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Estimating product market competition: Methodology and application

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Abstract

In oligopolies, firms behave strategically and commit to actions that elicit favorable responses from rivals. Firm actions consequently are a function of the nature of these strategic interactions. In this paper, we develop a methodology for the empirical estimation of strategic interactions in product markets. We then apply our measure of strategic interactions to CEO compensation. We use quarterly data on profits and sales from Compustat to estimate the slope of firm's reaction function. When the slope is negative and marginal profits decrease with an increase in the rival's actions the firm is classified as a strategic substitute. When the slope is positive and marginal profits increase with an increase in the rival's actions the firm is classified as a strategic complement. As predicted by theory, we find significant evidence that strategic substitutes decrease the pay for performance incentives of their CEOs. On the other hand, strategic complements significantly increase CEO pay for performance incentives. The empirical measure developed can be used to test a wide variety of strategic models.

JEL classification: G3; L2

Keywords: CEO incentives; Stock options; Strategic competition

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1. Estimating product market competition: Methodology and application

Traditional finance models often ignore competition in the product markets and its effect on firm value. However, in oligopolistic industries, individual firm profits as well as overall industry profits depend on how firms interact with each other. Firm value, therefore, is not just a function of its own actions but also a function of the choices made by rivals. Firms can increase value by behaving strategically, that is, by committing to actions that will elicit favorable responses from rivals. Brander and Lewis (1986), Sklivas (1987), and Fershtman and Judd (1987) show that in oligopolies, capital structure and incentive contracts respectively, can be used as commitment devices to draw forth desired outcomes from the rival.[1]

Tilting the manager's compensation away from profit maximization and towards sales maximization gives incentives to the manager to pursue an aggressive output strategy. Similar incentives for aggressive output strategy can be achieved with higher debt levels. With debt outstanding managers, acting on behalf of equity holders, maximize profits only over states in which the firm is not bankrupt. As the states of bankruptcy are also states of low marginal productivity, optimization over the non-bankrupt states, i.e., the high marginal productivity states, leads to a higher equilibrium output (see Brander and Lewis (1986)).

However, this commitment to an aggressive output strategy is valuable only if it induces the rival to respond favorably, i.e., by behaving less aggressively. Fershtman and Judd (1987) and Brander and Lewis (1986) show that this happens when the firms are engaged in Cournot competition. When the firms are engaged in Bertrand competition, it is optimal to give the firm incentives to commit to a less aggressive output strategy. This is achieved by increasing the sensitivity of managerial compensation to profits (see Fershtman and Judd (1987)) or by reducing debt (see Showalter (1985)).

Though there has been theoretical work that models the interactions between financial decisions and competition in product markets, there has been very little empirical work.[2] This is partially explained by the difficulty in empirically implementing strategic models. As these strategic models have different implications based on the nature of competition, it is important to estimate product market competition for empirical tests of these models. This paper contributes by developing a measure for empirical estimation of firm-level competition. This empirical measure explicitly takes into account interactions between firms at the four-digit SIC level, going beyond generalized measures of market power used previously in the literature. Once the sensitivity of a firm's marginal profits to changes in the behavior of rivals can be empirically estimated, more interesting and powerful insights can be drawn.

Strategic interactions between firms in their product markets are classified as strategic substitutes or strategic complements (see Bulow et al. (1985)). A firm's decisions are called strategic substitutes when its marginal profits are decreasing in the rival's actions. A firm's decisions are called strategic complements when its marginal profits are increasing in the

[1] See also Bolton and Scharfstein (1990), Dotan and Ravid (1985), Hart (1983), Maksimovic (1988), Ravid (1988), and Scharfstein (1988).

[2] The exceptions are Clayton and Ravid (2002), Chevalier (1995), Kovenock and Philips (1997), Phillips (1995), Ryan and Wiggins (2002) and Sundaram et al. (1996).

rival's actions.[3] Strategic substitutes and strategic complements differ fundamentally in the way they interact with their rivals. To fix our intuition, consider the case of a duopoly with firm i and firm j competing in quantity. Suppose the rival, firm j experiences a firm-specific cost shock that causes it to decrease output. Strategic substitutes respond to this decrease in the rival's output by increasing their own output. Strategic complements response, on the other hand, is exactly the opposite. They respond to this decrease in rival's output by decreasing their own output.[4] Both strategic substitutes and strategic complements would like to commit to actions that induce the rival to reduce output. To induce the rival to reduce its output, strategic substitutes commit to increasing their output. Strategic complements on the other hand, behave exactly the opposite. To induce the rival to reduce its output, they commit to a less aggressive output strategy.

We develop an empirical methodology to estimate the strategic interactions between firms in an industry. We use quarterly data on profits and sales from Compustat to estimate the slope of firm's reaction functions, i.e., the firm's optimal response to changes in rival's decisions. If the estimated slope is significantly negative, the optimal response of the firm to an increase in output by the rival is to decrease its output. The firm is therefore classified as a strategic substitute. In contrast, if the estimated slope is significantly positive the optimal response of the firm to an increase in output by the rival is to increase its output. The firm is therefore classified as a strategic complement. When the estimated slope is not significantly different from zero, the firm is classified as not facing any strategic interactions. We find that about 20.9% of the industries had firms that were strategic substitutes and 21.4% had firms that were strategic complements.

Next, we use the methodology for estimating strategic interactions to empirically test strategic models of managerial incentives. For this, we first show that the major results of the strategic models derived under Cournot and Bertrand competition can be generalized to competition between strategic substitutes and strategic complements. In a simple extension of the models presented in Fershtman and Judd (1987) and Sklivas (1987), we show that strategic substitutes find it optimal to tilt the managers incentives away from profit maximization towards sales maximization. In contrast, strategic complements find it optimal to increase the manager's incentives for profit maximization and discourage him from sales maximization.[5]

We then empirically examine the effect of strategic interactions on incentives features of CEO compensation contracts. As the late nineties have seen a rapid increase in the popularity of stock options, the impact of strategic interactions on incentives contracts in this period may be muted (Hall and Murphy (2003)). Consequently, we examine incentives features for 656 firms over the eight-year period 1984–1991. Consistent with the predictions of the theory, we find that strategic substitutes significantly lower CEO pay-for-performance incentives. This reduction in CEO incentives is achieved by lower incentives from

[3] Henceforth, a firm will be called a strategic substitute when its output market decisions are strategic substitutes. Similarly, a firm will be called a strategic complement when its output market decisions are strategic complements. Output market decisions here refer to firm's choosing prices or quantities in the product markets.

[4] The concept of strategic substitutes and complements was introduced by Bulow et al. (1985).

[5] Incentives for profit maximization are equivalent to shareholder wealth maximization in our model. The objective of sales maximization provides incentives for maximizing sales, over and above that required for profit maximization. A manager with this objective will increase output beyond the profit maximizing output. Performance criteria based on increasing market share, are equivalent to maximizing sales.

stock options and lower CEO ownership. On the other hand, strategic complements increase the pay-for-performance incentives of their CEOs. This is primarily achieved by increasing incentives from cash compensation.

The rest of the paper is organized as follows. Section 2 develops the methodology for the empirical estimation of strategic interactions. Section 3 lays down the theory and discusses empirical application to CEO compensation. Finally, Section 4 concludes.

2. Estimating strategic interactions

Consider a duopoly in which firm i and firm j play a simultaneous move game. Let $\pi^i = \pi(x_i, x_j)$ be the profit function for firm i, where x_i and x_j are the actions of firm i and its rival, firm j and let $\pi^i_{ij} = \partial^2\pi(x_i, x_j)/\partial x_i \partial x_j$. Firm i is defined to be a strategic substitute if $\pi^i_{ij} < 0$ and a strategic complement if $\pi^i_{ij} > 0$.

Strategic substitutes and strategic complements differ in the way they respond to their rival. If the rival (firm j) behaves aggressively (increases x_j), the optimal response of firm i is to be less aggressive (reduce x_i) if competition is in strategic substitutes and to be more aggressive (increase x_i) if competition is in strategic complements. Therefore, to increase firm profits and induce the rival to reduce output, strategic substitutes commit to increasing their output while strategic complements commit to decreasing their output.

In this section, we develop an empirical measure of the strategic interactions faced by firms, i.e., π^i_{ij}. Sundaram et al. (1996) were the first to develop an empirical measure of strategic interactions. They use the correlation coefficient between $\Delta\pi^i/\Delta x_i$ and Δx_j as a proxy for π^i_{ij} where the x's are firm sales. If the correlation coefficient is positive the firm is classified as competing in strategic complements and when it is negative, it is classified as competing in strategic substitutes. They examine the effect of this measure, called the competitive strategy measure (CSM), on the abnormal returns of firms announcing R&D changes and their competitors. The observed correlation between $\Delta\pi^i/\Delta x_i$ and Δx_j in the CSM measure however could be due to some common external variables. For example, if the entire industry is subject to declining costs then $\Delta\pi^i/\Delta x_i$ and Δx_j will both move in the same direction and the correlation coefficient will be positive. The firms will therefore be classified as strategic complements even though the firms might actually be strategic substitutes. Therefore the correlation coefficient may not be a good proxy for π^i_{ij}.

In the case of linear demand functions and constant marginal cost, π^i_{ij} is a function of the parameters of the demand function. To estimate this requires firm level price and output data. As this data is unavailable, we are constrained to using sales data to proxy for the firms decision variables as Sundaram et al. (1996). However, with linear demand functions and constant marginal cost, it can be shown that the measure of strategic interaction developed here has the same sign as the true strategic interaction though it differs in magnitude.[6] The measure developed here is able to correctly estimate the sign of the slope of the reaction function though not its absolute value. As the sign determines the nature of competition, the measure correctly classifies firms as strategic substitutes and strategic complements. However, as the absolute value of the slope of the reaction function is not correctly estimated, the empirical methodology is unable to shed light on the relation

[6] The proofs are available from the author on request.

between the *intensity* of strategic competition and the *degree* of increase or decrease observed in the actions of firms.

A further problem in the estimation of the slope of the reaction function is the identification of these reaction functions. The position of the reaction functions in each period is determined by shifting the true reaction functions by the amount of their respective disturbances for that period. What is observed over time is the equilibrium point, i.e., the intersection of the two reaction functions as they jump around randomly in response to each period's disturbance term. Since the slope of the reaction function is to be inferred from these equilibrium points over time, its estimation requires identification of at least one of the reaction functions.

The measure of strategic interaction developed in this paper mitigates the identification problem in two ways. First, we control for changes in the cost function of firms, one of the important factors causing the reaction function to move. Second, for each firm in my sample, the rival is defined as all other firms in the respective four-digit SIC. Instead of estimating the reaction function of an individual (rival) firm, we estimate the aggregate reaction function of all other firms in the industry. As individual (rival) firm's reaction function jumps around in response to randomly distributed errors and these errors are independently distributed across all firms, the aggregate reaction function is more stable and can be identified where the individual reaction function could not be. The movement of each firm's reaction function against this industry reaction function helps estimate the slope of the reaction function. Besides, the identification problem is going to be more important when the reaction functions are not stable over time (i.e., the disturbance terms are large). As our sample consists of mature industries and large Fortune 500 firms, to be discussed later, the reaction functions are likely to be more stable over time. Further, we examine the empirical characteristics of the estimated strategic interaction variable and find that the estimated strategic interaction variable behaves in line with economic intuition.

A proxy for the slope of the reaction function, π^j_{ij} is obtained by taking the total differential of the firms marginal profits

$$d[\partial\pi^i/\partial x_i] = \pi^i_{ii}\,\mathrm{d}x_i + \pi^i_{ij}\,\mathrm{d}x_j, \tag{1}$$

where π^i_{ij}, the coefficient of $\mathrm{d}x_j$, is the measure of the strategic competition faced by firm i. With generalized demand and cost functions, this can be expressed as

$$d[\partial\pi^i/\partial x_i] = \beta_1 x_i\,\mathrm{d}x_i + \beta_2\,\mathrm{d}x_i + \beta_3 x_i\,\mathrm{d}x_j + \beta_4\,\mathrm{d}x_j, \tag{2}$$

where the functional form of the β's depend on the characterization of the demand and cost functions, $\pi^i_{ij} = \beta_3 x_i + \beta_4$, and $\pi^i_{ii} = \beta_1 x_i + \beta_2$ (see Appendix B).

OLS regressions of Eq. (2) using sales data to proxy for firms' decision variables, x_i and x_j, give estimates of β_3 and β_4 with strategic interactions given by $\hat{\beta}_3 x_i + \hat{\beta}_4$. The dependent variable $d[\partial\pi^i/\partial x_i]$, in Eq. (2) can be approximated by

$$d[\partial\pi^i/\partial s_i]^t = [\partial\pi^i/\partial s_i]^{t+1} - [\partial\pi^i/\partial s_i]^t, \tag{3}$$

where $[\partial\pi^i/\partial s_i]^t = \Delta\pi^i/\Delta s_i$ and $\Delta s_i = s_{i,t+1} - s_{i,t}$, the changes in sales for firm i. The independent variables, in Eq. (2) are the sales for firm i (s_i), the change in sales for firm i (Δs_i), and the change in sales for the rest of the industry (Δs_j). Sales for the rest of industry are defined as sales of all firms (except firm i), reported in the same four-digit SIC as firm i, in COMPUSTAT.

The strategic interaction variable can be estimated for all firms and for each year. To estimate the strategic interaction variable for a year, 12 quarters of sales and net income data were used. The 12 quarters used, were the eight quarters prior to and the four quarters in the year of estimation. Strategic interaction is given by $\hat{\beta}_3\overline{s_i} + \hat{\beta}_4$, where $\overline{s_i}$ is the average sales of firm i for the 12 quarters used in the OLS estimation of (2).

Firms are classified as facing no strategic competition in a given year, if the null hypothesis of $\hat{\beta}_3\overline{s_i} + \hat{\beta}_4 = 0$ cannot be rejected, by an F test at the 10% level. When $\hat{\beta}_3\overline{s_i} + \hat{\beta}_4$ is significantly different from zero and positive, the firm is classified as a strategic complement for that year. The dummy variable SC takes the value 1 when the firm year is classified as a strategic complement and zero otherwise. Similarly when $\hat{\beta}_3\overline{s_i} + \hat{\beta}_4$ is significantly different from zero and negative, the firm is classified as a strategic substitute. The dummy variable SS takes the value 1 when the firm year is classified as a strategic substitute and zero otherwise.[7]

3. Strategic interactions: An application to compensation

In this section, we use the methodology developed in Section 2 for estimating strategic interactions and use it to test strategic interaction models of managerial compensation. We first begin with a simple extension of the models of Fershtman and Judd (1987) and Sklivas (1987) to competition between strategic substitutes and strategic complements. Next, we empirically test for the importance of strategic interactions in managerial compensation.

3.1. Strategic interactions and incentives

As defined above, strategic interaction between firm i and its rival, firm j is $\pi^i_{ij} = \partial^2\pi(x_i, x_j)/\partial x_i\partial x_j$ where x_i and x_j are the actions of firm i and its rival, firm j. Firm i is defined to be a strategic substitute if $\pi^i_{ij} < 0$ and a strategic complement if $\pi^i_{ij} > 0$.

To understand the role played by the manager's compensation contract, it is important to distinguish between two issues. One is the optimal product market strategy that the owners of the firm would like to follow and the second is the mechanism to commit to this output strategy. If the owners could credibly commit to output, contingent on the resolution of the output market uncertainty, they would commit to a more (less) aggressive output strategy if they were strategic substitutes (strategic complements). The managerial contract could then simply require the implementation of this state contingent schedule of output. However, since the owners do not observe the realization of the demand func-

[7] Other measures of strategic interactions were also estimated for robustness checks. First, we classified firms as having strategic interactions for the whole period rather than every year. For our sample, we classified firms as strategic substitutes and strategic complements for the entire eight-year period if they faced significant strategic interaction in at least two years. This measure mitigates the serial correlation in the errors that arises due to overlapping observations when quarterly data is used on a rolling basis. The results with this measure of strategic interaction were not significantly different and have not been reported in the paper. Strategic interaction was also estimated with 16 quarters of data instead of 12 quarters. Again, the results were qualitatively similar and have not been reported here.

tion, these quantity-indexed contracts are not feasible. The owners can then at best write contracts contingent on profits and sales to give manager's incentives to implement this more or less aggressive output strategy. As the manager's compensation contract is observed by the rival it serves as a commitment mechanism for the chosen output strategy. The mechanisms available for commitment in the product market are not restricted to compensation contracts. Brander and Lewis (1986) show that strategic substitutes can also use higher debt levels in their capital structure, to commit to this aggressive output strategy.

Consider a duopoly with firms i and j each having a owner and a manager and operating under uncertain demand and cost conditions. The owner offers the manager a compensation contract with an expected value at least as large as the manager's reservation wage, $\overline{H}$. Compensation contracts offered to the manager are contingent on the profits and sales of the firm and are common knowledge.[8] The manager is assumed to be risk neutral with a compensation contract that takes the form $\mathrm{CC}_i = \alpha_i + \beta_i\ O_i$ with $E(\mathrm{CC}_i) \geqslant \overline{H}$. α_i, β_i are positive constants, O_i is a function of performance of firm i and is specified below. The manager chooses actions to maximize his compensation CC_i. Since by assumption, α_i and β_i are positive constants, maximizing compensation CC_i is equivalent to maximizing O_i. Since O_i is the derived objective of the manager's optimization problem it is henceforth referred to as the manager's objective function. It takes the following form:

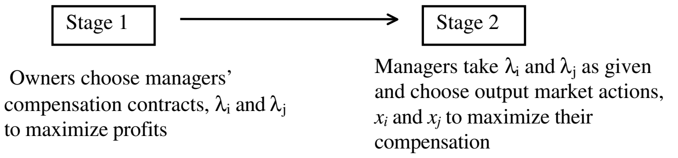
$$O_i = \lambda_i \pi^i(x_i, x_j) + (1 - \lambda_i)\mathrm{Sales}^i(x_i, x_j),$$

where λ_i, is the weight on profits in the manager's objective function.[9]

The game is played in two stages. In stage two, the managers observe the realization of the demand and cost functions and choose actions to maximize their compensation. In doing this, they take their compensation contract, i.e., the weights λ_i and λ_j as given. In stage 1 of the game, the owners choose λ_i and λ_j to maximize the profits of the firm. In doing so, they take into account the optimal response of the manager given his compensation contract, i.e., the Nash equilibrium solution of stage two. The two-stage game can be summarized as follows

[8] It is assumed that the owner does not observe the parameters of the demand and cost functions and can therefore not write contracts forcing the manager to undertake output levels contingent on their realization. Contracts offered to the manager can consequently be made contingent only on the observable value of profits and sales of the firm.

[9] The objective function, a linear combination of profits and sales, is one among several compensation contracts that can be designed. Other non-profit maximizing measures can also be used, instead of sales, to commit to output market strategies. One such measure, the profit of the rival firm, has been examined by Agarwal and Samwick (1999). Though theoretically, this compensation contract also serves as a pre-commitment mechanism its practical utility is doubtful. For example, their specification of the compensation contract implies that in equilibrium, strategic complements place a positive weight on own firm profits as well as on the profits of the rival in order to give managers incentives for less aggressive behavior. The owners of the firm therefore, perversely compensate the manager for the good performance of the rival. Though their specification of the compensation contract achieves the desired product market equilibrium, it is likely to significantly exacerbate agency problems. The use of sales in the managerial objective function does not have that problem. Further, it was first suggested by Baumol (1958) as a firm's objective and has been subsequently used in theoretical models (see Fershtman and Judd, 1987; Sklivas, 1987 among others). It also has practical validity as many firms explicitly mention sales growth as one of the criteria for evaluating managerial performance.



Theorem 1. *When competition is in strategic substitutes, the equilibrium value of λ_i is less than one. When competition is in strategic complements, the equilibrium value of λ_i is greater than one.*

Proof. See Appendix A.

The above result is a modest generalization of models developed by Fershtman and Judd (1987) (referred to as FJ) and Sklivas (1987), which examine managerial contracts in firms engaged in price or quantity competition. This paper generalizes their result to competition in strategic substitutes or strategic complements.[10] Classification of firms as strategic substitutes and strategic complements greatly facilitates the empirical estimation of competition in the product markets.

Intuition for the above result can be obtained by considering specific forms for the demand and cost functions. First, consider the case of duopoly with competition in strategic substitutes with a linear demand function $p = a - bQ$ where p is the market price, Q is the total output, and q_i and q_j being the individual firm outputs. a, $b > 0$ are constant parameters of the demand function. With constant marginal cost c_i and c_j, profit for firm i is simply $\pi_i = (a - b(q_i + q_j) - c_i)q_i$. As $\pi^i_{ij} = -b < 0$, the firms are strategic substitutes. In this case, it can be shown that equilibrium value of $\lambda_i = 1 - \frac{a+2c_j-3c_i}{5c_i} < 1$.

Similarly, equilibrium value of λ can be derived for a duopoly with competition in strategic complements. Consider the case of a demand function for differentiated goods given by $q_i = A - bp_i + ap_j$ where it is assumed that $b > a > 0$. With constant marginal cost c, profit for firm i are $\pi_i = (A - bp_i + ap_j)(p_i - c)$. As $\pi^i_{ij} = a > 0$, the firms are strategic complements. The equilibrium value of $\lambda_i = 1 + \frac{(A-(a-b)c)(a^3+2a^2b)}{bc(8b^3-4a^2b-a^3)} > 1$, in this case (see Fershtman and Judd, 1987 for further details of both cases).

Empirical implications of the theory are relatively straight forward. When firms compete in strategic substitutes, λ is less than one, i.e., managers are given compensation contracts with lower weight on profits and higher weight on sales. These firms should therefore display lower pay for performance sensitivity (referred to as PPS) in their managerial contracts than a firm, which faces perfect competition. The opposite holds for firms that compete in strategic complements.

As the equilibrium value of λ depends on the demand and cost functions, which are unobservable, we do not empirically estimate the value of λ. Instead, we test for the whether the value of λ is less than or greater than one by examining whether PPS for stra-

[10] Under the assumption of linear demand functions and constant marginal costs, firms competing in quantities will always be strategic substitutes and firms competing in prices will be strategic complements. With more complicated demand and cost functions this need not be true. See Bulow et al. (1985) for further details.

tegic substitutes (strategic complements) is less (greater) than that for firms that face no strategic interactions. Firms are classified as strategic substitutes and strategic complements based on the measure of strategic interaction developed above.

3.2. Empirical tests of the theory

In this section, we use our methodology to estimate strategic interactions to test for the presence of strategic factors in the design of CEO compensation contracts. The compensation data is for all firms, that were included in at least one of the four Forbes list, in at least four of the eight years between 1984 and 1991. This resulted in the selection of 792 firms. For each of these 792 firms, compensation data was collected from the SEC proxy, 10-K and 8-K filings.[11] Firms not reported on COMPUSTAT and firms without sufficiently long time series data on sales and profits to estimate the strategic competition measure were eliminated from the data set. This yielded a total of 656 firms. We did not use data on CEO compensation in the late nineties because the unprecedented rise in the popularity and use of stock options in this period is likely to mute the effect of strategic considerations in the design of compensation contracts.

Table 1, reports the summary statistics for CEO compensation in the dataset. The value of new stock options granted is calculated using the Black and Scholes (1973) formula adjusted for dividend payouts, (see Merton (1973)). The pay for performance incentives of stock options is the product of the hedge ratio of the options granted and the fraction of equity represented by the award.

3.2.1. Measure of strategic interaction

Strategic interactions were estimated for all 656 firms for each year from 1984 to 1991. These firms were distributed over 196 four-digit SIC. Except for 1984 and 1985, all other years have a higher incidence of strategic substitutes than strategic complements (see Table 2a). The average level of competition between strategic complements (0.15) is marginally higher than strategic substitutes (−0.12). About 46% of the firms do not face any strategic competition and there is no firm in the sample which faces strategic competition over the entire eight year period (see Table 2b).

Depending on the nature of the demand and cost functions in the industry, as well as the number of firms, industries could either have perfect competition (no strategic interactions) or have competition in strategic substitutes and complements. Industries with competition in prices among differentiated goods are more likely to compete in strategic complements. An example of a four-digit SIC where firms are strategic complements is 5311 (Department Stores). All the nine firms in this SIC, with the exception of one were strategic complements.[12] Four-digit SIC 2840 (Soap, detergent and toilet preparations) is another example where firms are strategic complements. Industries where firms compete in market share and where substantial investment is required in plant and equipment are more likely to compete in strategic substitutes. Example of industry with competition is

[11] This data set was collected and organized by David Yermack and has been analyzed in Yermack (1995).

[12] The nine firms in this category were Carter Hawley Stores, Dillard Department Stores, Federated Department Stores, May Department Stores, Mercantile Stores Co., Meyer (FRED) Co., Penney (J.C.) Co., and Sears Roebuck & Co.

Table 1
Summary statistics

Variable	Mean	Standard deviation	# of observations
(A) Summary statistics of compensation variables:			
Salary and bonus	796.04	701.97	5087
Change in salary and bonus	34.30	300.64	3900
Other compensation	163.84	580.29	5085
Value of new options granted[a]	480.28	2927.00	5061
Ratio of stock to cash compensation	0.506	1.65	5002
Pay-performance of stock options	0.0005	0.0020	5005
(B) Summary statistics of firm's board structure and ownership variables:			
Shares owned by the CEO[b]	0.023	0.074	5029
Shares held by other insiders[b]	0.055	0.095	5021
Proportion of outside directors	0.58	0.189	5033
Age of CEO	57.52	6.87	5037
Tenure as CEO	9.02	7.94	5037
(C) Summary statistics of firm's operating performance:			
Total assets[c]	7.99	1.27	5116
Net income[c]	196.32	464.00	5115
Q[d]	1.13	0.65	5037
Debt ratio[e]	0.18	0.16	5101
Interest cover[f]	7.47	11.97	5038
Annual holding return	0.077	0.36	5109
Volatility of stock[g]	0.139	0.39	5095

The value of all compensation is in ('000) of dollars.

[a] The value of new options granted is calculated using the Black Scholes Formula.

[b] The number represent the fraction of the firm owned.

[c] Deflated to reflect current dollar value.

[d] $Q = \frac{\text{Total assets(book value)+common stock(market value–book value)}}{\text{Total assets(book value)}}$ This measure is approximately equal to Tobin's Q and proxies for the firms growth opportunities.

[e] The figures are the ratio of long term debt (with maturity greater than one year) to total assets.

[f] The ratio of income available for interest payments to interest expense.

[g] This is the sample variance of daily logarithmic stock returns.

strategic substitutes is four-digit SIC category 2080 (Beverages), which had three firms which were all strategic substitutes.[13] Other examples of four-digit SICs with firms which were strategic substitutes are 2621 (Paper Mills), 4213 (Trucking, not local) and 3523 (Farm Machinery and Equipment). Industries with no strategic interaction are likely to be those with a large number of small firms, and those with low entry and exit barriers. Examples of industries where firms faced no strategic competition were 3270 (Concrete, Gypsum, Plaster pds), 3334 (Prim Production of Aluminum), 3678 (Electronic Connectors) and 3021 (Rubber and Plastic Footwear).

Industry characteristics can also be used to check on the efficacy of the strategic interaction measure. If the measure correctly classifies firms as strategic substitutes and strategic complements, then the incidence of industries which have both strategic complements and strategic substitutes should be low (see Table 2c). 71% of the SICs have firms that

[13] The three firms in the four-digit SIC 2080 are Coca-Cola Co., Pepsico Inc. and Brown-Forman.

Table 2
Empirical characteristic of the strategic interaction variable

(A) Distribution of the strategic interaction variables across years

Years	84	85	86	87	88	89	90	91
% of observations with SIG SI	13.45	13.32	14.21	10.02	11.69	13.66	11.77	14.76
% of observations with SC	7.79	6.75	6.26	4.04	4.42	5.65	5.02	6.51
% of observations with SS	5.66	6.57	7.95	5.98	7.27	8.01	6.75	8.25
Mean estimated interactions for SC	0.024	0.043	0.016	0.015	0.116	0.032	0.454	0.496
Mean estimated interaction for SS	−0.004	−0.023	−0.116	−0.018	−0.679	−0.019	−0.011	−0.043
# of firms	565	578	591	619	633	637	637	630

(B) Distribution of the incidence of strategic interaction variables

# of Years of significant SI	0	1	2	3	4	5	6	7	8
% of firms with significant SI	45.64	30.84	13.08	5.14	3.27	0.47	0.94	0.62	0.0
% of firms with SC	70.87	19.47	6.54	2.03	0.62	0.16	0.16	0.16	0.0
% of firms with SS	68.69	19.16	6.85	3.12	0.78	0.31	0.62	0.47	0.0
Mean interactions for SC	0.0	0.074	0.371	0.066	0.0007	7.5e−05	8.1e−05	0.0002	0.0
Mean interaction for SS	0.0	−0.314	−0.015	−0.023	−0.024	−0.0009	−0.002	−0.001	0.0

(C) Distribution of strategic interaction variable across four-digit SIC

	Percentage of SICs in the category
% of SIC with no strategic interaction (No. SI)	28.88
% of SIC with only strategic complements (SC)	21.39
% of SIC with only strategic substitutes (SS)	20.86
% of SIC with higher number of SC[a]	9.09
% of SIC with higher number of SS	12.3
% of SIC with equal number of SS & SC	7.48

The first row reports observations that were estimated as having significant strategic interactions. Rows two and three report the results for strategic complements (SC) and strategic substitutes (SS).

[a] This is the percentage of SIC's that have both SS and SC but the number of observations which are strategic complements are higher than the number of observations which are strategic substitutes.

exclusively belong to one of the three categories and only 7% of the SICs have equal number of strategic complements and strategic substitutes.[14]

[14] One explanation of why there are industries with both strategic substitutes and strategic complements is the broad definition of four-digit SIC codes. This leads to the classification of heterogeneous firms under the same industry, though they may belong to more narrowly defined industries, which differ in the nature of their strategic interactions. An example of an SIC in this category is Newspapers. New York Times and Washington Post are in the same SIC though they do not directly compete with each other on account of geographical segregation.

Table 3
Difference between strategic complements, strategic substitutes and firms that face no competition

Variable	SC	SS	No. SI	SC -SS	No. SI- SC	No. SI -SS
Log of total assets	7.84	7.88	8.04	−0.044	0.197	0.15
	276	339	4191	(0.47)	(2.58***)	(2.48***)
Q	1.105	1.09	1.14	0.017	0.034	0.05
	275	339	4177	(0.30)	(0.84)	(1.17)
Long term debt ratio	0.194	0.234	0.179	−0.04	−0.015	−0.055
	276	339	4191	(3***)	(1.49)	(5.8***)
Annual holding return	0.118	0.085	0.076	0.033	−0.042	−0.009
	280	345	4232	(1.14)	(1.91*)	(0.44)
Four firm concentration ratio	37.81	38.96	39.92	−1.16	2.11	0.96
	125	117	1759	(0.47)	(1.18)	(0.55)
Pay-performance of stock options	0.00046	0.00043	0.00052	0.00003	0.00006	0.00009
	(273)	(339)	(4148)	(0.23)	(0.61)	(1.016)
Ratio of stock to cash compensation	0.43	0.55	0.51	−0.12	0.074	−0.048
	(273)	(339)	(4145)	(1.09)	(1.12)	(0.49)
Fraction of the firm owned by the CEO	0.021	0.014	0.023	0.007	0.0015	0.0087
	275	339	4170	(1.55)	(0.39)	(2.8***)
Fraction owned by other officers and directors	0.062	0.047	0.053	0.015	−0.009	0.007
	274	339	4163	(1.9*)	(1.27)	(1.41)

The first to third columns give the average values of the variables for strategic complements (SC), strategic substitutes (SS) and firms that face no competition (No. SI). The figure reported below is the number of observations. The fourth column reports the differences in the mean value of strategic complements and substitutes. The *t*-statistics are reported in parentheses. The fifth (sixth) column reports the differences in the average values of firms that face no competition and strategic complements (substitutes). The four firm concentration ratios have been obtained from the Census of Manufacturing and are available only for the one digit SIC, 2 and 3. Pay-performance sensitivity of stock options is calculated as the product of the hedge ratio of stock options awarded and the fraction of equity represented by the award. The Black Scholes value of stock options is used in calculating the ratio of stock to cash compensation.

3.2.2. CEO incentives

Table 3 examines characteristics of strategic complements and strategic substitutes. Both strategic substitutes and strategic complements are significantly smaller than firms that face no strategic interactions. Strategic substitutes have significantly higher debt levels (0.234) in comparison to strategic complements (0.194) and others (0.174). We individually examine incentives provided to CEO through (1) salary and bonus, (2) stock option grants, and (3) equity ownership and see if these are a function of the nature of strategic interactions.[15]

3.2.2.1. Pay-for-performance incentives from changes in salary and bonus. To examine whether the pay for performance incentives provided to CEOs through salary and bonus are significantly different for strategic complements and strategic substitutes, we follow Jensen and Murphy (1990) and estimate the following:

[15] Since we have data only on the new option grants of CEO and not on the entire portfolio of stock options held, we are unable to calculate the total PPS of CEO compensation as done by Jensen and Murphy (1990). We therefore estimate separately the PPS of each component of compensation. This methodology, however allows us to shed light on which component of compensation is used to alter PPS.

$$\Delta\text{salbon} = \alpha + \beta_1\Delta\text{stweal} + \beta_2\Delta\text{stweal} + \delta_1\text{SC} + \delta_2 SS + \gamma_1(\text{SC} \times \Delta\text{stweal}) + \gamma_2(\text{SS} \times \Delta\text{stweal}) + \gamma_3(\text{SC} \times \Delta\text{stweal1}) + \gamma_4(\text{SS} \times \Delta\text{stweal1}),$$

where ΔSALBON is the annual change in salary and bonus, ΔSTWEAL is the change in shareholder wealth and ΔSTWEAL1 is the lagged value of change in shareholder wealth. The PPS, which is the change in salary and bonus for every dollar change in shareholder wealth, is then given by $\beta_1 + \beta_2$ for firms that face no strategic competition. For strategic complements it is given by $\beta_1 + \beta_2 + \gamma_1 + \gamma_3$ and for strategic substitutes is given by $\beta_1 + \beta_2 + \gamma_2 + \gamma_4$.

For firms with no strategic interaction, CEO salary and bonus changes by two cents for every $1000 change in shareholder wealth (see Table 4). γ_1 is significant and takes the value 0.025. For strategic complements, CEO salary and bonus changes by four cents for every $1000 change in shareholder wealth, twice that of firms that face no strategic interaction. The coefficient of interaction of SS with changes in shareholder wealth, γ_2 and γ_4, are not statistically significant. The PPS of cash compensation does not differ between strategic substitutes and firms that face no strategic interactions.

The theory on the effect of strategic interactions on CEO incentives also suggests that strategic substitutes should increase while strategic complements should decrease the

Table 4
Model estimates for pay-performance sensitivity of cash compensation

	Model 1	Model 2
Change in shareholder wealth (ΔSTWEAL)	.014	.013
	(2.67**)	(2.46**)
Lagged change in shareholder wealth (ΔSTWEAL1)	.007	.007
	(1.1)	(1.26)
Dummy for CEO departure (TOCODE)	−21.7	−18.89
	(0.9)	(0.79)
Dummy for strategic complements (SC)	−9.52	−8.74
	(0.4)	(0.39)
Dummy for strategic substitutes (SS)	−5.13	1.65
	(0.36)	(0.11)
SC × ΔSTWEAL	0.025	0.026
	(2.19**)	(2.24**)
SC × ΔSTWEAL1	−0.002	
	(0.01)	
SS × ΔSTWEAL	0.015	0.008
	(0.69)	(0.50)
SS × ΔSTWEAL1	0.03	
	(1.19)	
Change in sales (DIFFSAL)		0.02
		(4.38***)
SC × DIFFSAL		−0.017
		(0.80)
SS × DIFFSAL		0.062
		(1.85*)
Sample size	4200	4200
Adjusted *R* sq.	0.01	0.01

The table reports OLS regressions, the dependent variable being the annual change in salary and bonus. A constant was also included but is not shown here. It was estimated as having a significant positive coefficient. The heteroscedasticity corrected *t*-statistics are reported in parenthesis.

sensitivity of CEO salary and bonus to sales.[16] Consistent with the predictions of the theory, strategic substitutes significantly increase the sensitivity of CEO pay to changes in sales. Strategic complements, on the other hand, do not change sensitivity of CEO pay to sales. Though the evidence supports the theory, we should be careful in our interpretation due to the low explanatory power of the regression (R^2 of only 0.01).

3.2.2.2. PPS of stock options awarded to the CEO. The PPS of new stock options granted is estimated as the product of Δ, the hedge ratio of stock options awarded and the fraction of equity represented by the award. This measure (PAYPERF) provides an estimate of the change in the value of new stock options awarded for every dollar change in the value of the firm (see Yermack (1995)). The years in which there are no stock options granted, the dependent variable, i.e., PPS of new stock options awarded takes the value zero. To take care of this censoring in the data we follow Yermack (1995) in estimating a correlated random effects model with the general formulation as follows (see Greene, 1993):

$$y^*_{i,t} = \beta x_{i,t} + f_i + \varepsilon_{i,t}$$
$$y_{i,t} = 0 \quad \text{if } y^*_{i,t} \leqslant 0$$
$$y_{i,t} = y^*_{i,t} \quad \text{if } y^*_{i,t} > 0,$$

where $y^*_{i,t}$ is the latent variable for firm i at time t, $f_i = \delta\overline{x_i} + v_i$ is a firm specific term, $\overline{x_i}$ is the vector of average values of the independent variables for firm i. We model heteroskedasticity in the data by the following general specification (see Greene)

$$\sigma_i^2 = \sigma^2 \times \mathrm{e}^{(\alpha w_i)},$$

A lagrangian multiplier test was carried out against the null hypothesis of homoskedasticity, i.e., $\alpha = 0$ and was rejected at the 1% level. As this is a panel data set and heteroskedastic variances are likely to be a function of the average firm characteristics, the w_i used were simply $\overline{x_i}$, the average value of the independent variables for firm i.

We control for several other factors that might explain the PPS of stock options. First, we control for the presence of agency costs. The greater the agency problems the more likely it is that stock options will be used to align CEO incentives. Stock option awards should be negatively related to CEO ownership (OWNER), positively related to CEO age (AGE), and negatively related to the ratio of long-term debt to total assets (LTDEBT) (see for e.g. Eaton and Rosen, 1983; Lewellen et al., 1987; John and John, 1993; Yermack, 1995). A dummy variable TOCODE, takes the value 1 when the CEO leaves the firm and zero otherwise. This captures lower incentives provided to departing CEOs. We also control for the presence of information asymmetries in high growth firms by including Tobin's Q.

We also control for liquidity constraints, higher reporting costs and lower marginal tax rates (see Matsunaga et al. (1992) and Yermack (1995)). We include LIQ, a dummy var-

[16] According to the theory strategic complements place a negative weight on sales in the manager's objective function. As the theory is parsimonious, with the objective of understanding the effect of product market competition on managerial incentives, the negative sign should be interpreted carefully. Though the theory implies a weight of zero on sales for the benchmark case, when firms do not compete strategically, the data shows a significant positive weight. Therefore, the negative weight on sales in the manager's objective function for strategic complements should be interpreted as a relatively smaller, though still positive, weight on sales.

iable that takes the value one if the firm does not pay dividends, to proxy for liquidity constraints. We include interest coverage (INTCOV) to proxy for financial reporting costs. A dummy variable, (TAXLOSS) that takes the value one if the firm has tax losses carried forward is used to proxy for low marginal tax rates. Log of total assets (DASSETS) controls for firm size while net income and stock returns control for firm profitability. Finally, to test for the effect of strategic interaction, we include dummy variables for strategic complements (SC) and strategic substitutes (SS).

The results of the tobit estimation are displayed in Table 5. The coefficient of SS is negative, as predicted, and significant at 1% level. This supports the theory that strategic substitutes lower incentives from stock options. The coefficient of SC is positive, as predicted, but not significant. The data support the tax and liquidity explanations for the use of stock options. There is also support for the use of stock options in the presence of information asymmetries. Firms with a higher value of Q, award stock options with higher PPS. Age of CEO appears to influence the incentives provided to the CEO. However, contrary to the

Table 5
Tobit estimation of the pay-performance sensitivity of stock options awarded to CEOs

Variables	Coefficient estimates
Ratio of long term debt to total assets (LTDEBT)	0.00019 (0.74)
Interest coverage ratio (INTCOV)	−1.02E-07 (0.092)
Dummy variable when firms skip dividend payments (LIQ)	0.0006 (3.61***)
Dummy variable for tax loss carried forward (TAXLOSS)	0.00014 (1.73*)
CEO ownership in the firm (OWNER)	−0.003 (0.84)
Age of the CEO (AGE)	−0.00001 (4.54***)
Q	0.00019 (4.4***)
Dummy for CEO departure (TOCODE)	−0.000071 (2.55**)
Dummy for strategic complements (SC)	0.000069 (1.55)
Dummy for strategic substitutes (SS)	−0.000036 (2.85***)
Net income (DNI)	−1.16e−08 (2.5**)
Log of total assets (DASSETS)	−0.000009 (0.27)
Rate of return on firm's stock (CRRET)	0.00018 (3.47***)
Sample size	4709

The dependent variable is the pay-performance sensitivity of stock options awarded to the CEO as measured by the product of the hedge ratio of the stock options and the fraction of total shares represented by the award. A constant was also included but is not shown here. *t*-Statistics are reported in parenthesis.

* Indicates significance at 10%.
** Indicates significance at 5%.
*** Indicates significance at 1%.

horizon theory the coefficient is negative implying that younger CEO's get stock options with greater incentives.

3.2.2.3. CEO ownership in the firm. CEO ownership of the firm leads to an alignment of his incentives with those of other shareholders. The theory predicts that strategic substitutes (complements) should lower (increase) CEO ownership to decrease (increase) PPS.[17]

Demsetz and Lehn (1985) first studied ownership concentration of firms and found that it was negatively related to the size of the firm and positively related to the "control potential of the firm". We use log of total assets (DASSETS) to proxy for size and standard deviation of stock returns (VOL) to capture uncertainty of the firm's environment and the "control potential" of the firm. We also include measures of board effectiveness, i.e., the proportion of outside directors on the board (PROOUT), the fraction of the firm held by other officers and directors (INPCT), and CEO tenure (TENURE) (see Weisbach (1988), Brickley and James (1987), and Hermalin and Weisbach (1998)). All these governance mechanisms are expected to be negatively correlated with CEO ownership.

We find that CEOs of strategic substitutes own on average 1.4% of the firm. This is significantly lower (at the 1% level) than 2.3%, the average CEO ownership in firms which face no strategic interactions (Table 3). There is, however, no significant difference between strategic complements and others, in the level of CEO ownership. The percentage of the firm owned by other insiders of the firm, is also lower for strategic substitutes (4.7%) and higher for strategic complements (6.2%) in comparison to firms, which do not face any strategic interaction (5.3%), though only the difference between strategic complements and strategic substitutes is statistically significant.

Table 6 reports the results of a fixed effects model of CEO ownership. The coefficient of SS is negative and significant at the 1% level. The coefficient of SC is statistically insignificant. Strategic complements do not differ from firms that face no strategic competition, in the level of CEO ownership. As the incentives from CEO ownership account for a large fraction of overall PPS, the significant reduction in CEO ownership in strategic substitutes provides strong evidence of lower PPS provided to the CEO. Though strategic complements increase PPS from cash and stock-based compensation, the lack of higher CEO ownership suggests that the overall increase in incentives are not comparable in magnitude to the decrease in incentives observed in strategic substitutes.

As expected, firms with more effective boards (proxied by PROOUT) and with higher inside ownership (INPCT) have lower CEO ownership levels. The data also provide evidence that CEOs of larger firms hold a smaller fraction of the firm and CEOs with longer

[17] Theory implies that owners of oligopolistic firms will increase or decrease CEO ownership in the firm. However, CEO ownership is strictly not under the control of the board of directors and therefore it might be argued that it is not under the discretion of the board to change. Casual evidence suggests that boards worry about CEO's owning too small a fraction of the firm i.e., boards are likely to have a problem that the CEO voluntarily holds a smaller rather than larger percentage of the firm in comparison to the desired level. The boards can increase CEO ownership through grant of restricted stock. Boards will also take CEO ownership into account in designing incentives from other sources of compensation. Also, to the extent CEO ownership in the firm is likely to be the result of previous exercise of stock options awarded, it is not entirely out of the control of the board.

Table 6
Model estimates for the determinants of CEO ownership

Variables	Coefficient estiamtes
Proportion of outside directors (PROOUT)	−0.039 (7***)
Ownership by other officers of the firm (INPCT)	−0.076 (8***)
Volatility of stock returns (VOL)	−0.0016 (0.9)
Log of total assets (DASSETS)	−0.0064 (5.5**)
CEO tenure (TENURE)	0.00053 (6***)
Dummy for strategic complements (SC)	−0.00033 (0.20)
Dummy for strategic substitutes (SS)	−0.0038 (2.55***)
Sample size	4776
Adjusted R sq.	0.89

The dependent variable is the fraction of total common shares outstanding that are held by the CEO. A fixed effects model was fitted to control for firm effects which were significant. t-Statistics are reported in parenthesis.
** Indicates significance at 5%.
*** Indicates significance at 1%.

tenures hold a higher fraction of the firm. Fixed firm effects were included and were found to be highly significant. That explains the high R^2 of about 0.89.[18]

4. Conclusions

This paper develops an empirical measure of strategic interactions between firms in an industry and applies it to test strategic models of managerial incentives. Firms are classified as strategic substitutes when their marginal profits are decreasing in the rival's action and as strategic complements when they are increasing in the rival's action. The methodology for the estimation of strategic interactions can be implemented using readily available Compustat data and used to test a wide variety of strategic models.

We apply our measure of strategic interactions to strategic models of CEO incentives. Simple extensions of the theory predict that strategic substitutes decrease the pay for performance incentives of their CEO while strategic complements increase these incentives. In a sample of 656 firms, over the period 1984–1991, we find significant evidence in support of the theory. We find that strategic substitutes significantly reduce CEO incentives from stock options and stock ownership. Further, we find that strategic substitutes increase the sensitivity of CEOs cash compensation to sales. Strategic complements, on the other hand, increase pay for performance incentives of their CEOs by increasing incentives from cash compensation. By providing strong empirical evidence of the importance of strategic interactions in explaining CEO incentives, this paper highlights the potential importance of product markets in the financial decisions of the firm, an area not well understood.

[18] We also estimated the effect of strategic interactions on the probability of CEO dismissal following poor firm performance. We find some evidence that strategic substitutes that face low level of strategic interactions decrease the probability of CEO dismissal. This is in line with the predictions of theory.

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Appendix A

Proof. If $\mathrm{d}\pi/\mathrm{d}\lambda < 0$ (>0) around $\lambda = 1$ in stage two of the game, then in stage one owners will find it optimal to decrease (increase) the value of λ from its value of 1. The equilibrium value of λ will consequently be less (greater) than one. Firm profits at the end of stage two, for given values of λ_i and λ_j can be expressed as $\pi^i = \pi^i[x_i^*(\lambda_i, \lambda_j), x_j^*(\lambda_i, \lambda_j)]$. Differentiating with respect to λ_i gives

$$\frac{\partial \pi^i}{\partial \lambda_i} = \frac{\partial \pi^i}{\partial x_i^*}\frac{\partial x_i^*}{\partial \lambda_i} + \frac{\partial \pi^i}{\partial x_j^*}\frac{\partial x_j^*}{\partial \lambda_i}. \tag{A.1}$$

Since $O_i = \pi^i$ at $\lambda = 1$, the first order condition for the maximization of the manager's objective function $\partial O_i/\partial x_i = 0$ implies that $\pi_i^i = \partial \pi^i/\partial x_i^* = 0$. The first term in Eq. (A.1) is negligible and drops out. The term $\partial x_j^*/\partial \lambda_i$ can be written as $\frac{\partial x_j}{\partial \lambda_i} = \frac{\partial R_j}{\partial x_i^*}\frac{\partial x_i^*}{\partial \lambda_i}$ as $x_j^* = R_j(x_i^*, \lambda_j)$ is the reaction function of firm j. Substituting for these in A1, gives

$$\frac{\partial \pi^i}{\partial \lambda_i} = \frac{\partial \pi^i}{\partial x_j^*}\cdot\frac{\partial x_i^*}{\partial \lambda_i}\cdot\frac{\partial R_j}{\partial x_i^*}. \tag{A.2}$$

The product of the first two terms $\mathrm{d}x_i/\mathrm{d}\lambda_i \times \mathrm{d}\pi^i/\mathrm{d}x_j$ is always positive irrespective of whether the strategic decision variables are prices or quantities.[19] Therefore the sign of $\partial\pi^i/\partial\lambda_i$ depends on the sign of $\partial R_j/\partial x_i^*$, the slope of the reaction curve. $\partial R_j(x_i, \lambda_j)/\partial x_i = -\pi_{ij}^j/\pi_{jj}^j$, as $\pi_{jj}^j < 0$ (the profit function is concave in x) the sign of $\partial R_j/\partial x_i$ depends on the sign of π_{ij}^j. For strategic substitutes, $\pi_{ij}^j < 0$ and $\partial\pi^i/\partial\lambda_i < 0$. The equilibrium value of λ is therefore less than one. For strategic complements $\pi_{ij}^j > 0$, $\partial R_j/\partial x_i^* > 0$ and therefore $\partial\pi^i/\partial\lambda_i > 0$. As $\partial\pi^i/\partial\lambda_i > 0$ the equilibrium value of λ is greater than one.

Appendix B

Let the demand function facing firm i be $D^i(x_i, x_j)$ where x_i and x_j are the decision variables of firm i and its rival, firm j respectively. Let $C^i(x_i, x_j)$ be the total cost function for firm i. Then

$$\pi^i = D^i(x_i, x_j)x_i - C^i(x_i, x_j). \tag{B.1}$$

[19] The sign of $\partial\pi^i/\partial x_j$ is obtained by differentiating profits π^i in equilibrium with respect to x_j^* and evaluating at $\lambda = 1$. The sign of $\partial x_i/\partial\lambda_i$ is obtained by the total differentiation of the first order condition, $\partial\pi^i/\partial x_i^* = 0$ with respect to x_i and λ_i. Details available upon request.

Differentiating (B.1) with respect to x_i gives

$$\pi_i^i = D_i^i(x_i, x_j)x_i + D^i(x_i, x_j) - C_i^i(x_i, x_j), \tag{B.2}$$

where the subscripts denote first differentials. Taking the total differential of π_i^i with respect to x_i and x_j gives

$$d[\pi_i^i] = [D_{ii}^i(x_i, x_j)x_i + 2D_i^i(x_i, x_j) - C_{ii}^i(x_i, x_j)]\mathrm{d}x_i + [D_{ij}^i(x_i, x_j)x_i + D_j^i(x_i, x_j) - C_{ij}^i(x_i, x_j)]\mathrm{d}x_j.$$

Strategic interaction, π_{ij}^i is given by $[D_{ij}^i(x_i, x_j)x_i + D_j^i(x_i, x_j) - C_{ij}^i(x_i, x_j)$, the coefficient of $\mathrm{d}x_i$. The above equation can be written as

$$\mathrm{d}[\pi_i^i] = \beta_1 x_i\,\mathrm{d}x_i + \beta_2\,\mathrm{d}x_i + \beta_3 x_i\,\mathrm{d}x_j + \beta_4\,\mathrm{d}x_j, \tag{B.3}$$

where $\beta_1 = D_{ii}^i(x_i, x_j)$, $\beta_2 = 2D_i^i(x_i, x_j) - C_{ii}^i(x_i, x_j)$, $\beta_3 = D_{ij}^i(x_i, x_j)$ and $\beta_4 = D_j^i(x_i, x_j) - C_{ij}^i(x_i, x_j)$. Strategic interaction is given by the coefficient of $\mathrm{d}x_i$. i.e., $\beta_3 x_i + \beta_4$.

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