This work analyses a managerial delegation model in which firms choose between two production technologies: a low marginal cost technology and a high marginal cost technology. For the former to be adopted more investment is needed than for the latter. By giving managers of firms an incentive scheme based on a linear combination of profit and sales revenue, we find that Bertrand competition provides a stronger incentive to adopt the cost-saving technology than the strict profit maximisation case. However, the results may be reversed under Cournot competition. If the degree of product substitutability is sufficiently low (high), the incentive to adopt the cost-saving technology is larger under strict profit maximisation (strategic delegation).

I. Introduction

This work examines the incentives to acquire cost-saving production technologies in a managerial delegation model. We find this analysis quite relevant since, although it is generally argued that a study of a firm’s objective function should take into account the owner-manager relationship, technology choice literature usually treats firms as economic agents with the sole objective of profit maximisation (see Bester & Petrakis, 1993; Röller & Tombak, 1990).1

The type of production technology choice we describe in this work can be illustrated by using the British steam generating industry as an example (see Wield, 1985). Given the large decline in the home market, in an attempt to make the firm internationally competitive Babcock Power Ltd designed a cost-reduction program in 1980 to cut costs by 25 per cent. The implementation of this program needed a £20 million investment: £8 million on plant, £8 million on a new building and £4 million on other facilities. We set our model in this context. We assume that firms invest in the modernisation of machinery, manufacturing and assembly facilities (i.e. firms invest in the setting up of a new production plant) which reduce their manufacturing unit costs. Since we do not consider the licensing of production technologies, the investment needed to implement a new technology is assumed to be exogenous.

The literature on strategic delegation, which started with Vickers (1985), Fershtman and Judd (1987) and Sklivas (1987), examines the incentive contracts that owners of competing firms give their managers and how these incentive contracts can affect the oligopoly outcome. These works show that profit-maximising owners will turn their managers away from strict profit maximisation. Nett (1994) moves away from strict profit maximisation. He studies the reasons for different production costs between public and private firms in the context of a mixed duopoly.
maximisation for strategic reasons. In this work we study how strategic delegation contracts affect firms’ technology choices in a differentiated industry. Like Fershtman and Judd (1987), we assume that firms’ managers will be given an incentive to maximise an objective function consisting of a linear combination of profits and sales revenue.

Bester and Petrakis (1993) analyse firms’ technology choices in a differentiated industry when firms’ objective is to maximise strict profits. They focus on the choice between two types of production technology: a low marginal cost technology and a high marginal cost technology. For the former to be adopted more investment is needed than for the later. In this framework, the gains from a low-marginal-cost technology over a high-marginal-cost technology depend on how the following variables are affected: (i) the difference between price and unit cost of production (i.e. the net price), (ii) the output level and (iii) the investment needed to adopt the cost-saving technology relative to the high marginal cost technology (denoted by \( F \)). Under both price and quantity competition, the cost-saving technology leads to higher prices and output. Thus, for both price and quantity competitions we find two opposing forces. On the one hand, (i) and (ii) lead to a positive incentive to adopt the low marginal cost technology. On the other hand, (iii) leads to a negative incentive. Thus, if \( F \) is sufficiently low, (i) and (ii) together dominate (iii) and, as a result, both firms find the adoption of the cost-saving technology profitable. If \( F \) is sufficiently high, the opposite result is obtained. For intermediate values of \( F \), the net price increase and the quantity increase induced by both firms’ adoption of the low marginal cost technology are not large enough for (i) and (ii) to offset the investment amount. However, the adoption of this technology by a single firm induces both a larger net price and a larger market share for the firm that adopts the cost-saving technology large enough for (i) and (ii) to offset (iii) in that firm.

Our model takes into account the fact that delegation of production decisions has strategic effects. We consider an oligopolistic industry consisting of two firms that produce a differentiated good in which owners have to choose the incentive contracts that are offered to managers. We analyse the implications of incentive contracts within Bester and Petrakis’s (1993) context. Let us briefly explain how incentive contracts affect firms’ technology choice decisions.

It is well known that under price competition, strategic delegation leads to higher prices than strict profit maximisation (see, for example, Fershtman & Judd, 1987). As a result, the positive effect (i) is reinforced and the positive effect (ii) is, in general, weakened. We find that the incentive to adopt the low marginal cost technology is at least as large when firms’ owners delegate price decisions than in the strict profit maximisation case. That is, under strategic delegation the reinforcement of effect (i) offsets the weakening of effect (ii), whereas effect (iii) is equal in both cases. Under quantity competition results depend on market parameter values. In this case, strategic delegation leads to greater outputs than strict profit maximisation, which weakens effect (i) and reinforces effect (ii). We obtain that if the degree of product substitutability is sufficiently low (high), the incentive to adopt the cost-saving technology is larger under strict profit maximisation (strategic delegation). In this case, the weakening of effect (i) provoked by owners’ incentives to managers is more (less) powerful as the reinforcement of effect (ii). We explain this result by the fact that the larger the degree of product substitutability is, the higher the market competition is. This effect is reinforced under strategic delegation since when firms compete by setting quantities, their owners make their managers more aggressive than under strict profit maximisation, which in turn leads to greater market competition. Hence the larger incentive to acquire a cost-saving technology under strategic delegation.

Since we assume that firms are considering whether to set up a new production plant, our approach considers the investment level as exogenously determined. By contrast, Saracho (2002) assumes that there is an innovator who sets the price of the innovation. She analyzes the
adoption of cost-reducing innovations in a context of strategic delegation by considering $n$ firms that produce a homogeneous good and compete in quantities. Other works study the influence of the way in which workers are organised to bargain wages on firms’ decisions about technology choice (see Tauman & Weiss, 1987; Calabuig & Gonzalez-Maestre, 2002) and the interaction between innovation and merger policy (Gonzalez-Maestre & Peñarrubia, 2005).

There are works related with our paper which combine the technology choice literature with the literature on strategic delegation. Lambertini and Primavera (2001) analyse a model of strategic delegation with cost-reducing R&D. However, they analyse a different question that our paper: the relative profitability of delegation versus process innovation. On the other hand, Zhang and Zhang (1997) develop a model of strategic delegation with cost-reducing R&D with the possibility of spillovers across firms. They assume that the decisions on R&D correspond to firms’ managers, while in our work, since we assume that firms invest in the setting up of a new production plant, firms’ owners decide whether to adopt the cost-saving technology. They show that if spillovers between firms are small (great) enough, then managerial firms have higher (lower) R&D than the firms managed by owners. Their result, thus, depends on R&D spillovers. We consider the model by Zhang and Zhang (1997) more appropriate for those cases where firms’ managers decide the investment in R&D and our model for those cases where firms’ owners decide whether to innovate. As in our model the two owners can set up the same cost-saving technology, there are no R&D spillovers. Both Lambertini and Primavera (2001) and Zhang and Zhang (1997) works analyse the incentives to acquire cost-saving production technologies under Cournot behaviour with homogeneous goods. However, we show in our paper that the results we obtain depend on the degree in which goods are substitutes. Therefore, our model is more general since we assume product heterogeneity and we also consider Bertrand competition.

The rest of the paper is organised as follows. Section II describes the general features of a differentiated duopoly model under strategic delegation. Section III analyses the gains from cost-saving technologies under price competition and shows how strategic delegation affects firms’ decisions compared to the strict profit maximisation case. Section IV takes up the case of quantity competition. Finally, Section V contains some conclusions.

II. The Model

We consider a single industry consisting of two firms that produce a differentiated good. Before the market opens firms can choose between two different production technologies: Technology-$l$ (low-marginal-cost technology), which has constant marginal cost $c_l$ and fixed cost $F_l$ and Technology-$h$ (high-marginal-cost technology), which has constant marginal cost $c_h$ and fixed cost $F_h$, with $c_l < c_h$ and $F_l > F_h$. For the sake of simplicity we normalise $F_h$ to zero and denote $F_l = F$.

Each firm’s owner delegates quantity or price decisions to a manager in order to improve his strategic position in the market. As in Fershtman and Judd (1987), we assume that owners offer ‘take it or leave it’ linear incentive schemes to risk-neutral managers. The manager of firm $i$ ($i = 1, 2$) receives a payoff: $\beta_i + B_i O_i$, where $\beta_i$ and $B_i$ are constant, $B_i > 0$, and $O_i$ is a linear combination of profits and sales revenue. The owner selects $\beta_i$ and $B_i$ so that the manager only gets opportunity cost, which is normalised to zero. Formally, firm $i$’s manager will be given an incentive to maximise:

$$O_i = \alpha_i \Pi_i + (1 - \alpha_i)S_i,$$

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where
\[ \Pi_i = (p_i - c_i)q_i - F_i \quad \text{and} \quad S_i = p_i q_i, \quad (2) \]
represent firm \( i \)'s profit and sales revenue, respectively and \( \alpha_i \) is the incentive parameter chosen by firm \( i \)'s owner. We make no restrictions on \( \alpha_i \). From (1) and (2) we obtain:
\[ O_i = (p_i - c_i \alpha_i)q_i - \alpha_i F_i, \quad i, j = 1, 2; \quad i \neq j. \quad (3) \]

As (3) shows, firm \( i \)'s manager considers \( \alpha_i c_i \) as the marginal cost of production when taking price or quantity decisions. In this way, firm \( i \)'s owner can make the manager more (less) aggressive, i.e. he can make his manager to produce a higher (lower) output level than a profit maximiser firm by choosing an incentive parameter such that the marginal cost of production considered by the manager is lower (higher) than that considered by a profit maximiser firm.

In order to study firms' technology choice when there is strategic delegation, we consider a three stage game. In the first stage, firms' owners simultaneously choose the production technology. In the second stage, firms' owners simultaneously determine the incentive structure for their managers. Finally, in the third stage, managers play an oligopoly game, with each firm's manager knowing their incentive contract, the incentive contract of the competing manager and the nature of demand and costs. We assume the timing of the above decisions based on the fact that the production technology choice is a more long-term decision than the setting of managers’ incentives.

The state of the game in the first stage is summarized in Figure 1. We solve the game by backward induction from the last stage of the game to obtain a subgame-perfect Nash equilibrium.

![Figure 1. Summary of the game](image)

In Figure 1, \( \Pi(ll) \) denotes the profit of a firm that adopts Technology-\( l \) when both firms adopt this technology. \( \Pi(hh) \) denotes the profit of a firm that adopts Technology-\( h \) when both firms adopt this technology. When only one firm adopts the cost-saving technology, \( \Pi(h) \) denotes the profit of the firm that adopts Technology-\( l \) and \( \Pi(hl) \) denotes the profit of the firm that adopts Technology-\( h \). If a firm is indifferent between the two technologies, we assume that it chooses the cost-saving technology.

To determine whether the result of this game is robust to changes in the type of competition in which firms are involved, we determine the equilibria in different contexts.

III. Bertrand Competition

We first study the Bertrand equilibrium in which firms compete by setting prices. The demand functions of both goods are assumed to be linear:
\[ q_i = a - p_i + bp_j; \quad a > q; \quad 0 < b < 1; \quad i, j = 1, 2; \quad i \neq j. \]

where \( p_i \) and \( q_i \) are the price and the quantity of good \( i \) produced by firm \( i \), respectively.\(^2\)

\(^2\) The assumption \( a > q, a = [(2 - b^2)c_a - bc_j]/(2 + b) < c_a \) is necessary to assure that each firm's output will be positive in equilibrium.
To show how strategic delegation affects firms’ decisions, we consider first the simple profit maximisation case.

**Benchmark case: Profit-maximiser firms**

In this case we have a two stage game. In the first stage, firms’ owners simultaneously choose the production technology. And, in the second stage, owners set prices.

In stage two, firm $i$’s owner chooses $p_i$ to maximise $\Pi_i$ taking the competitor’s price, $p_j$, as fixed. This problem leads to the following solution:

\[ \hat{p}_i = \frac{a(2+b) + 2c_i + bc_i}{4 - b^2}; \quad i, j = 1, 2; \quad i \neq j. \]  \hspace{1cm} (4)

In the first stage, firms’ owners simultaneously choose the production technology. Firms’ profits and prices are relegated to the appendix.

It can be seen from (4) that $\frac{\partial \hat{p}_i}{\partial c_i} > 0$ and $\frac{\partial \hat{p}_i}{\partial c_j} > 0$. Therefore, the marginal cost reduction on both firms induces firm $i$ to behave more aggressively (i.e. to set a lower price). As a result, we have $p(hh) > p(hl) > p(ll)$. That is, when both firms adopt Technology-$l$ the equilibrium price is lowest while if both firms adopt Technology-$h$ the equilibrium price is highest. We obtain intermediate prices when only one firm adopts the cost-saving technology, with the firm with the lowest marginal cost being the one that chooses the lowest price.

On the other hand, as (2) shows, the gains from a marginal cost reduction depend on how the following variables are affected: (i) the difference between price and marginal cost, i.e. the net price (denoted as $p^*$), (ii) the output level and (iii) the investment needed to acquire the cost-saving technology. We can easily see that $p(ll) > p(hl) > p(hh) > p(ll)$. Consequently, when analysing the technology choice under price competition, we find two opposing forces: on the one hand, (i) and (ii) lead to a positive incentive to adopt Technology-$l$, and on the other hand (iii) leads to a negative incentive. Solving the first stage of the game we obtain the following result. Let:

\[ F_l^p = \frac{(2 - b^2)(c_h - c_i)(2a(2+b) - (2 - b^2)(c_h + c_i) + 2bc_h)}{(4 - b^2)^2}, \]
\[ F_h^p = \frac{(2 - b^2)(c_h - c_i)(2a(2+b) - (2 - b^2)(c_h + c_i) + 2bc_i)}{(4 - b^2)^2}, \]

where $F_l^p$ and $F_h^p$ $(F_l^p < F_h^p)$ are the investment levels such that $\Pi(ll) = \Pi(hh)$ and $\Pi(hl) = \Pi(ll)$, respectively.

**Lemma 1** When firms owners do not delegate price decisions, in equilibrium:

i) Both firms choose the low-marginal-cost technology if $F \leq F_l^p$.

ii) Only one firm chooses the low-marginal-cost technology if $F_l^p < F \leq F_l^p$.

iii) Both firms choose the high-marginal-cost technology if $F > F_l^p$.

If the adoption of Technology-$l$ does not require any investment $F$, then $\Pi(ll) > \Pi(hh) > \Pi(hl)$. This reflects the positive incentive to adopt Technology-$l$ caused by both (i) and (ii). This incentive is larger if the other firm does not adopt this technology. But since in our model the adoption of Technology-$l$ requires an investment, different investment levels will produce

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3 The same result is given by Proposition 1 in Bester and Petrakis (1993).

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Equilibrium under strategic delegation

When firms’ owners hire managers to take price decisions, we have a three stage game. In the first stage, owners simultaneously choose the production technology. In the second stage, owners simultaneously determine the incentive structure for their managers. Finally, in the third stage, managers take price decisions. The objective function of firm \( i \)'s manager can be written as:

\[
O_i = (p_i - c_i \alpha_i) (a - p_i + bp_i) - \alpha_i F_i; \quad i, j = 1, 2; \quad i \neq j.
\]

In stage three, firm \( i \)'s manager chooses \( p_i \) to maximise \( O_i \), taking the competitor’s price, \( p_j \), as fixed. The reaction functions derived from the above maximisation problem are:

\[
p_i = \frac{a + bp_j + c_i \alpha_i}{2}; \quad i, j = 1, 2; \quad i \neq j.
\]

Which can be solved for the equilibrium prices:

\[
\hat{p}_i = \frac{a(2 + b) + 2c_i \alpha_i + bc_j \alpha_j}{4 - b^2}; \quad i, j = 1, 2; \quad i \neq j.
\] (5)

In the second stage, firm \( i \)'s owner chooses the incentive parameter of their manager, \( \alpha_i \), that maximises the firm’s profit, taking the competitor’s incentive parameter, \( \alpha_j \), as fixed. Solving this problem we obtain the equilibrium incentive parameters:

\[
\hat{\alpha}_i = 1 + \frac{b^2(a(4 + 2b - b^2) - (4 - 3b^2)c_i + b(2 - b^2)c_j)}{(16 - 12b^2 + b^4)c_i}; \quad i, j = 1, 2; \quad i \neq j.
\]

We can check that \( \partial \hat{\alpha}_i / \partial c_i < 0 \) and \( \partial \hat{\alpha}_j / \partial c_j > 0 \). Therefore, a marginal cost reduction in firm \( i \) (\( j \)) induces firm \( i \) to behave less (more) aggressively. Moreover, as \( |\partial \hat{\alpha}_i / \partial c_i| > |\partial \hat{\alpha}_j / \partial c_j| \), a reduction in both firms’ marginal cost makes firm \( i \)'s manager less aggressive. Consequently, \( \alpha(hh) > \alpha(ll) > \alpha(hl) \). If only one firm adopts Technology-\( l \) the equilibrium incentive is greater for the firm that adopts Technology-\( l \) and smaller for the firm that adopts Technology-\( h \). While we obtain intermediate values for the incentive parameter if both firms adopt Technology-\( h \) or neither firm adopts it with \( \alpha(ll) > \alpha(hh) \). Note that \( \hat{\alpha}_i > 1 \). Then, firm \( i \)'s manager considers a higher marginal cost of production than that considered by a profit-maximiser firm. Therefore, firm \( i \)'s owner makes the manager less aggressive (i.e. he makes the manager set a larger price) than a profit-maximiser firm.

Let subscript \( d \) denote the strategic delegation case. It is straightforward from (5) that \( \hat{p}_i \) increases with both \( \alpha_i \) and \( \alpha_j \). As a result, we have that \( p(hh)_d > p(hl)_d > p(ll)_d \) and therefore there exists a negative strategic incentive to adopt Technology-\( l \). Although strategic delegation leads to equilibrium prices which are higher than those corresponding to the strict profit maximisation case: \( p(hh)_d > p(hh), p(hl)_d > p(hl), p(ll)_d > p(ll) \) and \( p(ll)_d > p(ll) \).
To study which effect dominates, we solve the first stage of the game in which firms’ owners simultaneously choose the production technology. Firms’ profits, prices and incentive parameters are relegated to the appendix.

The first stage of the game leads to the following result. Let:

\[ F_{id}^p = \frac{2(2 - b^2)(4 - 3b^2)(c_h - c_l)(2a(4 + 2b - b^2) - (4 - 3b^2)(c_h + c_l) + 2b(2 - b^2)c_h)}{(16 - 12b^2 + b^4)^2}, \]
\[ F_{ld}^p = \frac{2(2 - b^2)(4 - 3b^2)(c_h - c_l)(2a(4 + 2b - b^2) - (4 - 3b^2)(c_h + c_l) + 2b(2 - b^2)c_l)}{(16 - 12b^2 + b^4)^2}, \]

where \( F_{id}^p \) and \( F_{ld}^p \) are the investment levels such that \( \Pi(\text{lh}) = \Pi(\text{hh}) \) and \( \Pi(\text{hl}) = \Pi(\text{ll}) \), respectively.

**Lemma 2** When firms’ owners delegate price decisions, in equilibrium:

i) Both firms choose the low-marginal-cost technology if \( F \leq F_{ld}^p \).

ii) Only one firm chooses the low-marginal-cost technology if \( F_{ld}^p < F \leq F_{id}^p \).

iii) Both firms choose the high-marginal-cost technology if \( F > F_{id}^p \).

If the adoption of Technology-\( l \) does not require any investment \( F \), then \( \Pi(\text{ll}) > \Pi(\text{lh}) > \Pi(\text{hh}) > \Pi(\text{ll}) \). This reflects the positive incentive to adopt this technology caused by both (i) and (ii). But since in our model the adoption of Technology-\( l \) requires an investment, different investment levels will produce different results in equilibrium. In fact, if \( F \) is sufficiently low (\( F \leq F_{ld}^p \)), (i) and (ii) together dominate (iii) and, as a result, both firms find the adoption of Technology-\( l \) profitable. The same argument used in Lemma 1 justifies the fact that for intermediate values of \( F \) (\( F_{ld}^p < F \leq F_{id}^p \)) only one firm adopts Technology-\( l \). Finally, if \( F \) is sufficiently high (\( F > F_{id}^p \)), (iii) dominates (i) and (ii) together and, as a result, neither firm finds the adoption of Technology-\( l \) profitable.

**Results**

To show how strategic delegation affects firms’ decisions about technology choice, we compare the results obtained under strict profit maximisation and strategic delegation.

Let \( \tilde{a} \) be defined in the appendix with \( \tilde{a} \) being the value of parameter \( a \) such that \( F_{id}^p = F_{ld}^p \).

Comparing Lemmas 1 and 2 we can see the following.

**Lemma 3** If \( \tilde{a} > c_h \) then \( F_{id}^p > F_{ld}^p \geq F_{il}^p > F_{ll}^p \) whenever \( a \geq \tilde{a} \) and \( F_{id}^p > F_{il}^p > F_{ld}^p > F_{ll}^p \) whenever \( a < \tilde{a} \). If \( \tilde{a} < c_l \) then \( F_{id}^p > F_{ld}^p \geq F_{il}^p > F_{ll}^p \).

Thus, from Lemmas 1 to 3 we obtain the following result.

**Proposition 1** Under price competition, the incentive to adopt the cost-saving technology is at least as great when firms’ owners delegate price decisions as in the strict profit maximisation case.

The result obtained in Proposition 1 is illustrated in Figures 2 and 3. More adoption of Technology-\( l \) is attained under strategic delegation than under strict profit maximisation in the following cases: i) when \( a > \tilde{a} \), if \( F_{id}^p < F < F_{ld}^p \) and ii) when \( a < \tilde{a} \), if \( F_{id}^p < F < F_{ld}^p \) or \( F_{il}^p < F < F_{ld}^p \). Note that if \( a > \tilde{a} \) and \( F_{id}^p < F < F_{ld}^p \), both firms adopt Technology-\( l \) under strategic delegation while neither firm adopts it under strict profit maximisation. In all other cases, one firm adopts Technology-\( l \) under strategic delegation while neither firm adopts it under strict profit maximisation.

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4 Let \( p_h^* \) denote the net price. We can easily see that \( p(lh)^* > p(ll)^* > p(hh)^* > p(hl)^* \) and \( q(lh)_d > q(ll)_d > q(hh)_d > q(hl)_d \).

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The maximum investment level for which both firms adopt Technology-$l$ is higher under strategic delegation than under strict profit maximisation, i.e. $F_{ld}^p > F_{ld}^s$. And the larger the market size, $a$, the larger the difference between $F_{ld}^p$ and $F_{ld}^s$. As a result, the range of values of parameter $F$ for which $(ll)$ is an equilibrium is larger under strategic delegation than under strict profit maximisation. Moreover, the larger the market size, the larger this difference. On the other hand, the minimum investment level for which both firms adopt Technology-$h$ is higher under strategic delegation, i.e. $F_{hd}^p > F_{hd}^s$. And the larger the market size, the larger the difference between $F_{hd}^p$ and $F_{hd}^s$. As a result, the range of values of parameter $F$ for which $(hh)$ is an equilibrium is smaller under strategic delegation than under strict profit maximisation. Moreover, the larger the market size, the larger this difference. We can also see that $(F_{ld}^p - F_{hd}^p) > (F_{ld}^s - F_{hd}^s)$. Therefore, the
range of values of \( F \) for which \((hl)\) is an equilibrium is smaller under strategic delegation. However, for the values of \( F \) for which only one firm adopts Technology-\( l \) under strict profit maximisation, at least one firm adopts this technology under strategic delegation. Hence, we conclude that the incentive to adopt the cost-saving technology under strategic delegation is at least as great as under strict profit maximisation.

We find various reasons for the preceding results. On the one hand, under price competition, strategic delegation leads to higher prices than with that of the competing firm. As a result, we have that output will be positive in equilibrium.

Inverse demand functions of both goods are assumed to be linear:

\[
p_i = a - q_i - bq_i; \quad a > \bar{a}; \quad 0 < b < 1; \quad i, j = 1, 2; \quad i \neq j,
\]

where \( p_i \) and \( q_i \) are the price and the quantity of good \( i \) produced by firm \( i \), respectively.\(^6\)

To show how strategic delegation affects firms’ decisions, we first consider the simple profit maximisation case.

**Benchmark case: Profit-maximiser firms**

In stage two, firm \( i \)'s owner chooses \( q_i \) to maximise \( \Pi \), taking the competitor’s quantity, \( q_j \), as fixed. This problem leads to the following solution:

\[
\hat{q}_i = \frac{a(2 - b) - 2c_i + bc_i}{4 - b^2}; \quad i, j = 1, 2; \quad i \neq j. \tag{6}
\]

In the first stage, firms’ owners simultaneously choose the production technology. Firms’ profits and quantities are relegated to the appendix.

We can see from (6) that \( \partial \hat{q}_i / \partial c_i < 0 \) and \( \partial \hat{q}_i / \partial c_i > 0 \). Therefore, a marginal cost reduction in firm \( i \) (\( j \)) induces firm \( i \) to behave more (less) aggressively, i.e. to produce a larger (smaller) quantity. Moreover, as \( |\partial \hat{q}_i / \partial c_i| > |\partial \hat{q}_j / \partial c_j| \), firm \( i \)'s output changes more with its own marginal cost than with that of the competing firm. As a result, we have that \( q(hl) > q(ll) > q(hh) > q(hl) \). Thus, the highest output level corresponds to a firm that adopts Technology-\( l \) when the other firm adopts Technology-\( h \), while the lowest output level corresponds to a firm that adopts Technology-\( h \) when the other firm adopts Technology-\( l \). Then, firm \( i \)'s marginal cost reduction is strategically advantageous for firm \( i \) and quantity competition thus creates a positive strategic incentive to adopt the cost-saving technology.

\(^5\) \( q(hl)_a < q(hl) \) if and only if \( a > a^* \), where \( a^* = [2(2 - 8b^2 - b^4) + b^4] / (8 - 8b^2 - b^4 + b^4) > c_\alpha \).

\(^6\) The assumption \( a > \bar{a}, \bar{a} = [(4 - b^2)c_i - 2bc_i] / (4 - 2b - b^2) > c_\alpha \), is necessary to assure that each firm’s output will be positive in equilibrium.
Solving the first stage of the game we obtain the following result. Let:

\[ F_1^q = \frac{4(c_h - c_i)(a(2 - b) - (c_h + c_i) + bc_h)}{(4 - b^2)^2} \]

\[ F_2^q = \frac{4(c_h - c_i)(a(2 - b) - (c_h + c_i) + bc_i)}{(4 - b^2)^2} \]

where \( F_1^q \) and \( F_2^q \) (\( F_2^q < F_1^q \)) are the investment levels such that \( \Pi(hh) = \Pi(hl) \) and \( \Pi(ll) = \Pi(ll) \), respectively.

**Lemma 4** When firms owners do not delegate production decisions, in equilibrium:

i) Both firms choose the low-marginal-cost technology if \( F \leq F_2^q \).

ii) Only one firm chooses the low-marginal-cost technology if \( F_2^q < F \leq F_1^q \).

iii) Both firms choose the high-marginal-cost technology if \( F > F_1^q \).

If the adoption of Technology-\( l \) does not require any investment \( F \), then \( \Pi(hh) > \Pi(ll) > \Pi(hl) \). This reflects the positive incentive to adopt Technology-\( l \) caused by both (i) and (ii). However, the adoption of Technology-\( l \) requires an investment \( F \). If \( F \) is sufficiently low (\( F \leq F_2^q \)), (i) and (ii) together dominate (iii) and, as a result, both firms find the adoption of Technology-\( l \) profitable. If \( F \) is sufficiently high (\( F > F_1^q \)), the oposed result is obtained. For intermediate values of \( F \) (\( F_2^q < F \leq F_1^q \)), the adoption of the cost-saving technology by a single firm induces a higher net price and a larger market share for the firm that adopts this technology, at the expense of the other firm’s net price and market share, which is large enough for (i) and (ii) to offset (iii) in the firm that adopts Technology-\( l \). As a result, only one firm adopts the cost-saving technology.

**Equilibrium under strategic delegation**

The objective function of firm \( i \)'s manager can be written as:

\[ O_i = (a - q_i - bq_j - c_i\alpha_i)q_i - \alpha_i F_i; \quad i, j = 1, 2; \quad i \neq j. \]

In stage three, firm \( i \)'s manager chooses \( q_i \) to maximise \( O_i \), taking the competitor’s output, \( q_j \), as fixed. The reaction functions derived from the above maximisation problem are:

\[ q_i = \frac{a - bq_j - c_i\alpha_i}{2}; \quad i, j = 1, 2; \quad i \neq j. \]

Which can be solved for the equilibrium quantities:

\[ \hat{q}_i = \frac{a(2 - b) - 2c_i\alpha_i + bc_i\alpha_j}{4 - b^2}; \quad i, j = 1, 2; \quad i \neq j. \] (7)

In the second stage, firm \( i \)' owner chooses the incentive parameter of his manager, \( \alpha_i \), that maximises the firm’s profit, taking the competitor’s incentive parameter, \( \alpha_j \), as fixed. Solving this problem we obtain the equilibrium incentive parameters:

\[ \hat{\alpha}_i = 1 - \frac{b^2(a(4 - 2b - b^2) + 2bc_j - (4 - b^2)c_i)}{(16 - 12b^2 + b^4)c_i}; \quad i, j = 1, 2; \quad i \neq j. \]

---

7 The same result is given by Proposition 1 in Bester and Petrakis (1993).

8 We can easily see that \( p(hh)^* > p(ll)^* > p(hl)^* \) and \( q(hh) > q(ll) > q(hl) \).
We can check that $\partial \hat{\alpha}_i/\partial c_j > 0$ and $\partial \hat{\alpha}_i/\partial c_j < 0$, with $|\partial \hat{\alpha}_i/\partial c_j| > |\partial \hat{\alpha}_i/\partial c_j|$. Consequently, $\alpha(ll) < \alpha(hh) < \alpha(hl)$. Therefore, if only one firm adopts Technology-$l$ the equilibrium incentive is smaller for the firm that adopts Technology-$l$ and larger for the firm that adopts Technology-$h$. Note that $\hat{\alpha}_i < 1$. Then, firm $i$’s owner makes his manager more aggressive than a profit-maximiser firm.

From (7) we have that $\partial \hat{\alpha}_a/\partial a < 0$ and $\partial \hat{\alpha}_a/\partial a > 0$, being $|\partial \hat{\alpha}_a/\partial a| > |\partial \hat{\alpha}_a/\partial a|$. We have also seen that $\alpha(ll) < \alpha(hh) < \alpha(hl)$. As a result, we have that $q(ll) > q(hh) > q(hl)$, and therefore, there exists a positive strategic incentive to adopt Technology-$l$. Moreover, under strategic delegation equilibrium quantities are higher than those under strict profit maximisation: $q(ll) > q(hh) > q(hl)$, $q(ll)_d > q(hl)_d$ and $p(ll)* > p(hh)* > p(hl)*$. To study which effect dominates, we solve the first stage of the game, in which firms’ owners simultaneously choose the production technology. Firms’ profits, prices and incentive parameters are relegated to the appendix. The first stage of the game leads to the following result. Let:

$$F_{1d}^h = \frac{2(2 - b)(2 + b)(2 - b^2)(c_h - c_l)(a(8 - 4b - 2b^2) - (4 - b^2)(c_l + c_h) + 4bc_l)}{(16 - 12b^2 + b^4)^2},$$

$$F_{2d}^h = \frac{2(2 - b)(2 + b)(2 - b^2)(c_h - c_l)(a(8 - 4b - 2b^2) - (4 - b^2)(c_l + c_h) + 4bc_l)}{(16 - 12b^2 + b^4)^2},$$

where $F_{1d}^h$ and $F_{2d}^h$ are the investment levels such that $\Pi(ll) = \Pi(hh)$ and $\Pi(hl) = \Pi(ll)$, respectively.

**Lemma 5** When firms owners delegate production decisions, in equilibrium:

i) Both firms choose the low-marginal-cost technology if $F \leq F_{2d}^h$.

ii) Only one firm chooses the low-marginal-cost technology if $F_{1d}^h < F \leq F_{2d}^h$.

iii) Both firms choose the high-marginal-cost technology if $F > F_{1d}^h$.

If the adoption of Technology-$l$ does not require any investment $F$, $\Pi(ll)_d > \Pi(ll)_d > \Pi(hh)_d > \Pi(hl)_d$. This reflects the positive incentive to adopt Technology-$l$ caused by both (i) and (ii); (iii) leads to a negative incentive. In fact, if $F$ is sufficiently low ($F \leq F_{2d}^h$), (i) and (ii) together dominate (iii) and, as a result, both firms find the adoption of Technology-$l$ profitable. If $F$ is sufficiently high ($F > F_{1d}^h$), the opposed result is obtained. The same argument used in Lemma 4 justifies the fact that for intermediate values of $F$ ($F_{2d}^h < F \leq F_{1d}^h$) only one firm adopts Technology-$l$.

**Results**

Now we compare the results obtained under strict profit maximisation and strategic delegation.

Let $\bar{b} = 0.8466$ and $a_1, a_2, a_3$ and $a_4$ defined in the appendix, with $\bar{b}$ being the value of parameter $b$ such that the slopes of functions $F_{1d}^h$, $F_{2d}^h$, $F_{1d}^h$ and $F_{2d}^h$ are equal and $a_1, a_2, a_3$ and $a_4$ the values of parameter $a$ such that $F_{1d}^h = F_{1d}^h$, $F_{2d}^h = F_{1d}^h$, $F_{1d}^h = F_{2d}^h$ and $F_{1d}^h = F_{2d}^h$, respectively. Comparing Lemmas 4 and 5 we obtain the following result, which is illustrated by Figures 4 and 5.

**Lemma 6** If $b < \bar{b}$, then $F_{1d}^h > F_{2d}^h > F_{1d}^h > F_{2d}^h$ when $a \geq a_2$, $F_{1d}^h > F_{2d}^h > F_{1d}^h > F_{2d}^h$ when $a_1 < a < a_2$ and $F_{1d}^h > F_{2d}^h > F_{1d}^h > F_{2d}^h$ when $a_1 < a < a_2$ and $F_{1d}^h > F_{2d}^h > F_{1d}^h > F_{2d}^h$ when $a \leq a_1$. If $b = \bar{b}$, then $F_{1d}^h > F_{1d}^h > F_{2d}^h > F_{2d}^h$ for all $a$. Finally, if $b > \bar{b}$, then $F_{1d}^h > F_{2d}^h > F_{1d}^h > F_{2d}^h$ when $a \geq a_4$, $F_{1d}^h > F_{1d}^h > F_{1d}^h > F_{2d}^h$ when $a_3 < a < a_4$ and $F_{1d}^h > F_{1d}^h > F_{2d}^h > F_{2d}^h$ when $a \leq a_3$.

Thus, from Lemmas 4 to 6 we can verify the following result.
**Proposition 2** Under quantity competition, the incentive to adopt the cost-saving technology is at least as large when firms' owners delegate production decisions as under strict profit maximisation in the following cases: i) if \( b < \bar{b} \) and \( F_{1d}^i < F < F_{1d}^T \) and ii) if \( b \geq \bar{b} \) with the exception of the case \( F_{2d}^i < F < F_{2d}^T \). In all other cases the incentive to adopt the cost-saving technology is strictly smaller when firms' owners delegate production decisions than under strict profit maximisation.

The result obtained in Proposition 2 is illustrated in Figures 4 and 5.

![Figure 4](image-url) Cournot competition: \( b < \bar{b} \)

![Figure 5](image-url) Cournot competition: \( b > \bar{b} \)

We find a number of reasons for the result obtained in Proposition 2. On the one hand, strategic delegation leads to lower prices than strict profit maximisation. As a result, when owners delegate quantity decisions, positive effect (i) is weakened. On the other hand, it can be demonstrated that \( q(hl)_d > q(hl) \) for a market size, \( a \), sufficiently large\(^9\) while \( q(hh)_d > q(hh) \), \( q(ll)_d > q(ll) \) and

\[ q(hl)_d > q(hl) \text{ if and only if } a > a^{**}, \text{ where } a^{**} = \frac{8c_h - b(8 - b^2)c_l}{(8 - 8b^2 + b^3)} > \bar{a}. \]

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\( q(lh)_a > q(lh) \) for all \( a \). Consequently, when owners delegate quantity decisions, positive effect (ii) is, in general, reinforced. However, depending on the parameter values, the weakening of effect (i) may be more/less powerful than the reinforcement of effect (ii). It can be shown that \( \partial F_i^a / \partial a > 0, \partial F_i^a / \partial b > 0, \partial^2 F_i^a / \partial a \partial b > 0 \) and \( \partial^2 F_i^a / \partial a \partial b > 0 \) for \( i = 1, 2 \). As a result, both \( F_i^a \) and \( F_i^b \) increase with \( a \). However, the larger the degree of product substitutability, the smaller (larger) the increase that \( a \) provokes in \( F_i^a (F_i^b) \). We can explain this result by the fact that the larger the degree of product substitutability is (i.e. the larger the value of parameter \( b \)), the higher the market competition will be. Consequently, for a given value of parameter \( a \), the larger the value of parameter \( b \), the smaller the firms’ profits. This last effect is reinforced under strategic delegation: under quantity competition firms’ owners make their managers more aggressive than under strict profit maximisation, which in turn leads to a higher level of market competition. As a result, when products are highly differentiated \( (b < \bar{b}) \), then \( \partial F_i^a / \partial a > \partial F_i^b / \partial a \) for \( i = 1, 2 \). By contrast, when products are close substitutes \( (b > \bar{b}) \) we have that \( \partial F_i^a / \partial a < \partial F_i^b / \partial a \) for \( i = 1, 2 \). This is illustrated by the slopes of functions \( F_i^a \) and \( F_i^b \) in Figures 4 and 5. Let us analyse these results in more detail.

If the degree of product substitutability is sufficiently low \( (b < \bar{b}) \), we find that \( F_2^a > F_{2d}^a \) for all \( a \). As a result, the range of values of \( F \) and \( a \) for which both firms adopt Technology-\( l \) is larger under strict profit maximisation than that under strategic delegation (see Figure 4). It can also be shown that \( F_1^a > F_{1d}^a \) if and only if \( a > a_1 \). Consequently, for a sufficiently large market size, the range of values of \( F \) and \( a \) for which neither firm adopts Technology-\( l \) is smaller under strict profit maximisation. The opposing result is obtained for \( a < a_1 \). However, as Figure 4 shows, the area for which both firms adopt Technology-\( h \) is larger under strategic delegation. Moreover, since \( (F_2^a - F_{2d}^a) > (F_1^a - F_{1d}^a) \), the range of values of \( F \) and \( a \) for which only one firm adopts Technology-\( l \) is larger under strategic delegation. Lastly, the only range of values for which more adoption of Technology-\( l \) is attained under strategic delegation than under strict profit maximisation is given by \( a < a_1 \) and \( F_1^a < F < F_{1d}^a \) (under strategic delegation one firm adopts Technology-\( l \) while under strict profit maximisation both firms adopt Technology-\( h \)). However, as Figure 4 shows, this last area is smaller than the sum of areas in which more adoption of Technology-\( l \) is attained under strict profit maximisation. As a result, we can conclude that when the degree of product substitutability is sufficiently low the incentive to adopt the cost-saving technology is at least as large when firms owners do not delegate production decisions as when they do.

If the degree of product substitutability is sufficiently high \( (b > \bar{b}) \), we find that \( F_1^a > F_{1d}^a \) for all \( a \). As a result, the range of values of \( F \) and \( a \) for which neither firm adopts Technology-\( l \) is larger under strict profit maximisation than that under strategic delegation (see Figure 5). It can also be shown that \( F_{2d}^a > F_2^a \) if and only if \( a > a_2 \). Consequently, for a sufficiently large market size, the range of values of \( F \) and \( a \) for which both firms adopt Technology-\( l \) is larger under strategic delegation. The opposing result is obtained for \( a < a_2 \). However, as Figure 5 shows, the area for which both firms adopt Technology-\( l \) is larger under strategic delegation. Moreover, since \( (F_{1d}^a - F_{2d}^a) > (F_1^a - F_{2d}^a) \), the range of values of \( F \) and \( a \) for which only one firm adopts Technology-\( l \) is larger under strategic delegation. Lastly, the only range of values for which Technology-\( l \) is attained less under strategic delegation than under strict profit maximisation is given by \( a < a_2 \) and \( F_{2d}^a < F < F_{1d}^a \) (under strategic delegation one firm adopts Technology-\( l \) while under strict profit maximisation both firms adopt Technology-\( l \)). However, as Figure 5 shows, this last area is smaller than the sum of areas in which Technology-\( l \) is attained more under strategic delegation. As a result we can conclude that when the degree of product substitutability is sufficiently high, the incentive to adopt the cost-saving technology is at least as large when firms owners delegate production decisions as in strict profit maximisation.

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If \( b = \bar{b} \), then \( F_{1d}^a > F_{1d}^h > F_{2d}^h > F_{1d}^q \) for all \( a \). Thus, if \( F_{1d}^h < F < F_{1d}^q \), the incentive to adopt Technology-\( l \) is larger under strategic delegation while if \( F_{1d}^q < F < F_{2d}^h \), the incentive to adopt Technology-\( l \) is larger under strict profit maximisation.

V. Conclusions

This work analyses how strategic incentives may play a fundamental role in firms’ decisions to adopt cost-saving technologies in a context of duopolistic competition. The results suggest that it may be important to take into account the incentive scheme that profit-maximising owners design for their managers. These incentives imply that managers’ objective functions differ from strict profit maximisation.

We identify three different effects that determine the effectiveness of a cost-saving technology adoption. First, equilibrium net prices increase when firms’ production marginal costs are lower. Second, equilibrium outputs increase when firms’ production marginal costs are lower. We find that these two effects lead to a positive incentive to adopt the cost-saving technology. Third, the investment needed to acquire a low marginal cost technology is larger than for a high-marginal-cost technology. This last effect weakens the incentive to adopt the cost-saving technology.

In this work we determine conditions under which firms are more inclined to adopt cost-saving technologies and find that these conditions depend on the type of market competition in which firms are involved. Comparing the results obtained under strict profit maximisation and strategic delegation yields to the following. Under price competition, the incentive to adopt the cost-saving technology is at least as large when firms owners delegate price decisions as in the case of strict profit maximisation. However, under quantity competition the results depend on the values of the market parameters. More precisely, the degree of product substitutability plays an important role in this result. We show that if the degree of product substitutability is sufficiently low the incentive to adopt the cost-saving technology is larger under strict profit maximisation than under strategic delegation. By contrast, when products are perceived by consumers as being close substitutes, the incentive to adopt the cost-saving technology is larger under strategic delegation.

Appendix

Price competition under strict profit maximisation:

\[
\begin{align*}
\pi(ll) &= \frac{(a - c_l)^2}{(2 + b)^2} - F, \\
\pi(hl) &= \frac{(a(2 - b) - 2c_l + bc_h)^2}{(4 - b^2)^2} - F, \\
\pi(hh) &= \frac{(a - c_h)^2}{(2 + b)^2}, \\
q(ll) &= \frac{a - c_l}{2 + b}, \\
q(hl) &= \frac{a - c_l - 2c_h + bc_h}{4 - b^2}, \\
q(hh) &= \frac{a - c_h}{2 + b}.
\end{align*}
\]

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Price competition under strategic delegation:

\[
\pi(ll) = \frac{2(2 - b^2)(a - (1 - b)c_i)^2}{(4 - 2b - b^2)^2} - F,
\]

\[
\pi(lh) = \frac{2(2 - b^2)(a(4 + 2b - b^2) - (4 - 3b^2)c_i + b(2 - b^2)c_h)^2}{(16 - 12b^2 + b^4)^2} - F,
\]

\[
\pi(hl) = \frac{2(2 - b^2)(a(4 + 2b - b^2) - (4 - 3b^2)c_h + b(2 - b^2)c_i)^2}{(16 - 12b^2 + b^4)^2},
\]

\[
\pi(hh) = \frac{2(2 - b^2)(a - (1 - b)c_i)^2}{(4 - 2b - b^2)^2}, \quad p(ll) = \frac{2a + (2 - b^2)c_i}{4 - 2b - b^2},
\]

\[
p(lh) = \frac{2a(4 + 2b - b^2) + (2 - b^2)(2bc_h + (4 - b^2)c_i)}{16 - 12b^2 + b^4},
\]

\[
p(hl) = \frac{2a(4 + 2b - b^2) + (2 - b^2)(2bc_i + (4 - b^2)c_h)}{16 - 12b^2 + b^4},
\]

\[
p(hh) = \frac{2a + (2 - b^2)c_i}{4 - 2b - b^2}, \quad \alpha(ll) = \frac{ab^2 + (2 - b)(2 - b^2)c_i}{(4 - 2b - b^2)c_i},
\]

\[
\alpha(lh) = \frac{ab^2(4 + 2b - b^2) + (2 - b^2)(4(2 - b^2)c_i + b^3c_h)}{(16 - 12b^2 + b^4)c_i},
\]

\[
\alpha(hl) = \frac{ab^2(4 + 2b - b^2) + (2 - b^2)(4(2 - b^2)c_h + b^3c_i)}{(16 - 12b^2 + b^4)c_h},
\]

\[
\alpha(hh) = \frac{ab^2 + (2 - b)(2 - b^2)c_h}{(4 - 2b - b^2)c_h}.
\]

Quantity competition under strict profit maximisation:

\[
\pi(ll) = \frac{(a - c_i)^2}{(2 + b)^2} - F, \quad p(ll) = \frac{(a - c_i)(2 - b) - 2c_i + bc_i}{(4 - b^2)^2} - F,
\]

\[
\pi(lh) = \frac{(a(2 - b) - 2c_h + bc_i)^2}{(4 - b^2)^2}, \quad p(hh) = \frac{(a - c_h)^2}{(2 + b)^2},
\]

\[
q(ll) = \frac{a - c_i}{2 + b}, \quad q(lh) = \frac{a(2 - b) - 2c_i + bc_h}{4 - b^2},
\]

\[
q(hl) = \frac{a(2 - b) - 2c_h + bc_i}{4 - b^2}, \quad q(hh) = \frac{a - c_h}{2 + b}.
\]

Quantity competition under strategic delegation:

\[
\pi(ll) = \frac{2(2 - b^2)(a - c_i)^2}{(4 + 2b - b^2)^2} - F,
\]

\[
\pi(lh) = \frac{2(2 - b^2)(a(4 - 2b - b^2) - (4 - b^2)c_i + 2bc_h)^2}{(16 - 12b^2 + b^4)^2} - F,
\]

© Blackwell Publishing Ltd/University of Adelaide and Flinders University 2006.
\[ \pi(hl) = \frac{2(2 - b^2)(a(4 - 2b - b^2) - (4 - b^2)c_h + 2bc_i)^2}{(16 - 12b^2 + b^4)^2}, \]
\[ \pi(hh) = \frac{2(2 - b^2)(a - c_i)^2}{(4 + 2b - b^2)^2}, \]
\[ q(ll) = \frac{2a(4 - 2b - b^2) - 2(4 - b^2)c_i + 4bc_h}{16 - 12b^2 + b^4}, \]
\[ q(hl) = \frac{2a(4 - 2b - b^2) - 2(4 - b^2)c_h + 4bc_i}{16 - 12b^2 + b^4}, \]
\[ q(hh) = \frac{2(a - c_i)}{4 + 2b - b^2}, \]
\[ \alpha(l) = \frac{2(2 + b)c_i - ab^2}{(4 + (2 - b)b)c_i}, \]
\[ \alpha(hl) = \frac{2(4(2 - b^2)c_i - b^3c_h) - ab^2(4 - 2b - b^2)}{(16 - 12b^2 + b^4)c_i}, \]
\[ \alpha(hl) = \frac{2(4(2 - b^2)c_h - b^3c_i) - ab^2(4 - 2b - b^2)}{(16 - 12b^2 + b^4)c_h}, \]
\[ \alpha(hh) = \frac{2(2 + b)c_h - ab^2}{(4 + (2 - b)b)c_h}. \]

Critic values of parameter \( a \):

\[ a = ((512 - 896b^2 + 32b^3 + 544b^4 - 32b^5 - 136b^6 + 8b^7 + 2b^8 - b^9)c_i -
(512 - 768b^2 - 32b^3 + 352b^4 + 32b^5 - 48b^6 - 8b^7 + 2b^8 + b^9)c_h)/
(2b^3 - 4b^2 - 4b + 8)(2 + b)(b^2 - 2b - 4b^2), \]
\[ a_1 = ((128 - 96b - 64b^3 + 80b^3 - 8b^4 - 16b^5 + 2b^6 + b^7)c_h -
(96b - 80b^3 + 16b^5 - b^7)c_i)/(2 - b)(4 - 2b - b^2)(8 - 4b - 8b^2 + b^3 + b^4), \]
\[ a_2 = ((512 - 640b^2 - 96b^3 + 288b^4 + 80b^5 - 56b^6 - 16b^7 + 4b^8 + b^9)c_h -
(512 - 768b^2 + 96b^3 + 352b^4 - 80b^5 - 48b^6 + 16b^7 + 2b^8 - b^9)c_i)/
(2b^2(2 - b) (4 - 2b - b^2) (8 - 4b - 8b^2 + b^3 + b^4)), \]
\[ a_3 = ((128 - 96b - 64b^3 + 80b^3 - 8b^4 - 16b^5 + 2b^6 + b^7)c_i -
(96b - 80b^3 + 16b^5 - b^7)c_h)/(2 - b)(4 - 2b - b^2)(8 - 4b - 8b^2 + b^3 + b^4), \]
\[ a_4 = ((512 - 640b^2 - 96b^3 + 288b^4 + 80b^5 - 56b^6 - 16b^7 + 4b^8 + b^9)c_i -
(512 - 768b^2 + 96b^3 + 352b^4 - 80b^5 - 48b^6 + 16b^7 + 2b^8 - b^9)c_h)/
(2b^2(2 - b) (4 - 2b - b^2) (8 - 4b - 8b^2 + b^3 + b^4)). \]

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