize profits above the competitive level by mutually choosing their respective myopic best response price. When finding the myopic best response price becomes more intricate, subjects resort to imitation as a simpler strategy.

Further experiments of Bertrand-Edgeworth markets with increasing marginal costs and voluntary trading appear desirable for a validation of our results and a closer scrutiny of some phenomena we have found. As the conduct in our setting is quite competitive, it seems worthwhile to investigate whether changes in the setting such as the admission of overt communication or a variation in the amount of information provided to the subjects about the market or competitors' behavior and success will permit subjects to attain more collusion also in Bertrand-Edgeworth markets with increasing marginal costs.

Appendix A

English translation of the written instructions in treatment " $n = 2$, efficient, fixed".

Welcome to the Laboratory for Economic Experiments at Kiel University.

You are about to participate in an economic experiment where you will have to make some decisions. You can also earn some money. The amount of money will depend on both your own decisions and the decisions of the other participants in the experiment.

Please read these instructions carefully. If after reading there are any questions, please raise your hand. An experimenter will approach you and answer your questions in private. Please do not communicate with other participants during the experiment.

All participants receive the same instructions.

In this experiment you represent a **firm** that produces and sells a single good. On a market you **compete with one other firm** being represented by one of the other participants. Both firms produce and sell the same good.

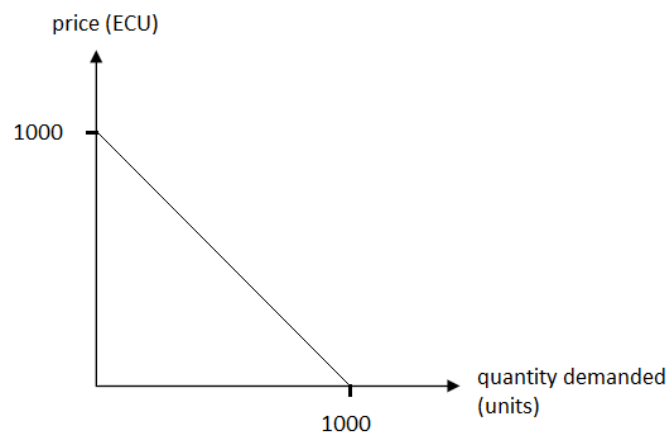
The experiment consists of **multiple periods**. There will be at least 20 periods. The exact number of periods will be determined by a random process. The experiment will end after the 20th period with probability 1/6. With probability 5/6, there will be another period. Provided that the 21st period will take place, after the 21st period there will be an identical random decision on whether the experiment will continue for another period. The same holds true after all following periods, if applicable. The random decisions made after each period will be independent of one another.

At the beginning of the experiment, the participants will be randomly matched into groups of two. The other member of your group will be your competitor. The grouping will be fixed throughout the experiment.

In each period you and the other firm must simultaneously and independently **decide on the price** at which to offer the good on the market. All **integers from 0 up to 1000 are admissible** prices.

Throughout the experiment, all money amounts will be accounted in **Experimental Currency Units (ECU)**. Your total profit will be paid off to you after the experiment at an **exchange rate of 120,000 ECU/Euro**, i.e. for each 120,000 ECU earned in the experiment you will receive 1 Euro.

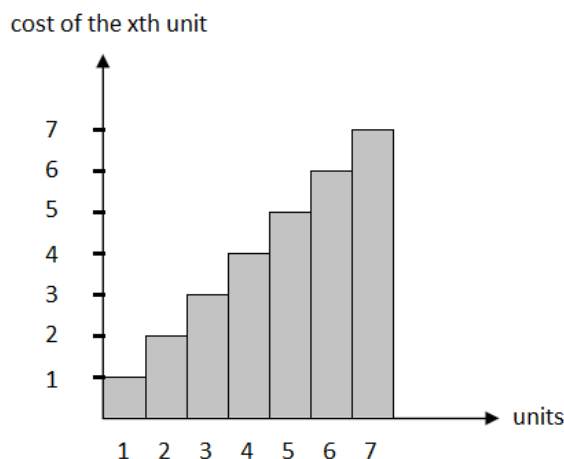
The demand side of the market will be simulated by the computer and will be identical in all periods. There are many different potential customers with different willingnesses to pay for the good. A sale will come about if the offer price is no higher than a customer's maximum willingness to pay. At a price of 0 ECU there will be a total demand for 1000 units on the market. With a price increase by 1 ECU, demand is reduced by 1 unit. At a price of 1000 ECU no one will be ready to buy the good. Here is a graphical representation of this relationship:



Customers will first try to purchase the good from the firm offering at a lower price. Those customers with the highest willingness to pay will be served first. In case one firm does not meet its whole demand, the remaining demand will be left for the other firm that offers the good at a higher price. If both firms choose the same price, demand will be divided equally among them.

Firms incur production costs that rise progressively in the quantity produced. The production costs are 1 ECU for the first unit produced, 2 ECU for the second unit, 3 ECU for the third unit, and so on. Your total production cost is the sum of the costs for the respective units. In the diagram below, total costs equal the grey area up to the respective quantity. Due to the progressive cost schedule, it can be unprofitable for a firm to satisfy its whole demand at a low price. You only want to produce and sell an additional unit of the good as long as the revenue from its sale exceeds its production cost. Therefore, for any offer price chosen by you, there exists an upper production limit above which further units become unprofitable to produce.

Example: Assume you choose an offer price of 5 ECU, i.e. every unit sold yields a revenue of 5 ECU. In this case it will be unprofitable for you to produce more than 5 units. The production of a 6th unit would incur costs of 6 ECU, while its sale would yield only 5 ECU. Your profit (revenues minus cost) would decrease.



The arrangements in the experiment are such that quantities are computed automatically; you only have to decide on your offer price. The algorithm calculating the quantities ensures that you will produce only up to your implicit production limit explained above. Furthermore, it is ensured that each firm in each period only produces as many units as it can sell at the effective prices.

Your **profit** (in ECU) per period equals the offer **price chosen by you multiplied by your sales quantity minus the production cost** for this quantity. Your profit thus depends on the offer prices chosen in that period by you and by the other firm.

To get a general idea of your quantities and profits resulting from different price combinations, you may use the "**profit calculator**". Simply enter two hypothetical prices (one for each firm) and click on "Calculate". Then your resulting quantity and profit will be displayed. You may use the profit calculator throughout the whole experiment.

Moreover, after each period a screen with a "**history**" will inform you about the outcomes so far. For all past periods the "history" shows the prices chosen by the two firms, your resulting quantity, your resulting profit per period, and your total profit over all previous periods so far.

The following two screenshots illustrate the use of the profit calculator and the history:

Here you can enter two hypothetical prices and have the results calculated.

Here you can enter and submit your price choice for the current period.

Profit calculator

My price:
Other price:

Calculate

Decision

My price:

Submit price choice

My price	Other price	My quantity	My profit
300	400	300	45000
400	400	300	75000
400	300	300	75000
400	399	201	60200

The results of the profit calculator are displayed here.

Your total profit so far is displayed here.

The results of the last period are displayed here.

History of results

Your total profit so far: 160014

Your price: 500
Other price: 346
Your quantity: 154
Your profit: 65142

Go to next period

Period	Your price	Other price	Your quantity	Your profit
-2.0	0	0	0	0
-1.0	0	0	0	0
0.0	0	0	0	0
1.0	500	325	175	72188
2.0	213	432	213	22685
3.0	500	346	154	65142

This is the history showing the outcomes of all past periods. Zeros are displayed for trial periods.

To practice there will be **three trial periods** before the actual periods start. The procedures in the trial periods are the same as in the actual periods described above, but the outcomes of the trial periods will not add to your total profit or payoff. After the trial periods, the participants will be randomly re-matched into new groups. The new groups will stay fixed throughout all actual periods of the experiment. The profit calculator will be available to you during both trial and actual periods. The history, however, will not be displayed after trial periods and will only contain the data of the actual periods.

Your **total profit** is the **sum of your profits in the single periods** of the experiment (not including the trial periods).

Your total profit will be **paid to you** after the experiment at the above-mentioned exchange rate. None of the other participants will come to know your profit, and neither will you come to know the profit of any other participant. Furthermore, no participant will come to know with whom he or she interacted during the experiment.

If you click on the "Continue" button on your screen, some statements will appear to check whether all participants have understood the instructions. Please decide whether those statements are right or wrong. As soon as all participants will have evaluated the statements correctly, the first trial period will start.

If there are any questions concerning the experimental procedures, please raise your hand. Enjoy the experiment!

Appendix B

Evolution of the market price in single markets with fixed matching.

- Figure B1 here -

- Figure B2 here -

- Figure B3 here -

- Figure B4 here -

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Tables and figures

		$n = 2$	$n = 3$
full competition	p^W	333	250
	Π_i^W	55,444.5	31,250
	Π^W	110,889	93,750
Cournot	p^Q	500	400
	Π_i^Q	93,750	60,000
	Π^Q	187,500	180,000
full collusion	p^C	600	571
	Π_i^C	100,000	71,248.5
	Π^C	200,000	214,285.5

Variables p , Π_i , and Π denote market price, firm profit, and market profit, respectively. Superscripts W , Q , and C denote the fully competitive, Cournot, and fully collusive benchmarks.

Table 1: Benchmark outcomes.

	Individual Price	Individual Profit
$n = 2$, efficient	395.745 (17.665) [396.000]	68,451.259 (7,527.133) [66,978.000]
$n = 2$, proportional	487.008 (55.471) [490.000]	71,010.396 (40,439.669) [76,050.000]
$n = 3$, efficient	289.007 (12.577) [289.000]	37,167.132 (5,322.551) [37,812.500]
$n = 3$, proportional	416.191 (73.463) [416.000]	44,498.162 (33,204.116) [52,448.000]

Standard errors in parentheses. Medians in square brackets.

Table 2: Nash equilibrium predictions of individual price and profit.

<i>periods</i>	Market Price		Market Profit	
	<i>1-24</i>	<i>15-24</i>	<i>1-24</i>	<i>15-24</i>
<i>n = 2, efficient, random</i>	392.697 (17.985) [389.148]	383.403 (9.379) [383.797]	133,917.068 (9,444.181) [135,713.250]	134,762.983 (2,721.021) [135,006.250]
<i>n = 2, efficient, fixed</i>	405.315 (30.514) [399.563]	393.777 (20.763) [390.331]	135,566.395 (10,044.922) [136,720.250]	137,297.132 (7,475.537) [136,723.250]
<i>n = 2, proportional, random</i>	432.096 (42.099) [424.051]	423.052 (35.679) [415.891]	142,633.735 (9,211.928) [143,414.098]	143,913.980 (7,961.372) [144,112.625]
<i>n = 2, proportional, fixed</i>	445.288 (33.845) [444.422]	437.411 (32.472) [434.477]	143,006.802 (9,984.003) [143,162.621]	144,168.121 (8,983.197) [143,998.267]
<i>n = 3, efficient, random</i>	289.756 (13.854) [287.577]	279.861 (4.902) [279.866]	110,913.016 (4,133.332) [111,193.250]	110,089.409 (3,237.614) [110,126.500]
<i>n = 3, efficient, fixed</i>	306.348 (39.612) [293.510]	294.207 (36.899) [283.134]	112,813.473 (8,786.764) [111,952.375]	111,194.639 (5,848.259) [110,979.250]
<i>n = 3, proportional, random</i>	317.398 (22.457) [313.313]	311.301 (22.585) [304.648]	118,115.571 (6,498.513) [116,081.110]	118,712.124 (6,175.035) [116,395.410]
<i>n = 3, proportional, fixed</i>	316.841 (26.550) [313.149]	314.193 (31.302) [305.775]	118,590.824 (7,392.573) [115,928.617]	118,267.086 (7,984.267) [115,570.282]

Standard errors in parentheses. Medians in square brackets.

Table 3: Average market price and profit.

Variable	significant			insignificant	significant with wrong sign
	$p < 0.01$	$0.01 \leq p < 0.05$	$0.05 \leq p < 0.1$	$p \geq 0.1$	$p < 0.1$
supported hypothesis					
Market Price					
$(n = 2) > (n = 3)$	40/40	0/40	0/40	0/40	0/40
proportional > efficient	28/40	10/40	0/40	2/40	0/40
fixed > random	0/40	1/40	5/40	33/40	1/40
Market Price: Collusiveness Index					
$(n = 2) > (n = 3)$	32/40	5/40	3/40	0/40	0/40
Market Profit					
$(n = 2) > (n = 3)$	40/40	0/40	0/40	0/40	0/40
proportional > efficient	30/40	8/40	1/40	1/40	0/40
fixed > random	0/40	0/40	2/40	36/40	2/40
Market Profit: Collusiveness Index					
$(n = 2) > (n = 3)$	39/40	0/40	1/40	0/40	0/40

Pairwise comparison of treatments in periods 15 to 24. Frequencies of results of two-tailed Mann-Whitney tests. Table entries in the first three columns indicate the number of cases in which the null hypothesis of equal medians is rejected at the displayed significance level in favor of the supported hypothesis. " $(n = 2) > (n = 3)$ " ("proportional > efficient", "fixed > random") means that the median of the variable is higher in the duopoly than in the triopoly (under proportional than under efficient rationing, under fixed than under random matching).

Table 4: Results of significance tests for treatment effects.

Dependent Variable	Market Price		Market Profit	
	(1)	(2)	(3)	(4)
c	392.131*** (2.411)	389.716*** (3.364)	135,133.745*** (460.711)	134,276.370*** (616.179)
1/period	46.325*** (3.452)	46.325*** (3.452)	-1,381.658 (1,271.250)	-1,381.658 (1,212.250)
n = 3	-112.867*** (2.399)	-110.008*** (4.709)	-24,291.920*** (429.267)	-23,492.088*** (831.167)
proportional	31.710*** (2.399)	34.098*** (4.709)	7,291.657*** (429.267)	8,496.899*** (831.167)
fixed	7.432*** (2.399)	7.303 (4.601)	966.909** (429.267)	2,005.167** (812.057)
(n = 3)*proportional		0.339 (6.751)		-468.684 (1,191.661)
(n = 3)*fixed		3.736 (6.583)		-156.196 (1,162.013)
proportional*fixed		8.100 (6.583)		-1,245.670 (1,162.013)
(n = 3)*proportional*fixed		-24.008** (9.430)		-1,555.620 (1,664.431)
Observations	1,920	1,920	1,920	1,920
Adjusted R ²	0.573	0.589	0.645	0.659

GLS regressions with clustered errors on the market level. Clustered standard errors in parentheses. ***, **, and * denote significance at the 1, 5, and 10 percent level. See accompanying text for variable definitions.

Table 5: Regression results for market level data.

	$pcoll < 0$	$0 \leq pcoll < 0.25$	$0.25 \leq pcoll < 0.5$	$0.5 \leq pcoll < 0.75$	$0.75 \leq pcoll < 1$	mean $pcoll$
all treatments	0.002 (3/1920)	0.612 (1175/1920)	0.318 (610/1920)	0.063 (120/1920)	0.006 (12/1920)	0.251
$n = 2$, efficient, random	0.004 (1/240)	0.708 (170/240)	0.288 (69/240)	0.000 (0/240)	0.000 (0/240)	0.224
$n = 2$, efficient, fixed	0.008 (2/264)	0.492 (130/264)	0.439 (116/264)	0.061 (16/264)	0.000 (0/240)	0.271
$n = 2$, proportional, random	0.000 (0/240)	0.233 (56/240)	0.579 (139/240)	0.158 (38/240)	0.029 (7/240)	0.371
$n = 2$, proportional, fixed	0.000 (0/240)	0.079 (19/240)	0.675 (162/240)	0.238 (57/240)	0.008 (2/240)	0.421
$n = 3$, efficient, random	0.000 (0/240)	0.975 (234/240)	0.025 (6/240)	0.000 (0/240)	0.000 (0/240)	0.124
$n = 3$, efficient, fixed	0.000 (0/240)	0.829 (199/240)	0.133 (32/240)	0.025 (6/240)	0.013 (3/240)	0.176
$n = 3$, proportional, random	0.000 (0/216)	0.806 (174/216)	0.194 (42/216)	0.000 (0/216)	0.000 (0/216)	0.210
$n = 3$, proportional, fixed	0.000 (0/240)	0.804 (193/240)	0.183 (44/240)	0.013 (3/240)	0.000 (0/240)	0.208

Relative frequencies of market prices in the respective collusiveness ranges and mean collusiveness. $pcoll = 0$ ($pcoll = 1$) corresponds to the fully competitive (collusive) price.

Table 6: Collusiveness of market prices: Frequencies.

Panel A: Individual Price

<i>periods</i>	<i>1-24</i>		<i>15-24</i>	
	<i>mean</i>	<i>comparison to Nash prediction</i>	<i>mean</i>	<i>comparison to Nash prediction</i>
<i>n = 2, efficient, random</i>	400.000 (42.032) [391.500]	=	385.800 (15.831) [380.000]	<***
<i>n = 2, efficient, fixed</i>	411.019 (41.956) [400.000]	>***	396.018 (25.546) [394.000]	=
<i>n = 2, proportional, random</i>	453.129 (89.636) [422.500]	<***	440.970 (74.413) [400.000]	<***
<i>n = 2, proportional, fixed</i>	463.646 (66.518) [450.000]	<***	452.405 (59.961) [440.000]	<***
<i>n = 3, efficient, random</i>	293.907 (35.222) [289.000]	=	281.190 (11.480) [280.000]	<***
<i>n = 3, efficient, fixed</i>	317.790 (66.201) [296.000]	>***	298.153 (46.154) [284.000]	<***
<i>n = 3, proportional, random</i>	338.704 (84.454) [312.000]	<***	332.611 (81.119) [299.000]	<***
<i>n = 3, proportional, fixed</i>	332.063 (67.082) [311.000]	<***	327.563 (67.829) [304.000]	<***

...

Panel B: Individual Profit				
<i>periods</i>	<i>1-24</i>		<i>15-24</i>	
	<i>mean</i>	<i>comparison to Nash prediction</i>	<i>mean</i>	<i>comparison to Nash prediction</i>
<i>n = 2, efficient, random</i>	66,958.534 (12,317.095) [66,486.000]	=	67,381.471 (4,485.735) [66,486.000]	=
<i>n = 2, efficient, fixed</i>	67,783.197 (18,852.463) [67,147.500]	=	68,648.566 (10,214.421) [66,937.500]	=
<i>n = 2, proportional, random</i>	71,316.868 (26,563.938) [73,142.560]	<***	71,956.990 (19,304.860) [73,052.280]	<***
<i>n = 2, proportional, fixed</i>	71,503.401 (30,193.821) [75,136.000]	=	72,084.061 (25,072.270) [74,305.250]	=
<i>n = 3, efficient, random</i>	36,971.005 (8,974.914) [38,642.000]	>***	36,696.470 (3,339.204) [37,812.500]	=
<i>n = 3, efficient, fixed</i>	37,604.491 (16,556.877) [38,920.500]	>***	37,064.880 (13,144.703) [37,950.250]	=
<i>n = 3, proportional, random</i>	39,371.857 (17,207.199) [43,512.500]	<***	39,570.708 (14,126.615) [42,050.000]	<***
<i>n = 3, proportional, fixed</i>	39,530.275 (16,750.299) [42,340.500]	<***	39,422.362 (15,943.523) [42,050.000]	<***

Standard errors in parentheses. Medians in square brackets. The entries in the columns "comparison to Nash prediction" show the results of two-tailed Wilcoxon signed rank tests with the null hypothesis that the observed median is equal to the predicted Nash equilibrium median stated in Table 2. "<" (">") indicates that the observed median is significantly lower (higher) than the Nash prediction, where ***, **, and * denote the 1, 5, and 10 percent significance levels. "=" indicates that equality of the two medians cannot be rejected at the 10 percent significance level.

Table 7: Individual price (Panel A) and profit (Panel B) data with comparison to Nash prediction.

	$n = 2$		$n = 3$		pooled
	efficient	proportional	efficient	proportional	
random	0.237 (109/460)	0.252 (116/460)	0.229 (158/690)	0.163 (101/621)	0.217 (484/2231)
fixed	0.069 (35/506)	0.133 (61/460)	0.159 (110/690)	0.091 (63/690)	0.115 (269/2346)

Relative frequencies of stable individual prices over two consecutive periods.

Table 8: Stable individual pricing: Frequencies.

Dependent Variable	stableprice
c	-0.639*** (0.083)
1/period	-0.676** (0.295)
$n = 3$	-0.037 (0.071)
proportional	-0.092 (0.070)
fixed	-0.418*** (0.068)
Observations	4577
McFadden R^2	0.025

Probit regression. Heteroskedasticity and autocorrelation consistent standard errors in parentheses. ***, **, and * denote significance at the 1, 5, and 10 percent level. "stableprice" equals 1 if a subject has not changed her price compared to the last period and 0 otherwise.

Table 9: Stable individual pricing: Regression results.

Dependent Variable	$p_{i,t} - p_{i,t-1}$				
	(1)	(2)	(3)	(4)	(5)
Sample Restriction	None	None	None	$n = 2$	$n = 3$
c	-4.728*** (1.003)	-1.932** (0.937)	-1.902** (0.952)	-0.817 (1.551)	3.272** (1.381)
$BR_{i,t-1} - p_{i,t-1}$	0.219*** (0.009)	0.001 (0.011)	0.697*** (0.167)	0.451*** (0.154)	0.046*** (0.012)
$BR_{i,t-2} - p_{i,t-2}$	-0.012 (0.009)	0.002 (0.011)	0.001 (0.011)	-0.112 (0.154)	0.013 (0.011)
$p_{-i,t-1} - p_{i,t-1}$		0.468*** (0.017)	-0.238 (0.162)	0.019 (0.148)	
$p_{-t,t-2} - p_{i,t-2}$		-0.037** (0.017)	-0.040** (0.017)	0.100 (0.149)	
$(BR_{i,t-1} - p_{i,t-1}) * (n = 3)$			-0.365** (0.146)		
$(BR_{i,t-1} - p_{i,t-1}) * \text{proportional}$			-0.354*** (0.095)		
$(BR_{i,t-1} - p_{i,t-1}) * \text{fixed}$			0.014 (0.025)		
$(p_{-i,t-1} - p_{i,t-1}) * (n = 3)$			0.452*** (0.143)		
$(p_{-i,t-1} - p_{i,t-1}) * \text{proportional}$			0.315*** (0.094)		
$(p_{-i,t-1} - p_{i,t-1}) * \text{fixed}$			0.012 (0.037)		
$p_{-i,t-1}^L - p_{i,t-1}$					0.530*** (0.024)
$p_{-i,t-2}^L - p_{i,t-2}$					-0.107*** (0.023)
$p_{-i,t-1}^H - p_{i,t-1}$					0.054*** (0.020)
$p_{-i,t-2}^H - p_{i,t-2}$					-0.011 (0.019)
Observations	4,378	4,378	4,378	1,804	2,574
Adjusted R ²	0.127	0.253	0.259	0.230	0.320

OLS regressions. Standard errors in parentheses. ***, **, and * denote significance at the 1, 5, and 10 percent level. See accompanying text for variable definitions.

Table 10: Edgeworth price adjustment and imitation: Regression results.

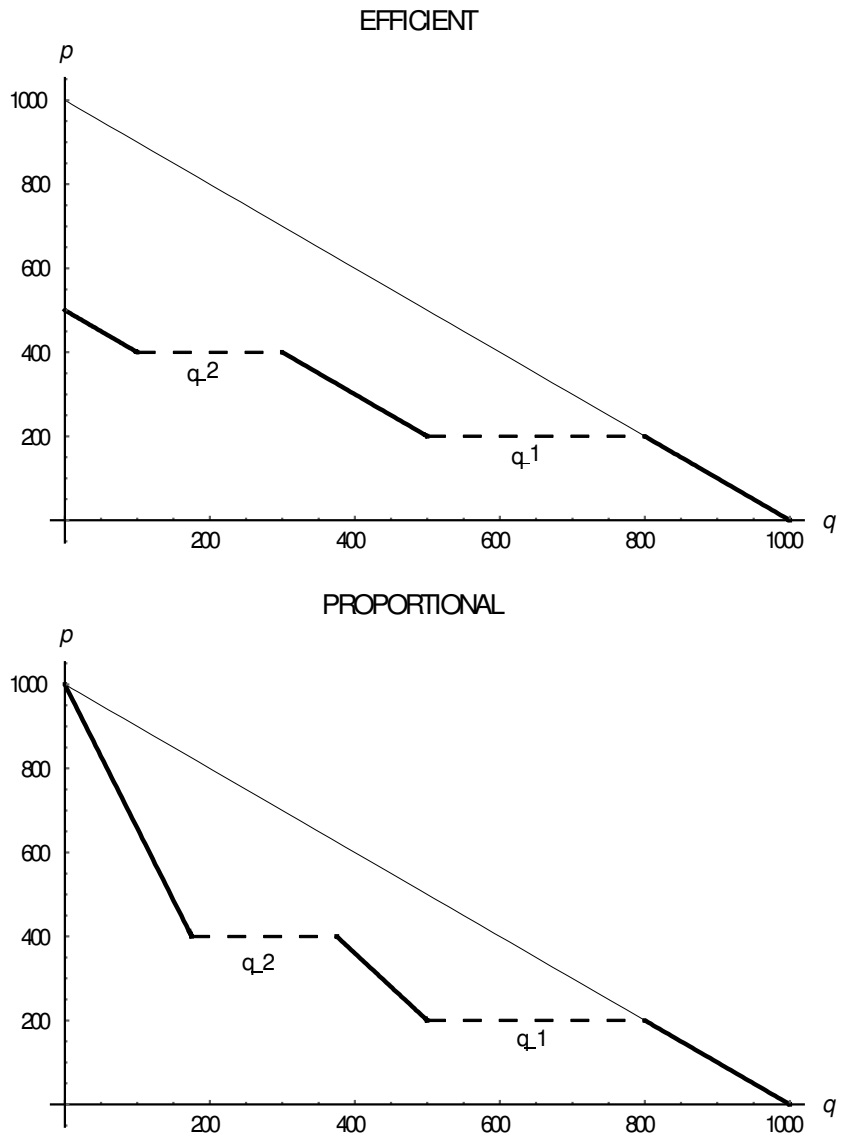


Figure 1: Residual demand under proportional and efficient rationing.

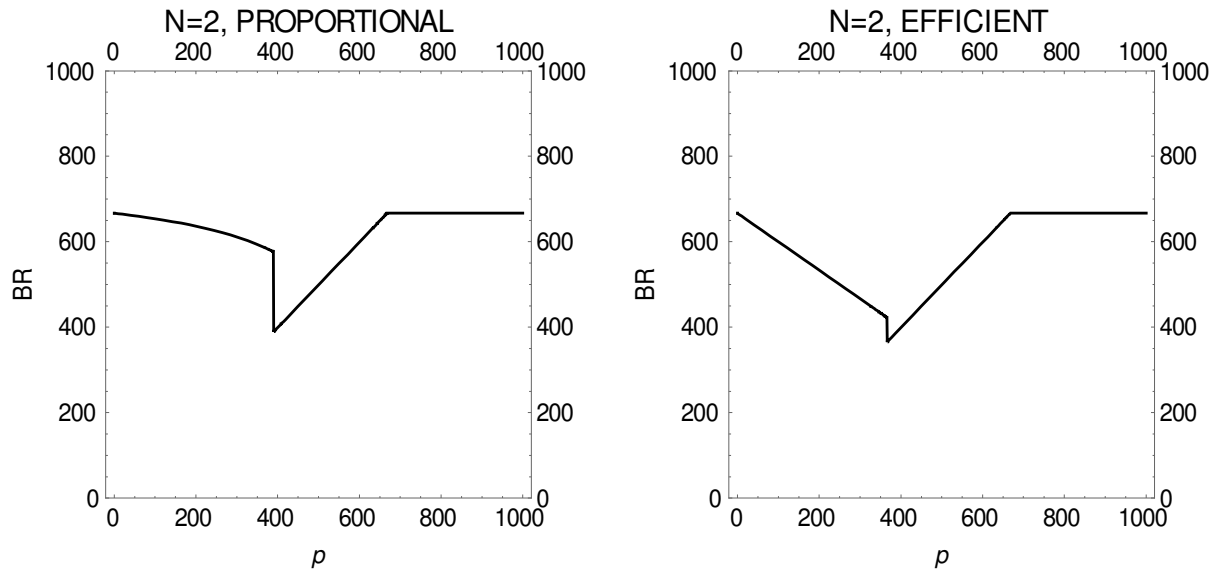


Figure 2: Best response functions in the two-player game.

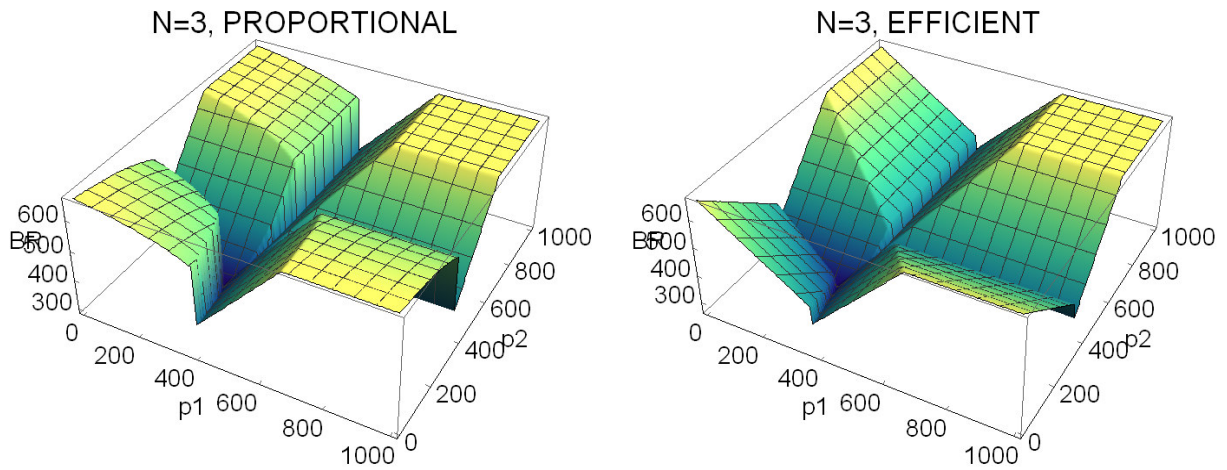


Figure 3: Best response prices in the three-player game.

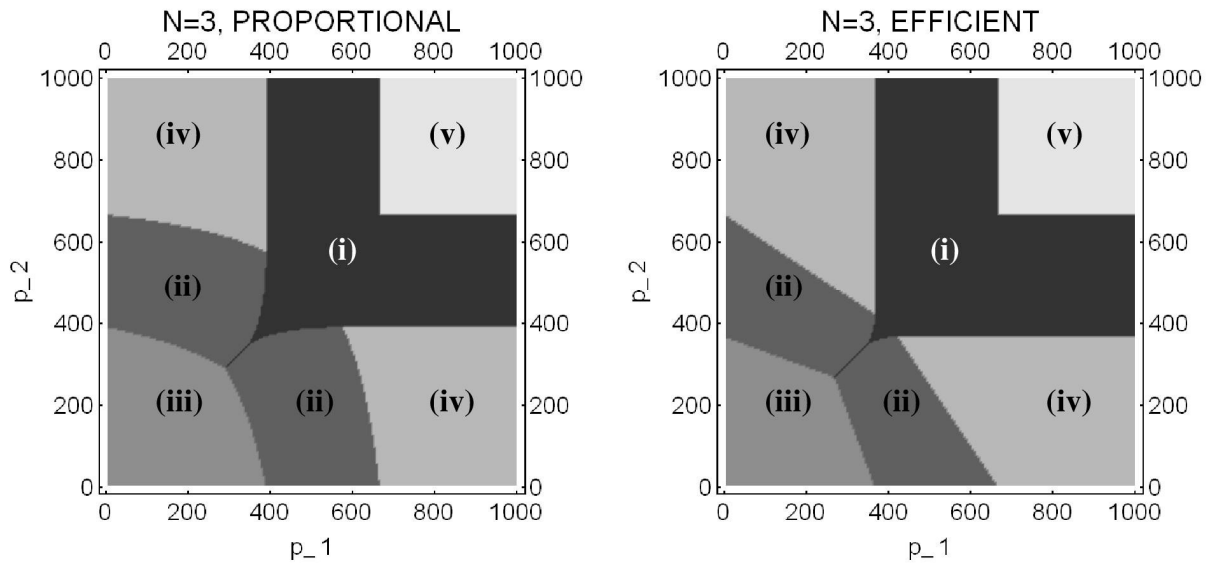


Figure 4: Best response strategies in the three-player game. The five regions, from darkest to brightest, indicate five different best response strategies: (i) underbid the lower other price, (ii) underbid the higher other price, (iii) set the highest price and monopolize residual demand, (iv) set the middle price and monopolize residual demand, and (v) set the lowest price and monopolize residual demand.

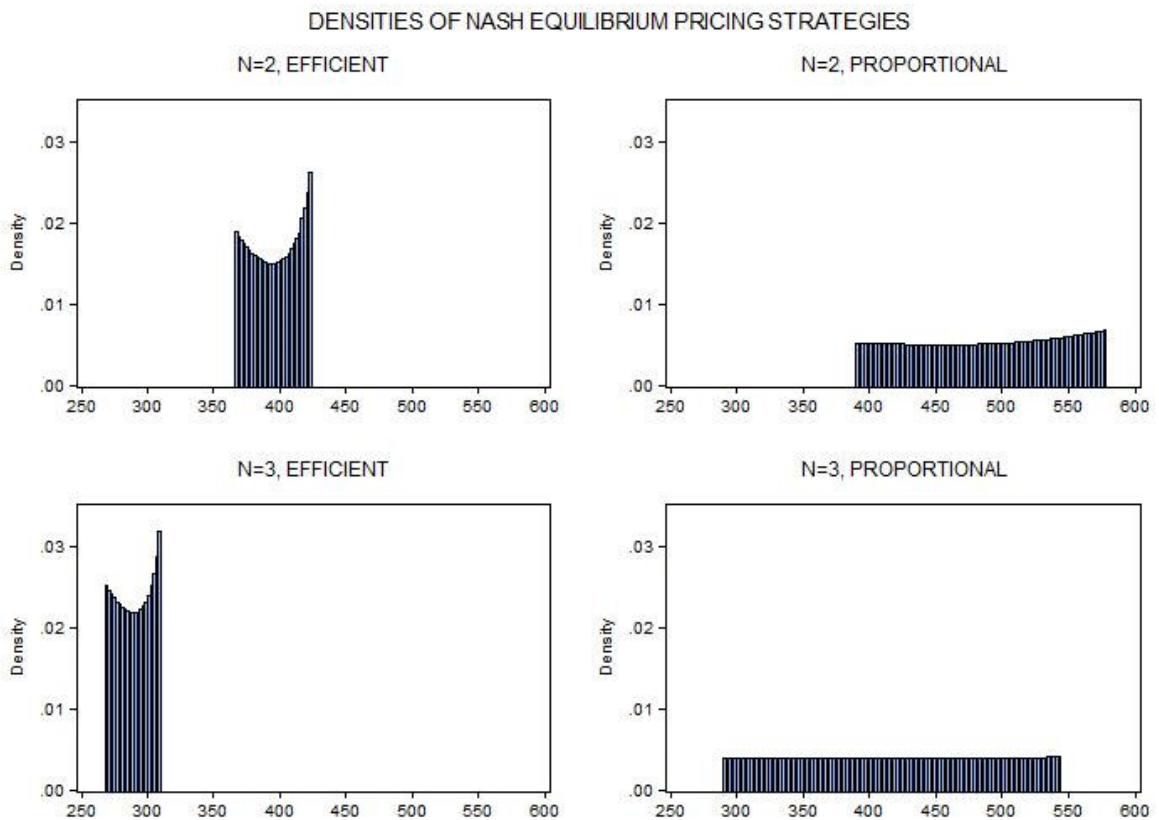


Figure 5: Densities of Nash equilibrium pricing strategies.

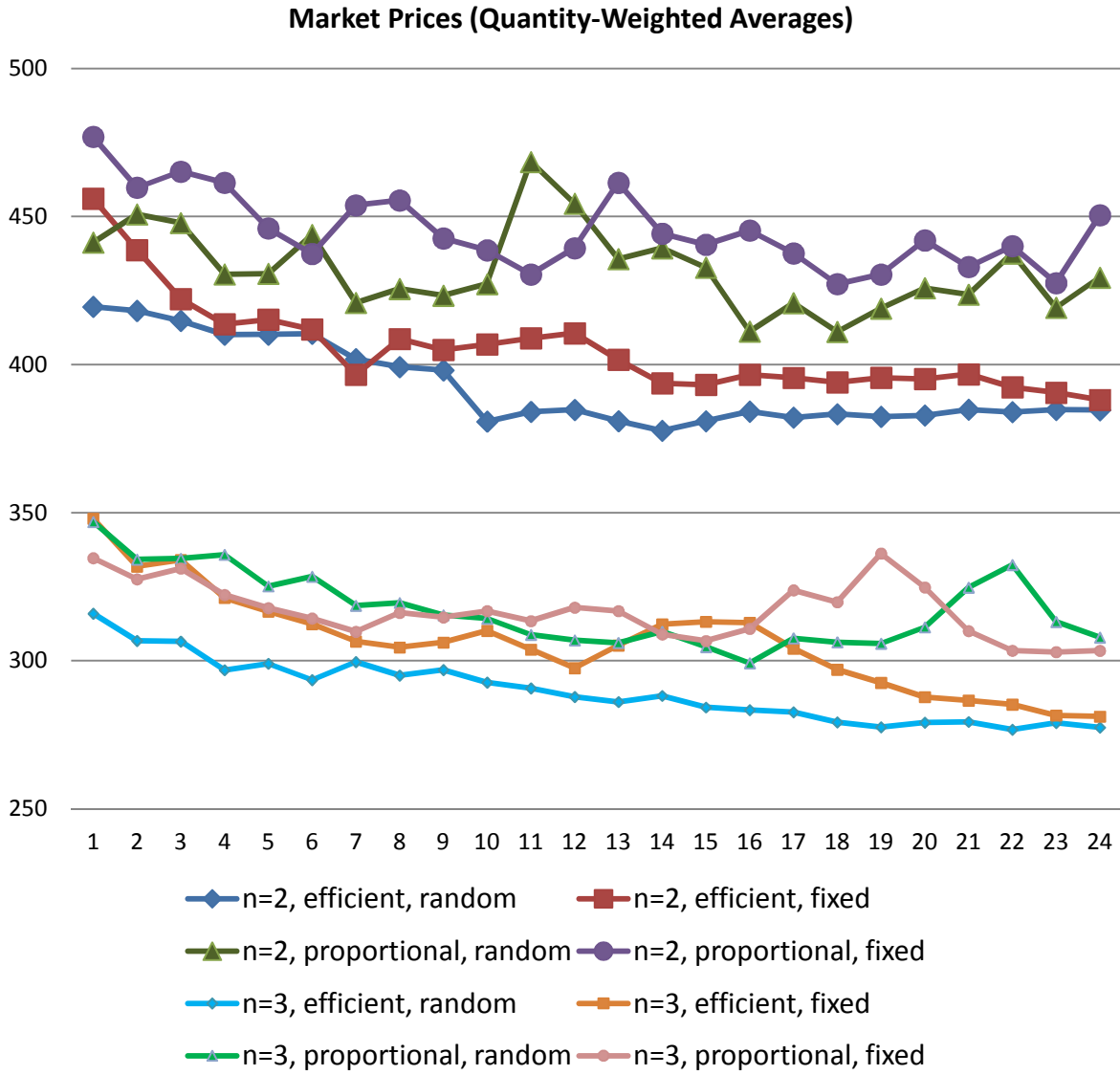


Figure 6: Series of market prices.

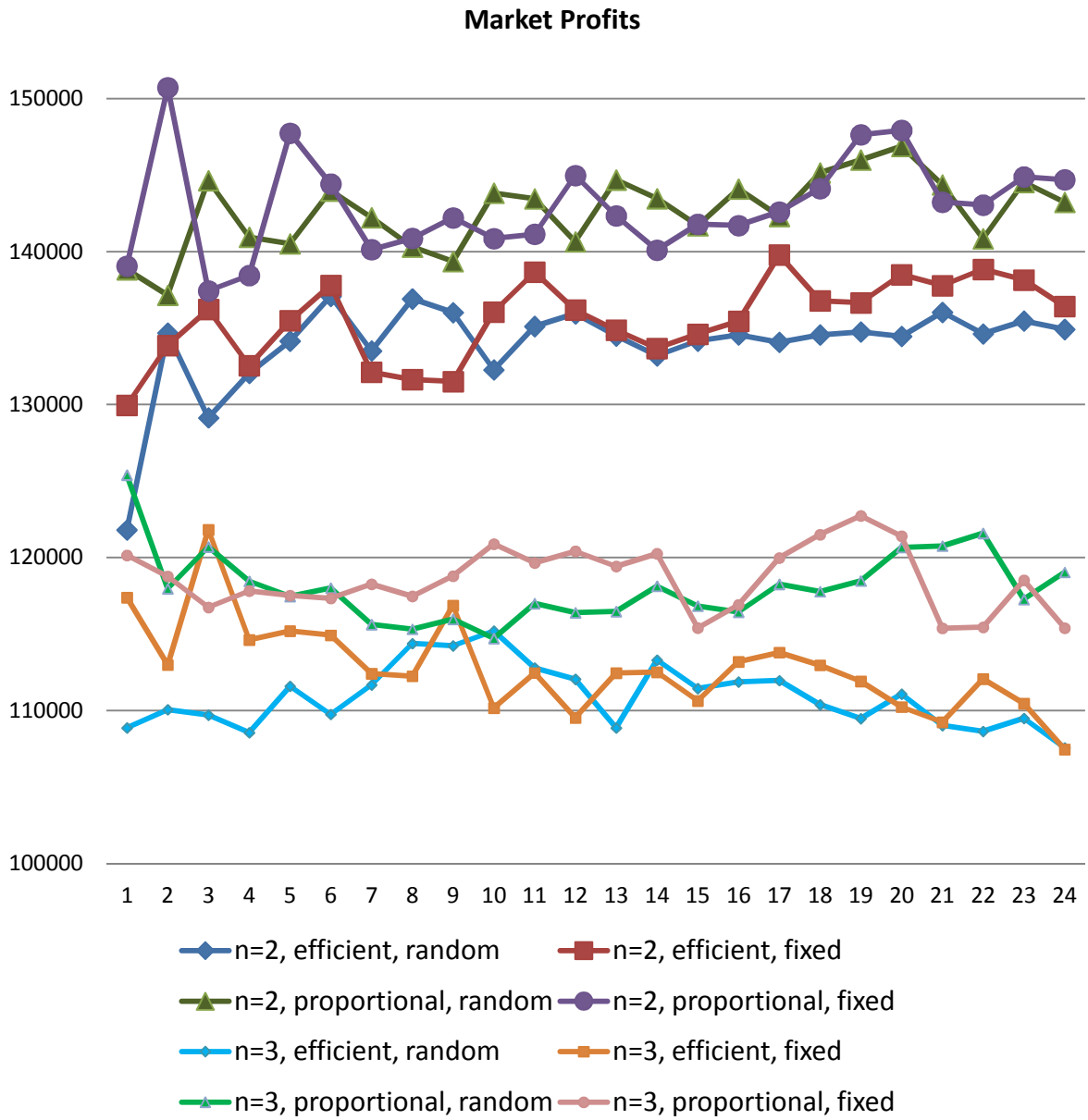


Figure 7: Series of market profits.

DENSITIES OF INDIVIDUAL PRICES BY TREATMENT

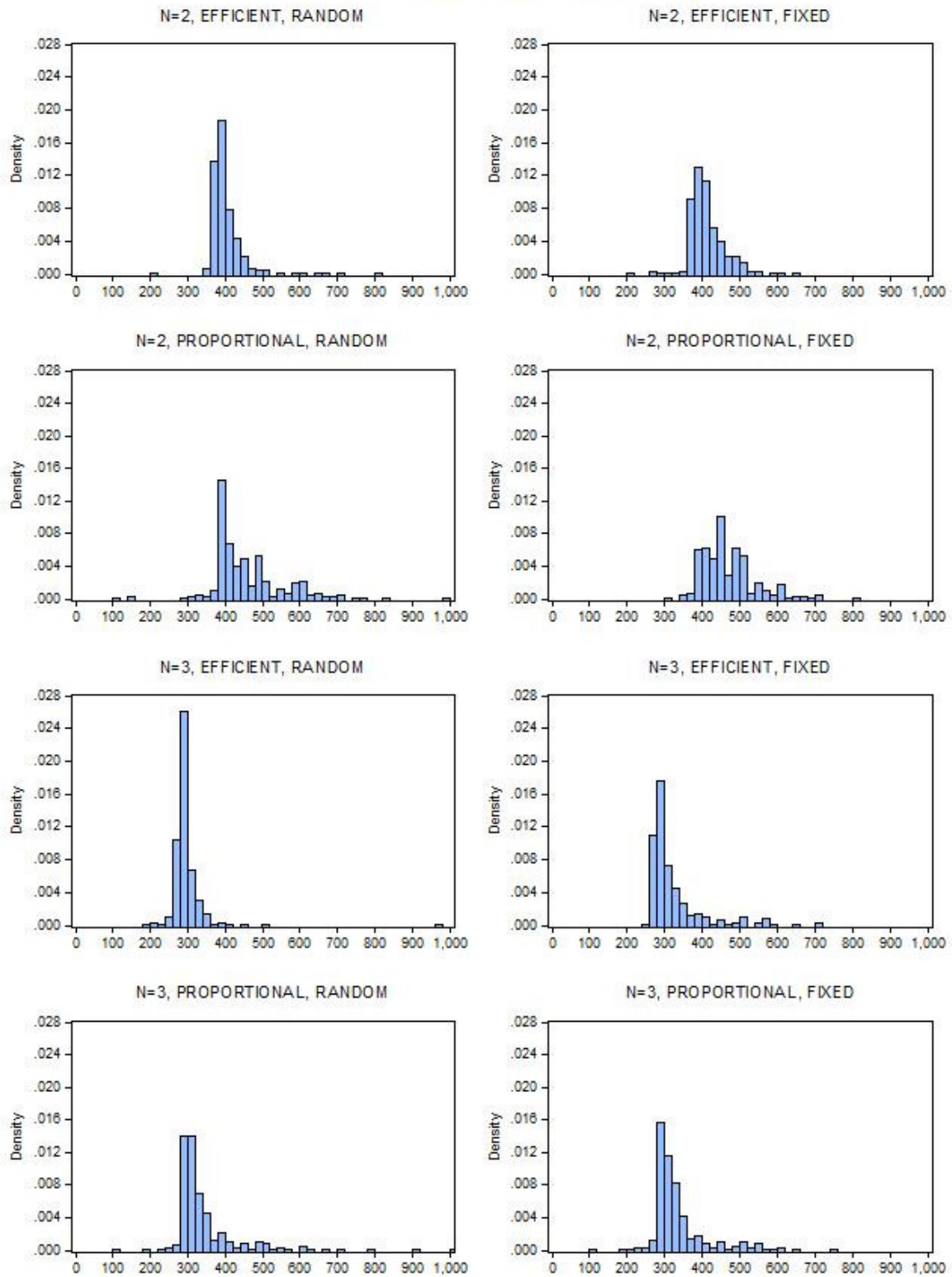


Figure 8: Densities of prices.

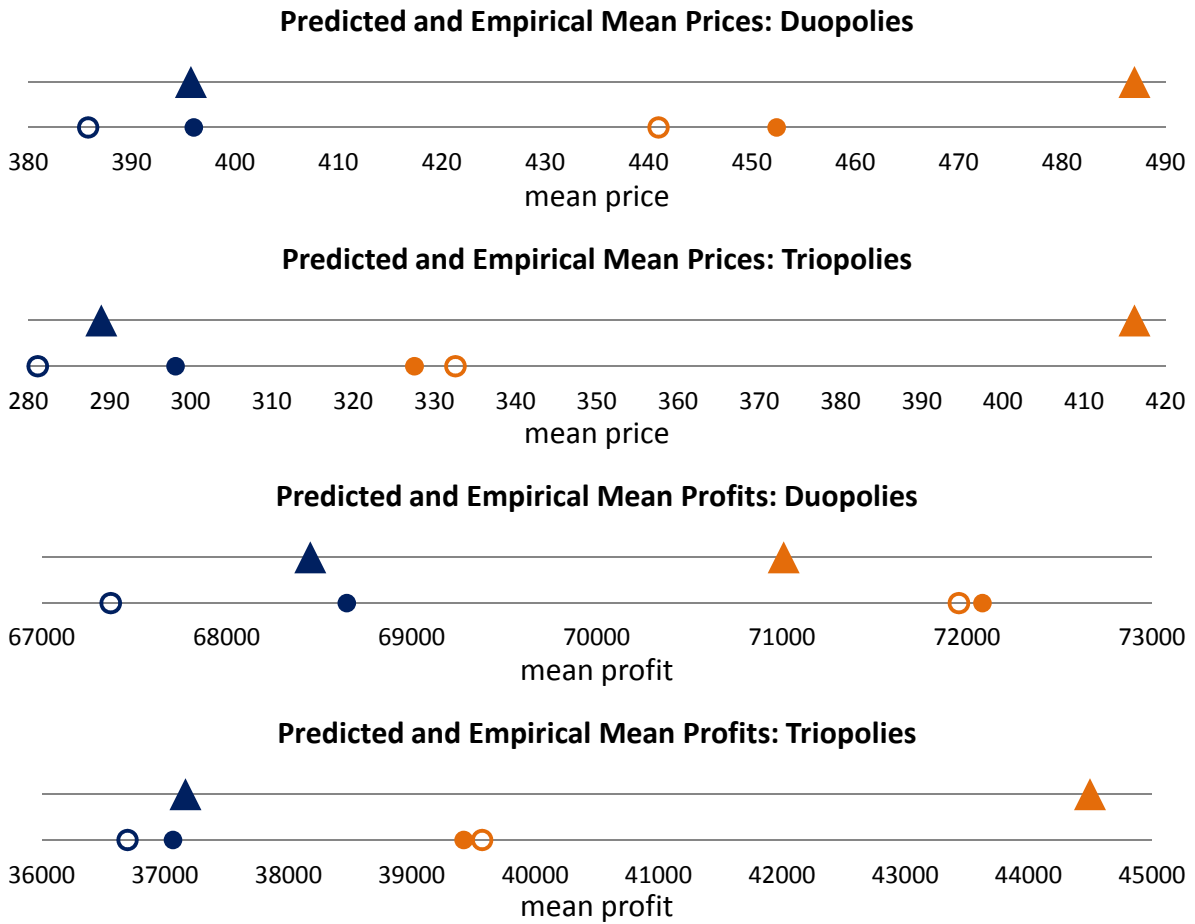


Figure 9: Comparison of Nash predictions (triangles) for mean individual prices and profits to empirical data (circles) from periods 15 to 24. Orange (blue) color corresponds to proportional (efficient) rationing. Filled (void) circles denote the empirical means in fixed (random) matching treatments.

DISTRIBUTION OF STABLE PRICES BY TREATMENT

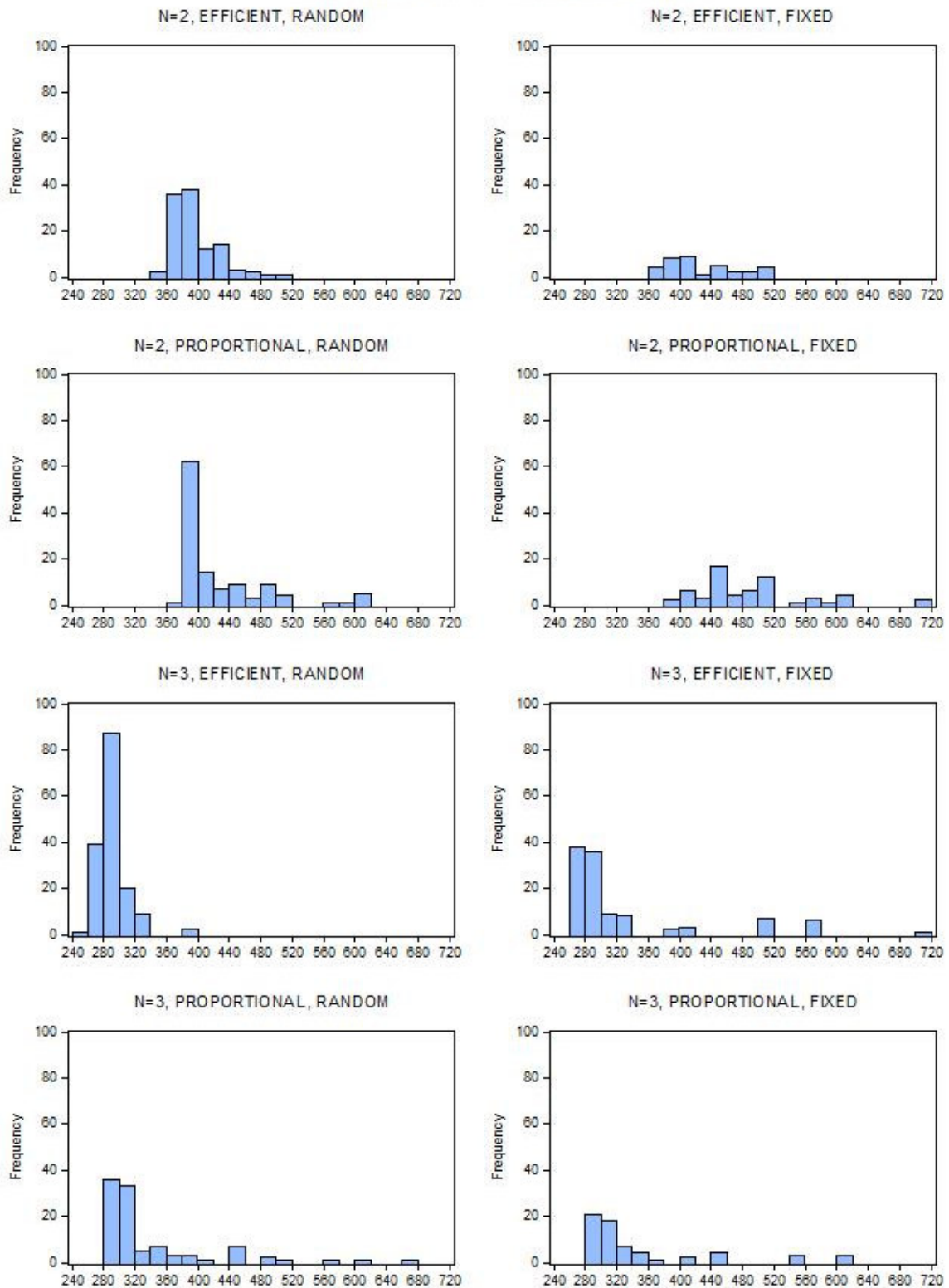


Figure 10: Distribution of stable prices.