Optimal Pricing Strategies in Dynamic Oligopolies

Growing Artificial Society – ECON650

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1. Overview

Purpose: The purpose of this model is to explore how oligopolists might determine their prices in the face of a linear demand function. Our extensions upon the original model allow us to break away from the assumptions of Bertrand price competition by allowing firms the option of competing through methods besides cost cutting. In the original model, in order to dominate the market, competitors reduce price below that of competitors, until the price equals marginal cost. In order to further explore price determination, we added "reduce cost" and "reduce product value" strategies to the list of available strategies that competitors can choose from by checking competition and consumer preferences. The model and its extension allow us to examine the (dis)advantages of different price determination strategies and the emergent outcomes.

Review of some related literature

The hallmark of oligopolistic markets is that, given the small number of firms dominating the market, firm's decisions affect and are affected by the decisions of the other market participants. Therefore, strategic planning by oligopolists plays a key role in their success to reduce competition (Shapiro 1989). Optimal pricing strategies in dynamic oligopolies are studied extensively in recent literature. Dockner and Jorgensen (1988) analyze three basic classes of sales dynamics: competition with price effects only, competition with price as well as adoption effects, and competition with adoption effects only. The authors conclude that it might be the case that the results which hold for a monopolistic market carry over to oligopolistic markets.

What significantly differentiates oligopoly market structure from monopoly is competitive interdependencies, which significantly affects the rates of change of optimal prices. In order to examine adoption effects, we utilized Dockner and Jorgensen (1988) assumption that cost learning effects are such that unit costs are decreasing with cumulative outputs and added a “reduce sot” strategy to the model. In another paper by Nevil, McGill, and Nediak (2007), a dynamic pricing model for oligopolistic firms is presented in which strategic behavior by both firms and also consumers are studied. The authors find that strategic behavior by consumers can have serious impacts on revenues if firms ignore that behavior in their dynamic pricing policies. In order to examine the impact of consumers’ response to firms strategies, we added a “reduce product value” strategy to the model. In our implementation, the firms reduce product value to reduce production cost, but in return the quantity demanded by consumers is diminished. This extension allows us to examine the magnitude by which firm’s revenue is affected due to consumers’ behavior.

2. Entities, State variables, and scales

The agents included in this model are firms or oligopolists. The market and the firms are characterized by the following variables:

-Price: the bid price by each firm. – Current price: the price for which sales are made in the market in each episode. – Cost: firm’s unit cost of production, - Delta: the parameter by which firms increase or decrease their price in each episode. – Epsilon: the parameter by which firms increase or decrease their price, when the epoch is over and firms determine whether on average they did better by offering more than their current price or less. - Strategy: the method by which firms determine their bidding price. - Product value: firm's value of unit of production. - Value Delta: the parameter by which firms decrease their product value. - Cost Delta: the parameter by which firms decrease their unit cost. - UpReward/DownReward: the profit the firm would have had by bidding high/low, based on price and quantity of the winner. - TotalReward: total profit of the firm. - The winner: an attribute that distinguishes the firm with the lower bid price in each episode. - First mover: an attribute that distinguishes the firm that dominates the market in the first episode.

3. Process overview and scheduling

In this model, the firms adjust prices. During each market episode, each firm announces its unit price. The market satisfies its entire demand at the lower of the two prices (or randomly in the case of a tie). This is, then, a winner-take-all market during each episode. After each episode, each firm observes the winning bid and resulting demand, then calculates the profit it would have had had it won with that bid. During an epoch (a number of episodes), each agent records the profit it achieved for each episode. If the agent did not win the bid, the profit is 0, otherwise it is: price * quantity - cost * quantity. If, during the epoch, firm's bids above its current price returned on average more than its bids below the current price, the firm raises its price by epsilon. If not, the firm lowers its price by setting it equal to the maximum value of 'price minus epsilon' or 'the cost' (bid price can't go below marginal cost). Firms with "reduce cost" or "reduce product value" strategies can bid lower price given their lower marginal cost.

4. Design concepts

● Basic Principles: The basic concept for this model is a “winner-takes-all’’ oligopoly simulation. The original model only allows for Bertrand competition (price cutting), but our revisions to the code allow for cost, and quality competition as well.

● Emergence: What emerges from the model is that in an oligopoly, firms’ success to reduce competition and dominate the market entirely depends on their strategic planning. However, In order to achieve the optimal pricing strategy, firms are limited to experimenting with their production function parameters: cost or quality, which are also accompanied by limitations. For example, lowering the quality parameter is accompanied by consumer’s response in form of reduction in quantity demanded. Given the limitations, the model utilizes differential competition methods to examine the potential for increased gains due to forgoing of price competition in favor of other competitive themes (quality, and cost).

● Adaptive Behavior: each firm observes the winning bid and resulting demand, then calculates the profit it would have had had it won with that bid. This reward is recorded in the list of upRewards or downRewards depending on whether the WinningBid is > or <= currentPrice. If, during the epoch, firm's bids above its current price returned on average more than its bids below the current price, the firm increases its price. Otherwise, it lowers its price by setting it equal to the maximum value of 'current price minus epsilon' or 'the cost'. By how much the firm lowers its price depends on the firm’s pricing strategy. In the "Market Returns" strategy, the cost equals Unit Cost* Unit Quality. In the “ reduced cost” strategy, unit cost is reduced by (1 – Cost Delta), so cost = (1 – Cost Delta) * Unit Cost* Unit Quality. In the “ reduce product value” strategy, unit quality is decreased by (1 – Value Delta), so cost = Unit Cost* (1 – Value Delta) * Unit Quality.

● Fitness: The goal of the agents in this model is to offer the lowest bid price and be the winner of the ‘winner-take-all’ market. The agent’s survival is determined by gaining more profit in each episode.

● Learning: Our agents will not have the capability of changing their adaptive traits. This is one of the limitations of the model. Once their pricing strategy is set before the first run, they are not able to change it afterwards.

● Prediction: Observing the winning bid and resulting demand, the agents then calculates the profit they would have had had it won with that bid

● Sensing: All of the agents observe the winning and the resulting quantity demanded.

● Interaction: There is no direct interactions between the agents. Firms can only observe the other firm’s price bid and their resulting demand.

● Stochasticity: In each episode, the agent sets its bid price using a random determination. The new price is randomly decreases or increase by a variation of delta as follows: Price = (random-float 2 * delta) - delta + Price

● Collectives: While the potential for collusion could be examined in the model, there is no explicitly defined collectives (groups of firms).

● Observation: The primary outputs of interest are observed as a time series line graph of the current bid price plotted with the winning bid, the monopoly price at 0 costs, monopoly price of firm 0, and monopoly price of firm 1. Also of paramount importance is a monitor of average winning bid. In order to gain a fuller understanding of the results of the model, the data on each episode's winning bid, each firm's bid price, total profit, and number of bids won will be exported, using the behavior space tool. The exported data will be analyzed based on different model parameters and agent's attributes such as the initial cost and product quality, their pricing strategy, and the parameters by which their reduced cost or product quality. Such analysis will help us to better understand how the oligopoly market functions and what are the determinants of the oligopolists dominance in the market.

5. Initialization

A table listing all of the parameters and their baseline values is presented at the end of this section.

6. Input data:

The model does not use input from external sources.

7. Submodels

The oligopoly model utilizing Bertrand price competition begins by endowing each firm with an initial price. In each episode, the firm probes its market by offering a price in the range [current Price - delta, current Price + delta]. Depending on the realized revenue, the firm increases its current Price by epsilon or decreases it by epsilon. Both delta and epsilon are set in the Interface.

There are two key passages regarding price determination in the code: 'observe-and-record', and 'postpare-episode'. The 'observe-and-record' procedure works as follows: If the winning bid is greater than the currentPrice, the firm updates upRewards list by adding profit to the end of the list; Otherwise, updates downRewards list by adding profit to the end of the list. As part of our extensions of the model, we modified the profit function of firms that employ "Decrease Product Value" strategy and introduce a penalty. Meaning that these firm's quantity demanded decreases by the changes in their product value: profit = price * (quantity * (1-VDelta)) - cost * (quantity * (1-VDelta)). If firm doesn't have a "Decrease Product Value" policy, it sets profit as price * quantity - cost * quantity.

The ‘postpare-episode’ procedure works as follows: if, during the epoch, firm's bids above its current price returned on average more than its bids below the current price (average upRewards > average downRewards), then firm raises its price by epsilon; Otherwise, the firm lowers its price by setting it equal to the maximum value of 'current price minus epsilon' or 'the cost'. By how much the firm lowers its price depends on the firm’s pricing strategy. Different pricing strategies are also defined in the ‘pospare-episode’ procedure. In the "Market Returns" strategy, the cost equals Unit Cost* Unit Quality. In the “ reduced cost” strategy, unit cost is reduced by (1 – Cost Delta), so cost = (1 – Cost Delta) * Unit Cost* Unit Quality. In the “ reduce product value” strategy, unit quality is decreased by (1 – Value Delta), so cost = Unit Cost* (1 – Value Delta) * Unit Quality.

Table 1 - Baseline Parameterization

Variable	Description	Baseline Value
Quantity Intercept	The intercept when price is zero (Linear Demand Function Parameters)	222
Slope	Slope of demand curve zero (Linear Demand Function Parameters)	0.5
Number of firms	Number of oligopolists in the market	2
Epsilon	the parameter by which firms 1 & 2 increase or	0.8

	decrease their price, when the epoch is over	
Delta	the parameter by which firm 1 & 2 increase or decrease their price, in each episode	3
Initial Price	Initial Price of firm 1 & 2	193
Unit Cost	Cost of production for firm 1&2	10
Cost Delta	the parameter by which firm 1 & 2 decrease their unit cost of production	0.1
Product Value	Quality of unit of production for firm 1 & 2	5
Value Delta	the parameter by which firm 1 & 2 decrease their product quality	0.1
Pricing Policy	The strategy firms use to determine their bid price	Market Returns
First Mover Advantage	The parameter by which the first mover can further reduce its cost	0.9

In our baseline parameterization, we have considered equal baseline values for both firms.

Experimental Design

Experiment 1
"Market Returns" vs. "Reduce Cost" Strategy – May 3rd, 2017

Hypothesis 1.1
Firm utilizing the ' reduce cost' strategy beats the firm utilizing 'market returns' strategy, since the 'reduce cost' strategy allows the firm to bid lower prices.

Hypothesis 1.2
As the value of the parameter by which the firm reduces its cost increases, the firm's dominance becomes stronger.

We test these hypotheses by comparing the number of times that each firm with different pricing strategy won the bid and dominated the market.

Table 2 – Experiment 1 Specifications

Exogenous Constants		
Names	Types	Values
Epsilon	float	0.8
Delta	float	3
Initial Price	float	193
Unit Cost	float	10
Product Value	float	5
Value Delta	float	0.1
Pricing Policy of firm 1	Attribute	"Market Returns"

Varying Parameters			
Names	Baseline Values	Value Ranges	
Pricing Policy of firm 2	“Market Returns”	“Reduce Cost”	
Cost Delta of firm 2	0.1	0.1- 0.2 - 0.4 - 0.8	

Outcomes	**No. Replications**	**Collection Method**	**Analysis Method**
No. of Bids Won	15	BehaviorSpace	Excel Spreadsheet

Results

We assigned different values to Cost Delta parameter and run the experiment 60 times to analyze how the value of this parameter affects chances of offering the lowest price by the firm that uses “reduce cost” strategy. Figure 1, compares the number of bids won based on different strategies. As shown in the figure, the firm with “reduce cost” strategy has the higher number of bids won in every single run. This result allows us to accept our Hypothesis 1.1.

Moreover, in Table 3, we compare the average number of bids won by each firm based on the value of the Cost Delta parameter. As its shown in the table, the larger this parameter, the bigger the difference between the number of bids won by the firm utilizing the “reduce cost” strategy. This result allows us to accept our Hypothesis 1.2.

Figure 1

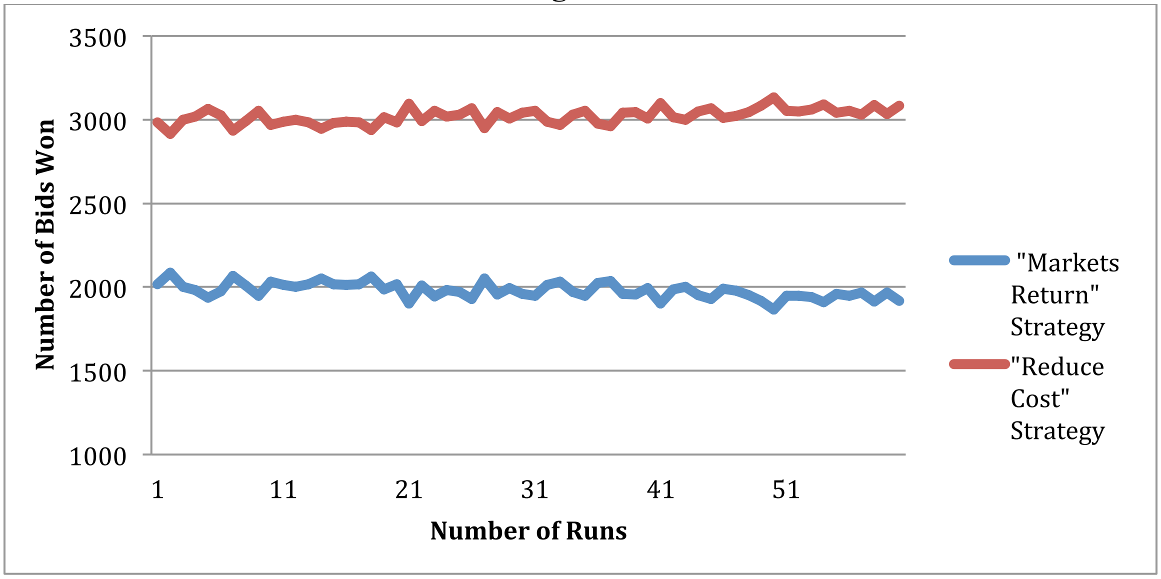

Table 3

Cost Delta	Average Number of Bids Won by Firm with Market returns	Average Number of Bids Won by Firm with Reduce Cost Strategy
0.1	2012.8	2988.2
0.2	1979.6	3021.4
0.4	1945.1	3055.9
0.8	1912.6	3206.6

Experiment 2

“Market Returns” vs. “Reduce Product Value” Strategy – May 3rd, 2017

Hypothesis 2.1

Firm utilizing the “reduce product value” strategy beats the firm utilizing 'market returns' strategy, since the “reduce product value” strategy allows the firm to bid lower prices.

Hypothesis 2.2

As the value of the parameter by which the firm reduces its product value increases, the firm's dominance becomes stronger.

We test these hypotheses by comparing the number of times that each firm with different pricing strategy won the bid and dominated the market.

Table 4 – Experiment 2 Specifications

Exogenous Constants			
Names	Types	Values	
Epsilon	float	0.8	
Delta	float	3	
Initial Price	float	193	
Unit Cost	float	10	
Product Value	float	0.1	
Cost Delta	float	5	
Pricing Policy of firm 1	Attribute	“Market Returns”	
Varying Parameters			
Names	Baseline Values	Value Ranges	
Pricing Policy of firm 2	“Market Returns”	“Reduce Product Value”	
Value Delta of firm 2	0.1	0.1- 0.2 - 0.4 - 0.8	
Outcomes	**No. Replications**	**Collection Method**	**Analysis Method**
No. of Bids Won	15	BehaviorSpace	Excel Spreadsheet

Results

We assigned different values to Value Delta parameter and run the experiment 60 times to analyze how the value of this parameter affects chances of offering the lowest price by the firm that uses “reduce product value” strategy. Figure 2, compares the number of bids won based on different strategies. As shown in the figure, the firm with “reduce product value” strategy has the higher number of bids won in every single run. This result allows us to accept our Hypothesis 2.1.

Moreover, in Table 5, we compare the average number of bids won by each firm based on the value of the Value Delta parameter. As its shown in the table, the larger this parameter, the bigger the difference between the number of bids won by the firm utilizing the "reduce product value" strategy. This result allows us to accept our Hypothesis 2.2.

Figure 2

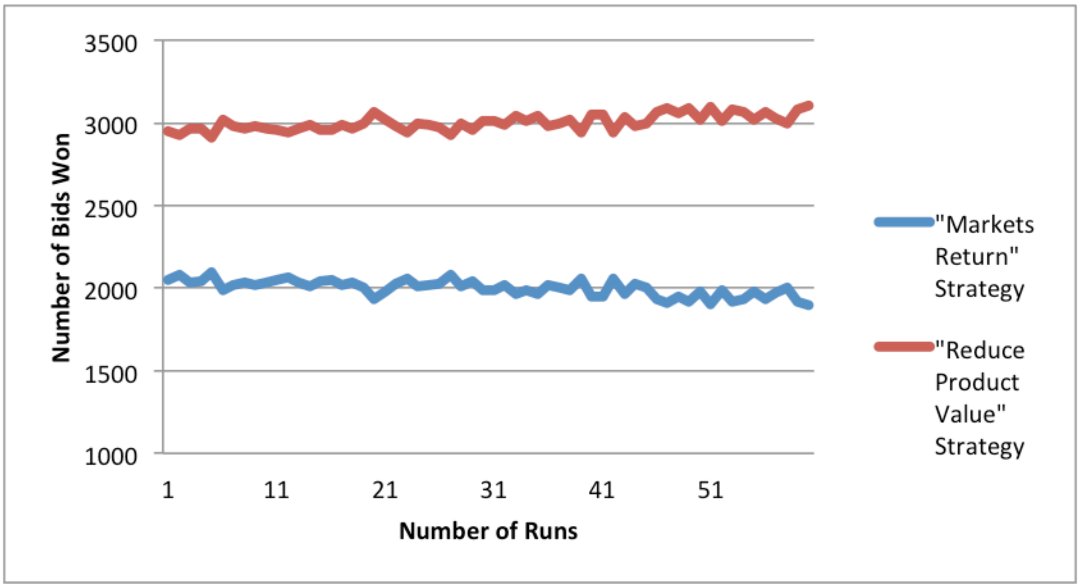

Table 5

Value Delta	Average Number of Bids Won by Firm with Market returns	Average Number of Bids Won by Firm with Reduce Product Value
0.1	2039.1	2961.9
0.2	2017.1	2983.9
0.4	1995.7	3005.3
0.8	1943.0	3058.0

Empirical Framework

In order to examine how the model parameters and the pricing strategies affect an oligopolists's profit and the number of times an oligopolist wins the bid we construct four linear regressions.

Panel A: Profit equation with "Reduce Cost" strategy

In this section, we intend to capture the effects the model variables have on the profit a firm gains when utilizing the "Reduce Cost" strategy:

$$ln(\pi_i) = \beta_0 + \beta_1 Cost_i + \beta_2 ProductValue_i + \beta_3 Delta_i + \beta_4 Epsilon_i + \beta_5 CostDelta_i$$

where Π_i denotes the profit gained by firm *i* , Costi denotes unit cost of firm i, ProdcutValue denotes the product quality of firm i, delta denotes the magnitude by which firm i changes its price in each episode, epsilon denotes the magnitude by which firm i changes its price at the end of the epoch, and cost delta denotes the magnitude by which firm i reduces its cost.

Panel B: Number of Bids Won Equation with "Reduce Cost" Strategy

In this section, we intend to capture the effects the model variables have on the number of bids won by a firm when utilizing the "Reduce Cost" strategy:

$$ln(BidsWon_i) = \beta_0 + \beta_1 Cost_i + \beta_2 ProductValue_i + \beta_3 Delta_i + \beta_4 Epsilon_i + \beta_5 CostDelta_i$$

where BidsWon denotes the number of times firm *i* offered the lowest price, $Cost_i$ denotes unit cost of firm i, $ProdcutValue_i$ denotes the product quality of firm i, delta denotes the magnitude by which firm i changes its price in each episode, epsilon denotes the magnitude by which firm i changes its price at the end of the epoch, and cost delta denotes the magnitude by which firm i reduces its cost.

Panel C: Profit equation with "Reduce Product Value" Strategy

In this section, we intend to capture the effects the model variables have on the profit a firm gains when utilizing the “Reduce Product Value” strategy:

$$ln(\pi_i) = \beta_0 + \beta_1 Cost_i + \beta_2 ProductValue_i + \beta_3 Delta_i + \beta_4 Epsilon_i + \beta_5 ValueDelta_i$$

where BidsWon denotes the number of times firm *i* offered the lowest price, $Cost_i$ denotes unit cost of firm i, $ProdcutValue_i$ denotes the product quality of firm i, delta denotes the magnitude by which firm i changes its price in each episode, epsilon denotes the magnitude by which firm i changes its price at the end of the epoch, and Value delta denotes the magnitude by which firm i reduces its product value.

Panel D: Number of Bids Won Equation with “Reduce Product Value” Strategy

In this section, we intend to capture the effects the model variables have on the number of bids won by a firm when utilizing the “Reduce Product Value” strategy:

$$ln(BidsWon_i) = \beta_0 + \beta_1 Cost_i + \beta_2 ProductValue_i + \beta_3 Delta_i + \beta_4 Epsilon_i + \beta_5 ValueDelta_i$$

where BidsWon denotes the number of times firm *i* offered the lowest price, $Cost_i$ denotes unit cost of firm i, $ProdcutValue_i$ denotes the product quality of firm i, delta denotes the magnitude by which firm i changes its price in each episode, epsilon denotes the magnitude by which firm i changes its price at the end of the epoch, and Value delta denotes the magnitude by which firm i reduces its product value.

Regression Results

Column (a) to (d) presents our regression results for Panel (a) to (d), respectively. As shown, in column (a), the amount by which a firm changes its price during an episode and at the end of the epoch (parameters Epsilon and Delta) do not affect firm’s profit significantly. The Cost and Product Value have negative and significant coefficients, meaning that, as one would expect, firm's profit significantly decreases as cost of production and quality of products rises. Furthermore, the magnitude by which a firm reduces its cost (Cost Delta) has a positive and significant coefficient, meaning that as the value of Cost Delta parametere rises, the firm gains more profit.

Column (b) represents our estimated coefficients regarding number of bids won with "Reduce Cost" strategy. The amount by which a firm changes its price during an episode (Delta) does not have a significant effect on firm's number of bids won. However, the amount by which a firm changes its price at the end of the epoch (parameters Epsilon) affects firm's chances of offering the lowest bid significantly and positively, meaning that as the range of changes in price after each epoch expands, the number of bids won by a firm increases. The Cost and Product Value have negative and significant coefficients: the number of times a firm offers the lowest price decreases significantly as cost of production and quality of products rises. Furthermore, the magnitude by which a firm reduces its cost (Cost Delta) has a positive and significant coefficient, meaning that as the value of Cost Delta parameter rises, the firm increases its chances of winning the bid.

Column (c) represents our estimated coefficients regarding firm's profit with "Reduce Product Value" strategy. The amount by which a firm changes its price during an episode and at the end of an epoch (Delta and Epsilon) do not have a significant effect on firm's profit. The Cost and Product Value variables have negative and significant coefficients, meaning that, firm's profit decreases significantly as cost of production and quality of products rises. Furthermore, the magnitude by which a firm reduces its product quality (Value Delta) has a positive and significant coefficient, meaning that as the value of Value Delta parameter rises, the firm increases its profit.

Column (d) represents our estimated coefficients regarding number of bids won with "Reduce Product Value" strategy. The amount by which a firm changes its price during an episode (Delta) does not have a significant effect on firm's number of bids won. However, the amount by which a firm changes its price at the end of the epoch (parameters Epsilon) affects firm's chances of offering the lowest bid significantly and positively, meaning that as the range of changes in price after each epoch expands, the number of bids won by a firm increases. The Cost and Product Value have negative and significant coefficients, meaning that, the number of times a firm offers the lowest price decreases significantly as cost of production and quality of products rises. Furthermore, the magnitude by which a firm reduces its product quality (Value Delta) has a positive and significant coefficient, meaning that as the value of Value Delta parameter rises, the firm increases its chances of winning the bid.

Table 6 – Regression Results

Variable	OLS(a)	OLS(b)	OLS(c)	OLS(d)
Epsilon	-0.487	2.004***	-0.391	2.066***
	(0.679)	(0.414)	(0.751)	(0.420)
Delta	0.006	0.007	0.007	0.008
	(0.067)	(0.041)	(0.075)	(0.042)
Cost	-0.282***	-0.141***	-0.314***	-0.146***
	(0.023)	(0.014)	(0.026)	(0.014)
Product Value	-0.541***	-0.252***	-0.583***	-0.252***
	(0.018)	(0.011)	(0.020)	(0.011)
Cost Delta	9.222***	4.445***		
	(0.679)	(0.414)		
Value Delta			10.063***	4.534***
			(0.751)	(0.420)
R sq.	0.37	0.36	0.47	0.36

Standard errors in parentheses.
*p<0.1. **p<0.05, ***p<0.01.

Conclusions

The purpose of this model was to explore how oligopolists might determine their prices in the face of a linear demand function. Our extensions upon the original model allowed us to break away from the assumptions of Bertrand price competition by allowing firms the option of competing through more methods: “reduce cost” and “reduce product value”. Our experiments results indicates that firm utilizing the “reduce product value” and “reduce cost” strategies beats the competitor utilizing “market returns” strategy, since theses two strategies allow the firm to bid lower prices. Moreover, the experiments results indicate that as the value of the parameters by which the firm reduces its product value or its cost (Cost delta and Value delta) increases, the firm's dominance becomes stronger. We further constructed four regression models to better understand how the model parameters affect firm’s profit and chances of bidding the lowest price. We found that the parameters Cost delta and Value delta are positively and significantly correlated with firm’s profit and offering the lowest bid. In conclusion, firms’ success to reduce competition and dominate the market entirely depends on their strategic planning. However, In order to achieve the optimal pricing strategy, firms are limited to experimenting with their production function parameters: cost or quality, which are also accompanied by limitations. In the future, it would be interesting to expand this model and address one of its major shortcomings, which is firms’ limited learning capability. The oligopolists in this model do not have the capability of changing their pricing strategy, meaning that once their pricing strategy is set before the first run, they are not able to change it afterwards. We believe that in order to fully simulate an oligopoly market structure and given the importance of pricing strategy in their success, firms need to be allowed to learn from other participants decision and response accordingly.

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