Managerial Incentives in Oligopoly: The Hicks Conjecture Revisited☆

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Abstract

We analyze a simple incentive contracting model under oligopolistic competition to show that the nature of competition may have differential effects on the managerial incentives. In an effort to formalize the Hicks conjecture, which asserts that increased competition in the product market induces firms to elicit higher managerial efforts by offering more high-powered incentives, we show that when the new entrants in an oligopolistic market are allowed to set quantities along with the incumbents the above conjecture is refuted. On the other hand, when the entrants are Stackelberg followers in the product market, threat of entry induces the incumbents to offer stronger incentives which imply lower managerial slack. Thus, a model of sequential competition validates the Hicks conjecture.

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1. Introduction

> "It seems not at all unlikely that people in monopolistic positions will very often be people with sharply rising subjective costs; if this is so, they are likely to exploit their advantage much more by not bothering to get very near the position of maximum profit, than by straining themselves to get very close to it. The best of all monopoly profits is a quiet life."
>
> Sir John R. Hicks (1935)

Most economists agree with the Hicks conjecture, and believe that owners of the firms induce their managers to work harder by offering more high-powered incentives as competition in the product market increases. Nickell (1996) by analyzing around 670 U.K. firms concludes that TFP growth rate is positively correlated with competition, either measured by increased number of competitors or by lower rents. Cuñat and Guadalupe (2009) analyze the effect of globalization on executive compensation. They show that import penetration increases the sensitivity of CEO pay to performance. Both Kole and Lehn (1997), and Palia (2000) assert that CEOs receive stronger incentives in deregulated industries. Karuna (2007) finds a positive relationship between the degree of product substitutability and the stock option payment of CEOs. Therefore, a plethora of empirical works indeed support the view that increased product market competition, which may be measured by various fundamentals of the market, induces firms to elicit greater managerial effort by providing stronger incentives.[1]

Although there is an apparent consensus of empirical studies regarding the positive association between managerial incentives and product market competition, most of the theoretical predictions about such association have been ambiguous simply because competition affects the organizational structure of a firm via different channels which may not always point in the same direction. For example, Hermalin (1992) identifies three countervailing effects of product market competition on managerial incentives. CEOs in a firm typically receive a fraction of the firm's expected profit. Thus, when more stringent competition implies lower expected profit, the managers tend to consume fewer "agency goods", i.e., expend more effort, which is the positive "income effect". Second, the inherent riskiness of a firm varies with the competitive environments it operates in, and so does the actions of a CEO if he is not risk neutral. Higher volatility of firm's profit may thus result in lower managerial effort. Hermalin (1992) names this the "risk-adjustment effect". Finally, competition may change the difference in expected profits associated with different actions taken by a manager, which is the "change-in-the-relative-value-of-actions effect". If the marginal value of a 'better' action, say managerial effort is increasing (decreasing) with respect to the degree of product market competition, then greater competition leads to higher (lower) managerial effort. Thus, the overall effect of competition on managerial effort is ambiguous. Schmidt (1997) also identifies two countervailing effects. The "value-of-cost-reduction effect" is the same as the third effect in Hermalin (1992). In addition to that, there is a "threat-of-liquidation effect" which asserts that greater product market competition implies that a firm is more likely to go bankrupt, and hence to avoid liquidation of the firm's assets the manager tends to work harder since liquidation implies a loss of his reputation.

[1] Although a large portion of the empirical literature supports the Hicks conjecture, there are findings which suggest a negative relationship between competition and managerial incentives. For example, Aggarwal and Samwick (1999) in a cross-sectional study of relative performance evaluation show that the ratio of own-firm to rival-firm pay-performance sensitivity decreases as the product becomes closer substitutes.

The main objective of the present paper is to analyze a simple model of oligopolistic competition in order to derive a positive relationship between competition and managerial incentives, which validates the Hicks conjecture, and conforms to the empirical findings. To this end, we develop a stylized framework which offers a very simple explanation. The main objective of the present paper is to rationalize the Hicks conjecture by analyzing a simple model of oligopolistic competition that offers an intuitive explanation. Hence, our model intends to bridge the gap between empirical findings and theoretical results in the extant literature. We restrict our attention to the effect of competition on a firm's organization, namely the "expected-value-of-cost-reduction", which is very similar to the "change-in-the-relative-value-of-actions effect" of Hermalin (1992) or the "value-of-cost-reduction effect" of Schmidt (1997), and abstract from any additional effects some of which we have described in the previous paragraph. In particular, we analyze two models of oligopolistic competition. The first model considers an industry where a finite number of firms compete à la Cournot. Each firm hires a manager, by offering incentive contracts, who exerts R&D effort in order to reduce the constant marginal cost of production. Following the realizations of marginal costs the firms compete in quantities in the product market. We show that when there are more than two firms in the market, increased number of firms in the market leads to lower managerial effort and incentives in equilibrium. Hermalin (1994) identifies two countervailing effects. There is an adverse *scale effect* which implies that greater aggregate rival output induces an individual firm to reduce its production, and hence a lower expected benefits of cost reduction. On the other hand, there exists also a favorable *strategic effect*. Cost reduction by one firm induces the rivals to decrease their output. As a consequence, the market price increases. This price increase is effective if there are more competitors. In our case, when both the incumbents and entrants compete à la Cournot, the scale effect dominates, and hence increased competition leads to greater managerial slack and less high-powered incentives. In the second model, we fix the number of incumbent firms in the market, and allow for new firms to enter who behave as Stackelberg followers. We show that, anticipating greater competition in the market, the incumbents become more aggressive by expanding their production. Consequently, they offer more high-powered incentives to their managers and elicit greater efforts. This favorable *entry effect* of competition on incentives validates the Hicks conjecture, and conforms to the empirical findings that competition and incentives are positively correlated.

Following Leibenstein's (1966) theory of *X-efficiency* there has been a plethora of theoretical models which sought to analyze the effect of competition on managerial incentives. The majority of this theoretical literature takes the degree of product market competition as exogenously given, mainly being represented by some parameter that affects the firms' profitability, and analyze, using the standard principal-agent approach, the effect of a change in such parameter on the optimal organizational structure of a single firm abstracting from the strategic interaction among the firms in an imperfectly competitive market. Some exceptions have been the works by Martin (1993), Hermalin (1994), Raith (2003), and Golan, Parlour, and Rajan (2013) which, as in the present paper, consider agency relations between firms and managers in environments of strategic interaction among firms. Martin's (1993) is a model of Cournot oligopoly where each firm's average cost depends on the unobservable productivity of the manager. A menu of fee schedules and cost targets achieve optimality. He shows that the equilibrium managerial slack is positively correlated with the number of firms. Hermalin (1994) analyzes managerial incentives in a Cournot oligopoly where each firm-manager relationship is subject to moral hazard in effort choice by the manager, and characterizes the symmetric and asymmetric equilibria. He also shows that under certain parameter restrictions, the Hicks conjecture is validated, i.e., growing number of firms leads to lower managerial slack in equilibrium. Raith (2003) considers a model with risk averse managers and free entry under price competition in a Salop circle. A more competitive market is characterized by a larger demand or by lower entry costs, since both induce a higher number of firms in equilibrium. Raith (2003) finds that competition increases managerial incentives if more firms in the market imply a higher market-share for each firm. Golan et al. (2013) rely more on the *information effect* of competition on managerial incentives. Greater competition makes the firm-revenue a more noisy signal of managerial effort, i.e., the incentive problem becomes more costly. Thus, more competition leads firms to elicit low effort (higher managerial slack) in equilibrium.

Like the aforementioned papers, we also consider an agency model with strategic interaction. Our main contribution is to treat the change in competition as entry of new firms into the product market who behave as Stackelberg followers. When the leaders set their quantities they are not aware of the cost realizations of the entrants. This is in the spirit of Raith (2003) who model simultaneous competition with unobservable costs. The main driving force of our result that validates the Hicks conjecture is that the threat of entry induces the incumbent to be more aggressive, and hence the expected marginal benefit of cost reduction is higher following entry of new firms.

We have already discussed the works by Hermalin (1992) and Schmidt (1997) which identify several countervailing effects that determine equilibrium incentives in a competitive environment. Earlier works by Hart (1983) and Scharfstein (1988) rely on the fact that increased competition helps the owner of a firm to distinguish aggregate from idiosyncratic shocks, and reduces the cost of incentives. Hart (1983) shows that competition unambiguously improves managerial incentives. Scharfstein (1988) argues that Hart's (1983) result crucially depends on the specification of discontinuous preferences of the manager over income where below a certaint threshold income manager's utility tends to minus infinity. Scharfstein (1988) shows that, under continuous preferences, increased competition leads to greater managerial slack. It is worth noting that the aforementioned works do not consider strategic interaction among firms.

Our paper also contributes to an existing parallel literature on the effect of competition on incentives to innovate that originated following the seminal work of Arrow (1962). In a strict sense, innovation refers to an expansion of the production possibility frontier, whereas managerial effort refers to how far from the frontier does a firm operate. Nonetheless, our paper is closely related to this literature. A major part of the extant literature (e.g. Arrow, 1962; Bester and Petrakis, 1993; Belleflamme and Vergari, 2011) analyze the incentive of a single firm to innovate in a (imperfectly) competitive environment. The present model, like Hermalin (1994), extends the aforementioned models to an environment where all firms have incentive to innovate.[2]

2. The Model

Consider an industry in which n risk neutral firms produce a homogeneous product and compete in quantities. We measure the level of product market competition by the number of firms n which is exogenously given. The inverse demand function is given by $P(Q) = 1 - Q$ where $Q = \sum_{i=1}^{n} q_i$ is the aggregate industry output. Each firm has a linear cost of production function given by $C_i(q_i) = c_i q_i$. The marginal cost c_i of each firm i may take values in $\{0, c\}$. Firms are otherwise identical. The probability of low marginal cost 0 in firm i is given by e_i. We assume that the true realizations of marginal costs are independent across firms. Initially, all firms own the inefficient technology, i.e., the marginal cost of production is given by $c_i = c$ for all $i = 1, \ldots, n$. Each firm hires a risk neutral manager whose

[2]See Vives (2008) for a general model and a number of theoretical results in relation to competition versus innovation.

principal task is to exert R&D efforts in order to reduce the marginal cost.[3] Without loss of generality, the probability of success e_i will be interpreted as the managerial effort in firm i. We further assume that managerial effort is not publicly verifiable, and hence cannot be contracted upon by his employer, which gives rise to a potential moral hazard problem in effort choice. The manager in firm i incurs a total cost of effort which is given by:

$$\psi(e_i) = \frac{e_i^2}{2}.$$

Each firm i hires a manager by offering a binding contract (f_i, b_i) where f_i is the base salary and b_i is the bonus offered in the event that the manager succeeds in reducing firm's marginal cost. Our focus is on the effect of product market competition on managerial efforts and incentives. It is well-known in the agency literature that under risk neutrality, incentive problem becomes important only when the manager's limited liability constraint binds, i.e., $f_i = 0$. In other words, under limited liability the efficient level of effort cannot be implemented. We therefore normalize $f_i = 0$ for all $i = 1, \ldots, n$. Thus, b_i will be interpreted as the power of managerial incentives. Since the realizations of marginal costs are independent across firms in the industry, following Hölmstrom's (1979) 'sufficient statistic' theorem, managerial contract in one firm is not conditioned on the performance of a rival manager.

The economy lasts for four dates, $t = 0, 1, 2, 3$. At date 0, each firm i hires a manager by offering an incentive contract b_i. At $t = 1$ each manager exerts the non-verifiable effort e_i. At the end of the period, all firms observe its realized marginal cost and that of the rivals. At date 2, all firms compete in quantity in a common product market. Finally, at $t = 3$ all parties receive payments agreed upon in the contracts.

3. Managerial Incentives in Cournot Oligopoly

In this section we analyze managerial efforts and incentives in a symmetric Nash equilibrium with n Cournot firms. Assume $(n+1)c < 1$ so that no firm shuts down. It is easy to show that the symmetric equilibrium is unique, although we cannot a priori discard the possible asymmetric equilibria.[4] Consider a representative Cournot firm i. Define by $\pi_i(c_i \mid k)$ the realized profit of firm i at marginal cost $c_i \in \{0, c\}$ when k out of the $n-1$ rival firms realize high marginal cost c, which is given by:

$$\pi_i(c_i \mid k) = \left(\frac{1 - nc_i + kc}{n+1}\right)^2.$$

In a symmetric Nash equilibrium, firm i induces an effort level e_i given that each rival firm j chooses a common effort level, i.e., $e_j = e$ for all $j \neq i$. Note that the probability that k out of $n-1$ rival firms realize a high marginal cost c when the managers exert a common effort level e is given by the following binomial density:

$$p_k(n-1, e) = \binom{n-1}{k} e^{n-1-k}(1-e)^k.$$

Therefore, the expected profit of the representative firm i at marginal cost c_i is given by:

$$\pi_i(c_i \mid e) = \sum_{k=0}^{n-1} p_k(n-1, e)\pi_i(c_i \mid k)$$

[3] Assuming managers to be risk averse would not change any of our results qualitatively. We assume risk neutrality in order to abstract from possible risk-shifting effects of competition.

[4] Hermalin (1994) proves the existence of asymmetric equilibria in a more general context.

From the above it follows that the optimal managerial incentive and effort at firm i solve the following maximization problem:

$$\max_{\{e_i, b_i\}} \pi_i(e_i, b_i) := e_i[\pi_i(0 \mid e) - b_i] + (1 - e_i)\pi_i(c \mid e)$$

$$\text{subject to} \quad U(e_i, b_i) := e_i b_i - \frac{e_i^2}{2} \geq 0, \tag{IR$_i$}$$

$$e_i = \text{argmax}_{\hat{e}_i} \left\{ \hat{e}_i b_i - \frac{\hat{e}_i^2}{2} \right\} = b_i. \tag{IC$_i$}$$

Constraint (IR$_i$) is the *individual rationality* constraint of manager at firm i whose outside option is normalized to zero, and (IC$_i$) is the *incentive compatibility* constraint which asserts that the manager chooses effort e_i to maximize his expected utility given the bonus b_i. It is easy to show that (IR$_i$) always holds given (IC$_i$), and hence can be ignored. Further, substituting $b_i = e_i$ the objective function of firm i reduces to:

$$\pi_i(e_i, e) := e_i[\pi_i(0 \mid e) - e_i] + (1 - e_i)\pi_i(c \mid e). \tag{1}$$

Define by $\Delta\pi_i(e) := \pi_i(0 \mid e) - \pi_i(c \mid e)$ the expected marginal benefit of cost reduction of firm i, which is given by:

$$\Delta\pi_i(e) = \frac{nc(2 - nc) + 2c^2 n(n-1)(1-e)}{(n+1)^2}.$$

The first order condition of the above maximization problem thus yields the following best reply in effort:

$$e_i(e) = \frac{\Delta\pi_i(e)}{2}.$$

Note that managerial efforts and incentives are strategic substitutes since $e_i'(e) < 0$. The following lemma characterizes the managerial efforts and incentives in a symmetric oligopoly equilibrium.

Lemma 1 *Under a Cournot oligopoly in the product market there is a unique symmetric Nash equilibrium in which the efforts and incentives are given by:*

$$e^*(n) = b^*(n) = \frac{nc}{2}\left[\frac{2 + (n-2)c}{(n+1)^2 + n(n-1)c^2}\right].$$

The proofs of the above lemma and of the subsequent results are relegated to the Appendix. Note that the equilibrium managerial effort and bonus are increasing in c. This is to say that higher values of c which correspond to larger gain from cost reduction induces each Cournot firm to offer more high-powered incentives to its manager. Consequently, the managerial effort is also higher. The following proposition analyzes the effect of an increase in the number of firms on the equilibrium managerial efforts and incentives.

Proposition 1 *Let $e^*(n)$ and $b^*(n)$ be the managerial effort and incentives in the unique symmetric Nash equilibrium under a Cournot oligopoly in the product market. Then, $e^*(n) > e^*(n+1)$ and $b^*(n) > b^*(n+1)$ for $n \geq 2$.*

The equilibrium managerial efforts and incentives are determined by the expected value of cost reduction of each firm i in a Cournot oligopoly, which is decreasing in the number of firms whenever there are more than two firms in the market. We call this 'expected-marginal-benefit-of-cost-reduction' effect, which is similar in spirit to the 'change-in-the-relative-value-of-actions' effect identified by Hermalin (1992) or the 'value-of-cost-reduction' effect of Schmidt (1997). Thus, Proposition 1 puts old wine in a new bottle. What is new is the fact that we introduce strategic interactions among the Cournot firms as in Hermalin (1994). Both Hermalin (1992) and Schmidt (1997), among many others, take the degree of product market competition as parametrically given, and analyze the effect of this parameter on the incentive structure of a single representative firm. Such approach is related to the effect of competition on innovation (e.g Arrow, 1962; Belleflamme and Vergari, 2011) when only a single firm in a market innovates. In the current context, all n firms are engaged in process innovation in which action of one manager has strategic effects on that of others, and hence the marginal benefit of cost reduction is expressed in terms of its expected value.

When managerial incentives in one firm strategically affects that in the rival firms through interaction in the product market, the equilibrium efforts and incentives are determined by two countervailing effects (see Hermalin, 1994, for details). The first is an adverse *scale effect*. More firms in a market implies greater aggregate production by the rival firms. Since quantities are strategic substitutes, it is then optimal for an individual firm to reduce its output which implies lower expected marginal benefit of cost reduction. The second effect is a favorable *strategic effect*. Cost reduction by one firm induces its rivals to reduce production, and hence an increase in the market price. Thus, a greater price-cost margin enhances the expected marginal benefit of cost reduction. In the present context, the scale effect dominates, and hence the greater the number of firms, the lower are the managerial efforts and incentives in the Cournot equilibrium.

In order to interpret the above result more intuitively, define by:

$$\Delta\pi_i(k) := \Delta\pi_i(0 \mid k) - \Delta\pi_i(c \mid k)$$

the marginal benefit of cost reduction of a representative firm i in oligopoly when exactly k out of its $n-1$ rival firms realize high marginal cost c. The best response $e_i(e)$ in effort of manager in firm i can be written as

$$e_i(e) = \frac{\Delta\pi_i(n-1)}{2} - \frac{(n-1)[\Delta\pi_i(n-1) - \Delta\pi_i(n-2)]e}{2}$$

The term $\Delta\pi_i(n-1)$ is the marginal benefit of cost reduction of each firm i when no other manager has succeeded in reducing the marginal cost, and $\Delta\pi_i(n-2)$ represents that of firm i when there is another low-cost firm. It is easy to see that the numerator $\Delta\pi(n-1)$ of the above expression is strictly decreasing in n for $n \geq 2$ for all values of c, which is the scale effect. On the other hand, the term $\Delta\pi(n-1) - \Delta\pi(n-2)$ is increasing in n for all values of c. This is to say that the marginal gain from being the lone efficient firm, as opposed to being so along with another firm, is higher as there are more firms in the market. Therefore, as the rival firms induces higher managerial effort, it is optimal for an individual firm to reduce it, and hence an increase in the number of firms in the product market induces lower managerial efforts and weaker incentives.

4. Effect of Entry on Managerial Incentives: The Hicks conjecture

An implication of the Hicks conjecture is whether an individual firm in an industry would provide more high powered incentives to its manager to elicit greater effort if the product market becomes more competitive. In order to analyze this question, we consider an industry with n incumbent firms who employ n managers apiece and have the same characteristics as in our Cournot oligopoly model in Section 3. There are m potential entrants in the market who possess the same technology as the incumbent firms, and hire a manager apiece in order to carry out R&D activities. In what follows we analyze two different scenarios. First, the incumbents and the entrants set their quantities simultaneously, i.e., the pre- and post-entry equilibria are simultaneous quantity-setting Cournot equilibria. In the second scenario, the entrants behave as Stackelberg followers in the product market, i.e., they hire managers and set quantities after the incumbent firms have made the decision on how much to produce.

4.1. Incentives and Entry in Cournot Oligopoly

The result in Proposition 1 may be interpreted in two different ways. First, Proposition 1 allows us to compare incentives offered in two different industries, one with a greater number of identical Cournot firms than the other. In particular, it asserts that if we compare two such markets, then each of the n managers works harder in the market with n firms than each of the $n+1$ managers in the other market. This interpretation is in the same spirit as the majority of the works in the extant literature (e.g. Hart, 1983; Scharfstein, 1988; Martin, 1993) where the degree of product market competition is measured by an exogenous parameter such as number of firms, degree of product substitutability, market-specific regulation, and the comparative statics of equilibrium incentives with respect to this parameter is equivalent to comparing the equilibrium incentives under two different exogenously given market structures.

The second interpretation is how firms change their decision to offer incentives following the entry of a new firm into the [same] industry when in both the original and new equilibria firms set quantities simultaneously. Consider thus the entry of new m firms into the market with n incumbent firms. Assume now that $(n+m+1)c<1$ so that no firm shuts down. Since the incumbent and the entrants make their production decisions simultaneously, then following Lemma 1, the symmetric equilibrium managerial efforts and incentives are given by:

$$e^*(n+m)=b^*(n+m)=\frac{(n+m)c}{2}\left[\frac{2+(n+m-2)c}{(n+m+1)^2+(n+m)(n+m-1)c^2}\right].$$

Therefore, it immediately follows from Proposition 1 that

Proposition 2 *Let $e^*(n)$ and $b^*(n)$ respectively be the managerial effort and incentives in the unique symmetric Cournot equilibrium before entry into the product market, and $e^*(n+m)$ and $b^*(n+m)$ respectively be the managerial effort and incentives in post-entry symmetric Cournot equilibrium. Then, $e^*(n)>e^*(n+m)$ and $b^*(n)>b^*(n+m)$ for $n\geq 1$ and $m\geq 1$.*

The above proposition implies that if the entrants are able to set quantities simultaneously with the incumbents, then the manager in each of the n incumbent firms would exert lower effort in the new equilibrium. Thus, the Hicks conjecture is refuted if the post-entry quantity competition is simultaneous.

At this juncture, we must compare the result in Proposition 2 with that of Hermalin (1994, Proposition 4). As Novshek (1980) and Hermalin (1994) point out, increased competition may have several meanings: (a) change in any exogenous parameter such as number of firms, degree of product subsitutability, etc. and (b) firms behave more like price takers. Hermalin (1994) takes the second approach, and assumes that the inverse market demand is given by:

$$a - \frac{b}{n^{\nu}} \sum_{i=1}^{n} q_i, \text{ with } \nu \in (0, 1).$$

Thus, the greater the number of firms, the flatter is the inverse demand, i.e., firms are closer to be price takers. He shows that when the elasticity ν of the slope with respect to n is low enough, then entry of a new firm induces greater managerial slack in the new equilibrium. This is because the scale effect tend to dominate the strategic effect for low values of ν. Note that our model of post-entry Cournot competition is a limiting case of that of Hermalin (1994) with $\nu = 0$, and hence we obtain a similar result in Proposition 2.

4.2. Incentives and Entry in Stackelberg Oligopoly

Consider now an industry with n incumbent firms indexed by $l \in L := \{1, \ldots, n\}$, and m entrant firms indexed by $f \in F := \{1, \ldots, m\}$. The economy lasts for seven dates $t = 0, \ldots, 6$. At date 0, each incumbent firm l hires a manager by offering a binding contract to induce the manager to undertake R&D effort to reduce its constant marginal cost c_l. At $t = 1$, the manager of each incumbent firm chooses the non-verifiable effort $e_l \in [0, 1]$. Following the realizations of marginal costs of all the incumbent firms, which is publicly observable, at $t = 2$ the incumbent firms choose how much to produce. At date 3, m firms enter the market and hire a manager apiece by offering incentive contracts b_f for $f \in F$ for the purpose of cost reduction. At $t = 4$, the manager of each entrant firm chooses R&D effort $a_f \in [0, 1]$. In the following date, after the realization of its marginal cost $c_f \in \{0, c\}$ each entrant firm chooses how much to produce, i.e., the entrants act as Stackelberg followers in the product market. Finally, at date 6, the agreed upon payments are made to the managers. Assume that c, the gain from cost reduction is not too high so that no firm shuts down.[5]

Let $Q_L = \sum_{l \in L} q_l$ and $Q_F = \sum_{f \in F} q_f$ be the aggregate output of the incumbents and entrants, respectively, and $Q = Q_L + Q_F$. In order to measure the competitive pressure in the industry, we follow Daughety (1990) who analyzes a market with many leaders and many followers. In particular, we analyze a symmetric Stackelberg equilibrium where the incumbents first set outputs simultaneously, and then the entrants set output simultaneously. The classical Stackelberg case would be a market with n incumbents and $m = 1$ entrant. Thus in the last date, the product market profit of a representative entrant firm f conditional on the aggregate incumbent output and on h out of $m - 1$ rival entrants realize high marginal cost c is given by:

$$\pi_f(c_f \mid h, Q_L) = \left(\frac{1 - mc_f + hc - Q_L}{m + 1} \right)^2.$$

Since, following entry, the entrants behave as Cournot firms, at date $t = 4$ the optimal managerial contract in each of the follower firms will determined in the same manner as the optimal contracts in a Cournot market [described in the previous section] taking the aggregate leader output Q_L as given.Therefore, the optimal managerial effort in a symmetric equilibrium of the stage game, $a_f = a$ for all $f \in F$ is given by:

$$a(Q_L, m) = \frac{mc}{2} \left[\frac{2 - 2Q_L + (m - 2)c}{(m + 1)^2 + m(m - 1)c^2} \right]. \tag{2}$$

[5] See the proof of Lemma 2 in the Appendix for a precise expression.

At this stage only the marginal cost of the entrant firms are unknown. The realized marginal costs of the incumbents are publicly observable since they have already decided their quantities produced. Note that $a(Q_L, m)$ is strictly decreasing in Q_L implying that the more aggressive the leaders, the less are the incentives for the followers to reduce marginal costs. Also, $a(0, m) = e^*(m)$, i.e., given that no leader has produced positive quantity, the symmetric equilibrium managerial effort coincides with the effort level in a Cournot equilibrium with $n = m$ firms.

Let us now analyze the output decision of the incumbent firms. At $t = 2$, each incumbent l chooses its output to maximize the following expected profit, taking the aggregate production of the rival incumbents and the aggregate reaction of the followers as given

$$\max_{q_l} \; (1 - q_l - q_{-l} - E[Q_F(Q_L, m)] - c_l)\, q_l,$$

where $q_{-l} = Q_L - q_l$ and $E[Q_F(Q_L, m)]$ is the expected aggregate output reaction of m followers, which is given by:

$$E[Q_F(Q_L, m)] = \sum_{h=0}^{m} p_h(m, a(Q_L, m)) Q_F(h \mid Q_L, m) = \frac{m(1 - Q_L) - mc[1 - a(Q_L, m)]}{m+1},$$

where $p_h(m, a(Q_L, m))$ is the binomial probability that h out of m followers have high marginal cost c, and $Q_F(h \mid Q_L, m)$ is the aggregate follower output in this case. When, k out of $n-1$ rival incumbents have high marginal cost, the above maximization problem yields the following expected profit of the representative incumbent:[6]

$$\pi_l(c_l \mid k) = \frac{[B(m, c) + 2(m+1)A(m, c)(kc - nc_l)]^2}{4(n+1)^2 A(m, c)[A(m, c) - m^2 c^2]},$$

where

$$\begin{aligned} A(m, c) &:= (m+1)^2 + m(m-1)c^2, \\ B(m, c) &:= 2(1 + mc)(1 + m)^2 + m(m^2 c - 2)c^2. \end{aligned}$$

Therefore, prior to the realization of marginal cost c_l, the expected profit of the incumbent firm l reduces to:

$$\pi_l(c_l \mid e) = \sum_{k=0}^{n-1} p_k(n-1, e)\pi_l(c_l \mid k).$$

The optimal managerial contracting problem is now same as that in Section 3. Using the incentive constraint $e_l = b_l$, and the non-binding individual rationality constraint of the manager in firm l, the optimal effort in firm l in a symmetric equilibrium is obtained by maximizing the following expression:

$$\pi_l(e_l, e) := e_l[\pi_l(0 \mid e) - e_l] + (1 - e_l)\pi_l(c \mid e).$$

The first order condition of the above maximization problem yields best reply of manager at firm l which is given by:

$$e_l(e) = \frac{\Delta \pi_l(e)}{2},$$

[6] See the proof of Lemma 2 for the detailed steps.

where

$$\Delta\pi_l(e) := \pi_l(0 \mid e) - \pi_l(c \mid e) = \frac{nc[B(m,c) - c(m+1)A(m,c) + c(m+1)(n-1)A(m,c)(1-2e)]}{(n+1)^2[A(m,c) - m^2c^2]}.$$

The following lemma characterizes the managerial efforts and incentives in the equilibrium of a Stackelberg oligopoly with n incumbents and m entrants.

Lemma 2 *Under a Stackelberg oligopoly in the product market there is a unique symmetric Nash equilibrium among incumbents and entrants in which the equilibrium managerial effort and incentive in every incumbent are given by:*

$$e(n,m) = b(n,m) = \frac{nc}{2}\left[\frac{B(m,c) + (m+1)(n-2)A(m,c)}{(n+1)^2\{A(m,c) - m^2c^2\} + n(n-1)(m+1)A(m,c)c^2}\right].$$

Notice that $e(n,0) = e^*(n)$, i.e., the managerial effort in the Stackelberg equilibrium with no entrant coincides with the managerial effort in the symmetric Cournot equilibrium in Section 3.

In the following proposition, we compare managerial efforts and incentives in two equilibria: the first one in which there are n Cournot competitors, and the second one in which the n incumbent firms become Stackelberg leaders in the product market as they foresee entry of m new firms.

Proposition 3 *Let $e^*(n)$ and $b^*(n)$ respectively be the managerial effort and incentives in the unique symmetric Cournot equilibrium before entry into the product market, and $e(n,m)$ and $b(n,m)$ respectively be the managerial effort and incentives of each incumbent in the unique symmetric Stackelberg equilibrium when the incumbents are allowed to set quantities before the entrants. Then, $e^*(n) < e(n,m)$ and $b^*(n) < b(n,m)$ for $n \geq 1$ and $m \geq 1$.*

Proposition 3 suggests a favorable effect of entry on managerial efforts and incentives in a Stackelberg equilibrium. The managers of the incumbent firms would work harder in the new equilibrium with entry compared with the pre-entry equilibrium.

The reason is simple and induced by the fact that the incumbents are Stackelberg leaders in the product market. When these firms foresee entry, in order to induce the entrants to produce a lower aggregate quantity, they expand output aggressively. This is achieved by lowering the marginal cost, and hence the incumbents offer stronger incentives for cost reduction to their managers. This is identified as the favorable entry effect on managerial incentives. The intuition is clear from the expression for the managerial effort in an entrant firm in equation (2). Note that $a(Q_L, m)$ is decreasing in the aggregate leader output which in turn implies lower expected aggregate follower output. Thus, when the entrants behave as Stackelberg followers, the Hicks conjecture is validated. Note that the result does not depend on the number of entrants in the market. The threat of entry even from one entrant has a favorable effect on the managerial efforts in the incumbent firms. In other words, following entry, the incumbents always induce higher managerial efforts no matter how competitive the post-entry market is. The above proposition can be strengthened by saying that the incumbent firms induce greater managerial effort as the number of entrants grows, i.e., $e(n,m) < e(n,m+1)$ for any $m \geq 0$.[7] Clearly, m cannot be too large since the gain from cost reduction c has to be infinitesimally small.

[7] The proof of this assertion is cumbersome, and is available upon request to the authors.

5. Discussion

5.1. Process Innovation versus Product Innovation

In the present paper a manager's principal task is to undertake R&D efforts in order to make a firm's technology more efficient. But the model is amenable to incorporate alternative specifications of incentive contracts. Suppose firms produce differentiated products and compete in quantity. The inverse demand curve of firm i is given by:

$$p_i = \alpha_i - q_i - \delta \sum_{j \neq i} q_j, \quad \text{with } \delta \in (0, 1],$$

where $\alpha_i \in \{\alpha_H, \alpha_L\}$ with $\alpha_H > \alpha_L$. The constant marginal cost, which is common across all firms, is given by $c \in [0, \alpha_L)$. The parameter α_i can be interpreted as the quality of the product of firm i. Assume that Prob.$[\alpha_i = \alpha_H \mid e_i] = e_i$ where $e_i \in [0, 1]$ is the managerial effort. Thus, the principal task of a manager is enhancement of the quality of the firm's product (product innovation) rather than cost reduction (process innovation). Managerial effort may include actions such as firm-specific investment, market research, etc. to enhance the product quality.

Under this alternative specification, all our results hold qualitatively. The reason is simple. In the model described in the previos sections, cost-reducing activities of the firms are strategic substitutes in the sense that $\Pi^i_{ij}(c_i, c_{-i}) < 0$ for $j \neq i$ where $\Pi^i(c_i, c_{-i})$ is the profit of a firm i in the product market. This strategic substitutability translates into the strategic substitutability of managerial efforts in equilibrium. When managers exert efforts in enhancing the product qualities instead of cost reduction, a similar argument goes through. It is easy to show that quality-enhancing activities are strategic substitutes, i.e., $\Pi^i_{ij}(\alpha_i, \alpha_{-i}) < 0$ for $j \neq i$. Therefore in equilibrium, managerial efforts are also strategic substitutes.

5.2. Price Competition

The nature of product market competition such as price competition versus quantity competition has differential implications for managerial incentives. Aggarwal and Samwick (1999) show that the managerial incentive contracts behave in a different manner vis-à-vis the degree of product substitutability depending on whether their employees compete in price or quantity. Competition has such opposing implications for managerial incentives since managerial activities are strategic complements in a Bertrand market, and strategic substitutes in a Cournot market. In the current context, when managerial activities are strategic substitutes price competition, as opposed to quantity competition, does not lead to an opposite effect of increased competition on managerial incentives. Consider a model of differentiated oligopoly where firms compete in price instead of quantity. The inverse demand curve of firm i is given by:

$$p_i = 1 - q_i - \delta \sum_{j \neq i} q_j, \quad \text{with } \delta \in (0, 1],$$

and a manager exerts R&D efforts in order to reduce the marginal cost of his employer. It is easy to show that $\Pi^i_{ij}(c_i, c_{-i}) < 0$ for $j \neq i$. That is, even if firms compete in prices, the cost-reducing activities remain strategic substitutes which implies strategic substitutability of managerial incentives in equilibrium, and hence our results hold good qualitatively.

6. Conclusion

In a quantity-setting oligopoly the implications of competition for managerial incentives may be quite different depending on the nature of competition. In a simple model of strategic interaction among firms we show that when the incumbent and entrant firms compete à la Cournot, the incumbent firms offer weaker incentives to their managers, which imply greater managerial slack, following the entry of new firms in the market. This is because of a stronger scale effect which we have already discussed. When the incumbents, on the other hand, behave as Stackelberg leaders by setting their quantities prior to entry, managerial incentives are stronger in the incumbent firms in the post-entry equilibrium. This result is obtained due to the entry effect since the Stackelberg leaders behave more aggressively by expanding output in order to make less room for the entrants. Thus, in a Stackelberg quantity-setting game the well-known Hicks conjecture is validated. In other words, in a Cournot game with entry the incumbent firms do not react much to the threat of entry which is somewhat unanticipated, and hence the dominant scale effect induces greater managerial slack. In a Stackelberg quantity-setting game, the incumbent firms by anticipating entry of new firms strategically become more aggressive by expanding output which in turn increases the expected benefits of cost reduction.

Although managerial activities in the current model include only cost-reducing R&D efforts, the model may extend to other settings such as product innovation and price competition, and our results remain valid. This is because of the general conclusion of such models in the literature that the nature of strategic effects of managerial tasks, i.e., whether the activities are strategic substitutes or complements, translates into the same nature of strategic effects of managerial incentives.

The two models oligopolistic competition presented above have distinct empirical implications. result in Proposition 1 relates more adequately to a cross-section analysis in which managerial incentives within a firm and the competition level it faces are studied for different firms. However, Proposition 3 can be more intuitively interpreted in a context of panel-data analysis where we study firms in distinct periods in time and assess how a change in competition affects managerial incentives. A clear example of this is the literature that analyzes the effects that market deregulation has on managerial incentives (e.g. Kole and Lehn, 1997; Palia, 2000).

The existing literature has offered various explanations for the theoretical relationship between competition and managerial incentives by identifying determining effects such as information, risk, reputations, etc. which may be considered as integral elements of a more general agency model. We have abstracted from such general considerations by assuming risk neutrality and independent realizations of idiosyncratic technology shocks since our aim has been to identify a new channel through which product market competition affects managerial incentives. Therefore, we have made an effort to offer a simple framework for strategic interaction among firms, and provide a simple explanation for the empirically observed fact that why increased competition may lead to more high-powered incentives for managers. An interesting research agenda for the future would be to consider a sequential model using a more robust principal-agent framework in order to analyze the interactions between the aforementioned effects from which we have abstracted away.

Appendix

Proof of Lemma 1

Consider the n-firm oligopolistic product market, and consider a reference firm i. At $t = 2$, firm i chooses its output q_i by solving the following maximization problem:

$$\max_{q_i} (1 - q_i - q_{-i} - c_i)q_i,$$

where $q_{-i} = Q - q_i$ is the aggregate output produced by the rival firms. The above maximization problem implies the following profit for firm i:

$$\pi_i(c_i, c_{-i}) = \left(\frac{1 - nc_i + c_{-i}}{n+1}\right)^2,$$

where $c_{-i} = \sum_{j=1}^{n} c_j - c_i$. If k out of $n-1$ rivals have high marginal cost c, which happens with the binomial probability $p_k(n-1, e)$, then $c_{-i} = kc$, and the above expression reduces to:

$$\pi_i(c_i \mid k) = \left(\frac{1 - nc_i + kc}{n+1}\right)^2.$$

Therefore,

$$\Delta\pi_i(k) := \pi_i(0 \mid k) - \pi_i(c \mid k) = \frac{nc(2 - nc + 2kc)}{(n+1)^2},$$

which is the marginal benefit of cost reduction of firm i when k out of its $n-1$ rivals have marginal cost c. Thus, the expected marginal benefit of cost reduction of firm i is given by:

$$\begin{aligned}\Delta\pi_i(e) := \pi_i(0 \mid e) - \pi_i(c \mid e) &= \sum_{k=0}^{n-1} p_k(n-1, e)\Delta\pi_i(k) \\ &= \frac{nc(2-nc) + 2c^2n(n-1)(1-e)}{(n+1)^2}.\end{aligned}$$

The first order condition of the maximization of the objective function in (1) yields

$$e_i(e) = \frac{\Delta\pi_i(e)}{2},$$

which is the best reply of the manager at firm i. In a symmetric equilibrium $e_i = e = e^*(n)$. Substituting this into the above best reply function we get

$$e^*(n) = \frac{2nc(1-c) + n^2c^2}{2[(n+1)^2 + n(n-1)c^2]}.$$

It follows from the incentive compatibility constraint (IC_i) that $e^*(n) = b^*(n)$.

Proof of Proposition 1

Note that

$$
\begin{aligned}
e^*(n) - e^*(n+1) &= \frac{1}{2}\left[\frac{2nc(1-c)+n^2c^2}{(n+1)^2+n(n-1)c^2} - \frac{2(n+1)c(1-c)+(n+1)^2c^2}{(n+2)^2+n(n+1)c^2}\right] \\
&= \frac{c[2(1-c)(n^2+n-1)-c(2n^2+4n+1)]+c^3(2-c)n(n+1)}{2[(n+1)^2+n(n-1)c^2][(n+2)^2+n(n+1)c^2]}
\end{aligned}
$$

Note that the denominator as well as the last term of the numerator of the above fraction is strictly positive for $n \geq 2$. Therefore, it is sufficient to show that $2(1-c)(n^2+n-1)-c(2n^2+4n+1) > 0$ in order to have $e^*(n) > e^*(n+1)$. Now,

$$
2(1-c)(n^2+n-1)-c(2n^2+4n+1) > 0 \iff c < \frac{2(n^2+n-1)}{4n^2+6n-1}. \tag{3}
$$

It is easy to show that

$$
\frac{2(n^2+n-1)}{4n^2+6n-1} > \frac{1}{n+1}
$$

which implies the inequality in (3) since $c < 1/(n+1)$.

Proof of Lemma 2

Consider the product market of n incumbents and m entrants. At $t=5$, a representative entrant firm f solves the following maximization problem to choose how much to produce:

$$
\max_{q_f} (1 - q_f - q_{-f} - Q_L - c_f)q_f,
$$

where $q_{-f} = Q_F - q_f$ is the aggregate quantity produced by the rival entrants, and Q_L is the aggregate quantity produced by the incumbents. Suppose that h out of $m-1$ rival entrants have marginal cost c. Then the first order condition of the above maximization problem yields the following optimal output and profit for firm f:

$$
\begin{aligned}
q_f(c_f \mid h, Q_L) &= \frac{1 - mc_f + hc - Q_L}{m+1}, \\
\pi_f(c_f \mid h, Q_L) &= \left(\frac{1 - mc_f + hc - Q_L}{m+1}\right)^2.
\end{aligned}
$$

At $t=4$, the optimal managerial contract in firm f thus solves:

$$
\max_{\{a_f, b_f\}} \pi_f(a_f, b_f) := a_f[\pi_f(0 \mid a) - b_f] + (1-e_f)\pi_f(c \mid a)
$$

$$
\text{subject to} \quad U(a_f, b_f) := a_f b_f - \frac{a_f^2}{2} \geq 0, \tag{IR$_f$}
$$

$$
a_f = \text{argmax}_{\hat{a}_f} \left\{\hat{a}_f b_f - \frac{\hat{a}_f^2}{2}\right\} = b_f, \tag{IC$_f$}
$$

where

$$\pi_f(c_f \mid a, Q_L) = \sum_{h=0}^{m-1} p_h(m-1, a)\, \pi_f(c_f \mid h, Q_L)$$

is the expected profit of firm f at marginal cost c_f when all the managers in the rival firms in F choose a common effort level a. It is easy to show that (IR$_f$) always holds given (IC$_f$), and hence can be ignored. Further, substituting $b_f = a_f$ the objective function of firm $f \in F$ reduces to:

$$\pi_f(a_f, a, Q_L) := a_f[\pi_f(0 \mid a, Q_L) - a_f] + (1 - a_f)\pi_f(c \mid a, Q_L).$$

Let the symmetric equilibrium effort level be $a_f = a = a(Q_L, m)$ which is given by:

$$a(Q_L, m) = \frac{mc}{2}\left[\frac{2 - 2Q_L + (m-2)c}{(m+1)^2 + m(m-1)c^2}\right].$$

Let us now analyze the output decision of the incumbent firms. At $t = 2$, each incumbent l chooses its output to maximize the following expected profit, taking the aggregate production of the rival incumbents and the aggregate reaction of the followers as given

$$\max_{q_l}\ (1 - q_l - q_{-l} - E[Q_F(Q_L, m)] - c_l)\, q_l,$$

where $q_{-l} = Q_L - q_l$ and $E[Q_F(Q_L, m)]$ is the expected aggregate output reaction of m followers, which is given by:

$$E[Q_F(Q_L, m)] = \sum_{h=0}^{m} p_h(m, a(Q_L, m))Q_F(h \mid Q_L, m) = \frac{m(1 - Q_L) - mc[1 - a(Q_L, m)]}{m+1},$$

where $p_h(m, a(Q_L, m))$ is the probability that h out of m followers have high marginal cost c, and $Q_F(h \mid Q_L, m)$ is the aggregate follower output in this case. Substituting the above, the objective function of firm $l \in L$ reduces to:

$$\pi_l := \frac{[1 + mc - Q_L - mca(Q_L, m) - (m+1)c_l]q_l}{m+1}.$$

The first order condition of the above maximization problem is given by:

$$1 + mc - Q_L - mca(Q_L, m) - (m+1)c_l = \frac{[A(m, c) - m^2c^2]q_l}{A(m, c)},$$

where $A(m, c) := (m+1)^2 + m(m-1)c^2$. Summing the above equation over $l \in L$ we get

$$Q_L = \frac{nB(m, c) - 2A(m, c)(m+1)\sum_{l \in L} c_l}{2(n+1)[A(m, c) - m^2c^2]}, \tag{4}$$

where $B(m, c) := 2(1 + mc)(1 + m)^2 + m(m^2c - 2)c^2$. As a digression, let us derive the condition under which no entrant firm shuts down. Recall that

$$q_f(c_f \mid h, Q_L) = \frac{1 - mc_f + hc - Q_L}{m+1}.$$

Notice that the firm with the lowest output in the market is an entrant who competes with all low-cost incumbents and entrants. The aggregate leader output Q_L when all incumbents have zero marginal costs is given by:

$$Q_L^0 = \frac{nB(m, c)}{2(n+1)[A(m, c) - m^2c^2]}.$$

Therefore, $q_f(c_f = c \mid 0, Q_L^0) > 0$ if

$$2(1-mc)(n+1)[A(m,c) - m^2c^2] - nB(m,c) > 0,$$

which puts an upper bound on c. Now substituting Q_L obtained in (4) in the expression for $a(Q_L, m)$ and the above first order condition, we get

$$q_l(c_l, c_{-l}) = \frac{B(m,c) - 2A(m,c)(m+1)(nc_l - c_{-l})}{2(n+1)(A(m,c) - m^2c^2)},$$

where $c_{-l} = \sum_{j \in L} c_j - c_l$. The above yields the following expected profit for firm l:

$$\pi_l(c_l, c_{-l}) = \frac{[B(m,c) - 2A(m,c)(m+1)(nc_l - c_{-l})]^2}{4A(m,c)(n+1)^2(m+1)(A(m,c) - m^2c^2)}.$$

When k out of $n-1$ rival incumbents have high marginal cost, $c_l = kc$, and hence the above expression reduces to:

$$\pi_l(c_l \mid k) = \frac{[B(m,c) + 2(m+1)A(m,c)(kc - nc_l)]^2}{4(n+1)^2 A(m,c)[A(m,c) - m^2c^2]},$$

Therefore, prior to the realization of marginal cost c_l, the expected profit of the incumbent firm l reduces to:

$$\pi_l(c_l \mid e) = \sum_{k=0}^{n-1} p_k(n-1, e)\pi_l(c_l \mid k),$$

where e is the common effort level chosen by the managers in the rival incumbent firms in L. The optimal managerial contracting problem is now same as that in Section 3. Using the incentive constraint $e_l = b_l$, and the non-binding individual rationality constraint of the manager in firm l, the optimal effort in firm l in a symmetric equilibrium is obtained by maximizing the following expression:

$$\pi_l(e_l, e) := e_l[\pi_l(0 \mid e) - e_l] + (1 - e_l)\pi_l(c \mid e).$$

The first order condition of the above maximization problem yields best reply of manager at firm l which is given by:

$$e_l(e) = \frac{\Delta \pi_l(e)}{2},$$

where

$$\Delta \pi_l(e) := \pi_l(0 \mid e) - \pi_l(c \mid e) = \frac{nc[B(m,c) - c(m+1)A(m,c) + c(m+1)(n-1)A(m,c)(1-2e)]}{(n+1)^2[A(m,c) - m^2c^2]}.$$

Let the symmetric equilibrium effort level be $e_l = e = e(nm)$. The corresponding equilibrium managerial bonus is thus $b_l = b = b(nm)$. These are given by:

$$e(n,m) = b(n,m) = \frac{nc}{2}\left[\frac{B(m,c) + (m+1)(n-2)A(m,c)}{(n+1)^2\{A(m,c) - m^2c^2\} + n(n-1)(m+1)A(m,c)c^2}\right].$$

This completes the proof of the lemma.

Proof of Proposition 3

Let n and m be the number of incumbents and entrants in the product market, respectively. Let $e^*(n)$ and $e(n, m)$ be the effort levels in the unique symmetric equilibrium among incumbents of a Cournot and a Stackelberg oligopoly, respectively. Define

$$G(n, m) := [a_0(c) + a_1(c)n + a_2(c)n^2 + a_3(c)n^3]m^2 + [b_1(c)n + b_2(c)n^2 + b_3(c)n^3](2m + 1),$$

where

$$a_0(c) = -c^2, \;\; a_1(c) = -c^4 + 2c^3 - 3c^2 + 2c + 1, \;\; a_2(c) = c^4 - 2c^3 + 3c^2 - 2c + 2, \;\; a_3(c) = c^2 + 1,$$
$$b_1(c) = -2c^2 + 2c + 1, \;\; b_2(c) = 2c^2 - 2c + 2, \;\; b_3(c) = 1.$$

Comparing the expressions for $e^*(n)$ and $e(n, m)$ it can be verified that $e^*(n) < e(n, m)$ if and only if $G(n, m) > 0$. We therefore show that $G(n, m) > 0$ for $n, m \geq 1$ in the following steps.

(a) Clearly, $b_3(c) > 0$ for all c. Next, $b_2(c) = 2[1 - c + c^2] \geq 0$ for all $c \in [0, 1]$. We now show that $b_2(c) < 3$ for all c. Note that $b_2(c)$ is strictly convex on $[0, 1]$ since $b_2''(c) = 4$, and hence $b_2(c)$ reaches its maximum either at $c = 0$, or at $c = 1$, or at both. Since $b_2(0) = b_2(1) = 2$ we have that $b_2(c) < 3$ for all $c \in [0, 1]$. Note that $b_1(c) = 3 - b_2(c)$, and hence $b_1(c) > 0$. Therefore, for any $n \geq 1$ and $m \geq 1$, the second term of $G(n, m)$ is strictly positive.

(b) Note that $a_0(c) + a_3(c)n^3 \geq a_0(c) + a_3(c) = 1 > 0$ for $n \geq 1$. Consider now the term $a_2(c)n^2 + a_1(c)n$. Note that $a_1(c) = 3 - a_2(c)$ and $a_2(c) = c^2(1 - c)^2 + b_2(c) \geq 0$ for all $c \in [0, 1]$. Therefore, $a_2(c)n^2 + a_1(c)n = a_2(c)n(n - 1) + 3n > 0$ for $n \geq 1$. The above two together imply that the first term of $G(n, m)$ is also strictly positive for $n, m \geq 1$. This completes the proof of the proposition.

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