〈論　　文〉

Strategic Outsourcing and Quality Choice in a Vertically Differentiated Duopoly

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Abstract

This paper analyses how firms' choice of two types of organizational production mode, vertical integration and outsourcing, will influence their quality choice in a vertically differentiated duopoly. We use a three-stage game model to explore how strategic behaviour between the rivalrous firms can influence their asymmetric choices leading to intra-industry heterogeneity. We show that the asymmetric configuration, where the high-quality firm chooses vertical integration while the low-quality firm chooses outsourcing, is accepted as a subgame perfect equilibrium outcome. Furthermore, we study how much price competition differs from quantity competition in the firms' choices of quality and organizational production mode.

Keywords: Strategic outsourcing; Vertical integration; Vertical product differentiation

1. Introduction

Currently the question at issue in the Japanese digital consumer electronics industry is which business model will have a strategic advantage in enhancing an electronics company's corporate value, profitability and global competitiveness, "vertical integration" or "horizontal specialization" (see Ohki, 2008, on "suihei bungyou" in Japanese). The former means a fully integrated manufacturing style of carrying out everything from manufacture of key components to final assembly of finished goods, while the latter means the style of choosing to purchase all or part of its inputs, in particular the key components it needs, or even the finished goods from other companies. This question is directly related to a firm's 'make-or-buy' decision in industrial organization.

Take the Japanese digital consumer electronics industry, in particular the liquid crystal display television (LCD TV) market, for example. A value chain for an LCD television is a chain of the following activities; concept, development and design, production of LCD panels, assembly of LCD modules for TVs, production of system large-scale integrated circuits (LSIs) for LCDs, final assembly of TV sets and brand. Outsourcing is essentially a division of labour. Thus, the degree of "horizontal specialization" depends on which and how many activities an electronics company outsources to the outside. *The Nikkei* (November 16, 2009) says that Panasonic and Sharp are vertically integrated companies while Hitachi, Sony and Toshiba are aiming for "horizontal specialization".[1] Masaaki Oosumi, one of Executive Officers and Corporate Vice Presidents of Toshiba Co., (*The Nikkei*, October 19, 2009) says, "In LCD TVs, a matter of importance is concept and design. It hardly matters at which manufacturing plant the LCD TV sets are produced." Toshiba specializes in the production of system LSIs for LCDs and procures LCD modules for TVs from the outside. Also, it subcontracts production of lower-priced LCD TV sets to Taiwanese electronics manufacturing services providers.

Vizio is a producer of consumer electronics in the USA. It surged into the leading position in the North America LCD TV market in the first quarter of 2009. Vizio specializes in activities such as concept and design, and sales and after-sales service. Since it is a fabless LCD TV company, it does not have its own production facility. Amtran, a Taiwan-based company, specializes in the tasks of procuring components from Taiwan and South Korea, assembly of LCD TV sets in China, quality assurance and so on. It supplies finished LCD TV sets to Vizio. This example is typical of an international division of labour.

Outsourcing will offer a move from fixed costs to variable costs, thereby changing the ratio of fixed to variable costs and leading to a firm's cost restructuring. It may be said that Vizio's degree of 'horizontal specialization' is higher than that of Toshiba. Since Vizio is a fabless company, it doesn't have to make any irreversible investment in a production facility for supplying inputs in-house and any investment in R&D for the design and development of new products. It will follow from this fact that Vizio's ratio of fixed to variable costs is quite lower than that of Toshiba. In contrast, Panasonic and Sharp aiming for vertical integration have so far made massive investments in state-of-the-art facilities that carry out integrated production of large LCD TVs from manufacture of LCD panels to final assembly of TV sets. Moreover, because they consider that R&D serves as the basis for value-added activities and the development of new products with advanced technology, they attach great importance to investment in R&D, too. Vertical integration, therefore, implies that Panasonic and Sharp's ratios of fixed to variable costs will be much higher than those of Vizio and Toshiba.

Vizio is known for aggressively pricing its LCD TVs against major competitors

1 *The Nikkei* is a Japanese newspaper focusing on the Japanese economy.

such as Sony of Japan and Samsung of Korea in the North America LCD TV market. Then, what is consumers' image for Japanese consumer electrical appliances? Japanese consumer electronics companies have a reputation for high quality and innovation in both the Japanese and global LCD TV markets. Sharp says, "The quality of the plant correlates directly with the quality of the LCD TVs produced there. ... Since then (2004), the LCD TVs manufactured at this industry-leading plant (the Kameyama Plant) have been praised for their quality and have established the "made in Kameyama" brand image."[2] Furthermore, because this company aims at promoting manufacturing innovations such as dramatically reducing cost and improving manufacturing processes, it consolidates technology development and production sites in one area called Kameyama. Panasonic also says, "Under a basic policy expressed in the concept of Quality First, we are taking concerted companywide action to improve the quality of both customer service and products."[3]

As mentioned above, the LCD TV manufacturers face the problem of choosing between outsourcing and in-house production. Nowadays there are two 'extremes' of organizational production mode in LCD TV markets: one is an organizational production mode with exclusive in-house production; the other is that with exclusive outsourcing (see Shy and Stenbacka, 2005, p. 1174). We may say that Panasonic, Sharp and Samsung are representatives of the former and Vizio is typical of the latter. Also, there is partial outsourcing in between the two extremes. Hitachi, Sony and Toshiba will belong to this category. It follows from this fact that in real world LCD TV markets electronics manufacturers aiming for vertical integration (in-house production) coexist with electronics producers outsourcing the production of all or part of the inputs they need.

Grossman and Helpman (2002) and Shy and Stenbacka (2003) handle firms' choice of organizational production mode. The former present an equilibrium model of industrial structure in which the organization of firms is endogenous. They demonstrate that, except in a knife-edge case, there are no equilibria in which an industry is populated by both vertically integrated and specialized firms. The latter make use of the Hotelling duopoly model in a differentiated industry context in order to analyse oligopolistic firms' choice of whether to outsource the production of the input good or whether to self-produce it. They show that asymmetric production modes, where one firm outsources while the other produces in-house, are ruled out as subgame perfect equilibrium outcomes.

Nickerson and Bergh (1999) also refer to the firms' choice of organizational production mode. This paper investigates rivalrous firms' asset specificity and organizational mode choices in Cournot competition and demonstrates that strategic

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2 http://sharp-world.com/kameyama/fbature/kameyamamodel/index.html and http://sharp-world.com/kameyama/fbature/plantl/index.html

3 http://panasonic-electric-works.net/csr/customer/quality/index.html

interactions may lead rivals to make asymmetric choices from which intra-industry organizational heterogeneity follows. In contrast to Shy and Stenbacka (2003), Buehler and Haucap (2006) find that there may be asymmetric equilibria where one firm buys the input from an existing input market, whereas the other firm produces the input internally. The difference stems from the fact that they consider a non-specific input good, whereas Shy and Stenbacka focus on a specific input good. Similarly, this paper focuses on the firms' choice of organizational production mode in a vertically differentiated duopoly model and derives demand and cost conditions under which one firm chooses vertical integration while the other chooses to outsource.

The existing literature on vertical product differentiation has devoted little attention to the choice of an organizational production mode in an oligopolistic environment in which strategic considerations are of primary importance. A great deal of attention has been paid to the issues of a comparison of equilibrium qualities in price and quantity competition (see Motta, 1993; Lambertini, 1996; Amacher et al., 2005), the characterization of quality choice under full or partial market coverage (see Moorthy, 1988; Choi and Shin, 1992; Wauthy, 1996; Liao, 2008), the persistence of the high-quality advantage (see Lehmann-Grube, 1997; Aoki and Prusa, 1997) and the implications of a 'strategic-trade policy' for quality choice (see Zhou et al., 2002).

There seem no studies in the literature that investigate how firms' choice of two types of organizational production mode, vertical integration and outsourcing, will influence their quality choice in a vertically differentiated duopoly model. The purpose of this paper is to contribute to the analysis of this issue. In this paper, we would like to present a simple game-theoretic model which is concerned with outsourcing and quality choice in the context of vertical product differentiation. We consider strategic behaviour between rivalrous firms competing with their choices of quality and organizational production mode. In this context, the organizational production mode can be treated as a strategic instrument affecting quality and organizational production mode choices by rivalrous firms. Furthermore, we study how much price competition differs from quantity competition in the firms' choices of quality and organizational production mode.

There are a number of related earlier contributions on aspects of outsourcing different from those we focus on. Arya et al. (2008a) demonstrate that standard conclusions regarding the effects of Bertrand and Cournot competition (e.g., Singh and Vives, 1984) can be altered when the production of inputs is outsourced to retail rivals. Baake et al. (1999) consider a duopoly model to examine what they call "cross-supplies" within an industry. Focusing on the "endogenous Stackelberg effect" pointed out by Baak et al., Chen et al. (2011) find that it is typically not the case that a firm will outsource supplies to its rivals. Arya et al. (2008b) show that a rival's reliance on a supplier may prompt a firm to outsource to the same supplier rather than produce inputs internally even when the outsourcing is more costly than internal production. Van Long (2005) considers the outsourcing decision of a firm facing a foreign rival that could benefit from technology spillovers associated with the training of wokers by the outsourcing firm. In Spiegel

(1993) horizontal subcontracting is driven by the assumption that the upstream cost functions are strictly convex. Chen (2005) demonstrates that downstream competitors may strategically choose not to purchase from a vertically integrated firm, unless the latter's price for the intermediate good is sufficiently lower than those of alternative suppliers. In contrast, Chen (2001) reaches the result that vertical integration occurs in equilibrium if and only if one of the upstream producers is more efficient than the others. Chen et al. (2004) explore the strategic incentives of international outsourcing and its potential collusive effects associated with trade liberalization.

The remainder of this paper is arranged as follows. In Section 2 we describe the model and its assumptions. In Section 3 we use a three-stage game model of duopoly. First, each firm chooses the organizational production mode, and then, quality. Finally, both firms compete in prices. Section 4 examines the case where the firms compete in quantities in the marketing stage of the game. Section 5 draws a comparison of the firms' choices of the quality and organizational production mode in price and quantity competition. We conclude in Section 6.

2. The Model

There are two firms in the industry. Each firm produces a vertically differentiated good of quality s_i and sells it at price p_i, where i = H, L and $s_{\mathrm{H}} > s_{\mathrm{L}} > 0$. Lehmann-Grube (1997, p. 380) refers to the straightforward generalization of his model and suggests a setting where product quality is a function of both fixed and variable cost. Taking the quantity produced by firms into account, we can denote the total cost function in terms of output and quality as follows:

$$C(q_i, s_i) = c(s_i)q_i + F(s_i). \tag{1}$$

We assume that the variable cost and the fixed cost are a quadratic function in quality with the form below, respectively:

$$c(s_i) = \frac{1}{2}vs_i^2, \tag{2}$$

$$F(s_i) = \frac{1}{2}ks_i^2, \tag{3}$$

where $v > 0$ and $k > 0$. Since the total cost of firm i is linear in quantity q_i, its marginal cost is constant.

We consider a duopoly in which two firms play a three-stage game. The two firms simultaneously determine organizational production mode in the first stage of the game. We assume that two organizational production modes are available for the firms. To avoid unnecessary complications, our model focuses on polar organizational production modes, vertical integration (in-house production) and outsourcing. Vertical integration means a fully integrated manufacturing style of carrying out every activity from production of key components to final assembly of finished goods, while outsourcing is defined to mean the style of choosing to outsource the production of products to the outside and also to sell them under a seller's brand in a finished goods market.[4] In the second stage, each firm chooses a quality level of its product. In the third stage, given their own cost structures and quality levels, both firms compete in prices or quantities.

Under vertical integration, a firm makes a large investment in R&D activities to develop the advanced manufacturing technology and its related technologies, including quality improvement, and thereby a newly developed technology yields a new product of high quality. Thus, the technological development will prompt the firm to make a massive investment in a production facility for supplying components in-house that are needed to manufacture the new products. Also, such a large-scale investment will result in a dramatic rise in the ratio of fixed to variable costs. In this case, the main burden of quality improvement falls on R&D activities and R&D-related investments, while variable costs do not change with quality. This enables us to take constant unit costs of production to be zero. Therefore, the firm pursuing the strategy of vertical integration faces a cost function represented by (3). The firm's profits are written as:

$$\Pi_{i\mathrm{K}} = p_i q_i - F(s_i), \tag{4}$$

where the subscript K means that firm i adopts the strategy of vertical integration, and q_i denotes demand for the firm.

A firm adopting the strategy of outsourcing does not have to make any investments in R&D activities and a production facility. If it aims for an improvement in product quality, it will have to ask a subcontractor to improve the quality of key components. This request will lead the subcontractor to procure the key components of higher quality from the outside, otherwise it may improve their quality at its own plant. Thus the firm's request will lead to a rise in a price which the firm pays to the subcontractor for a finished product. In this case, because the firm's fixed costs are negligible as compared to variable costs, its cost function is given by (2). This firm's profits are then:

$$\Pi_{i\mathrm{V}} = (p_i - c(s_i))q_i, \tag{5}$$

where the subscript V means that firm i chooses the strategy of outsourcing.

There is a continuum of consumers uniformly distributed over the interval $[a, b]$ with unit density, $b - a = 1$, where $b > a \geq 0$. Each consumer, indexed by $\theta \in [a, b]$, purchases at most one unit of a differentiated good and maximizes the following utility function (see Tirole, 1988, pp. 96–97, pp. 296–298):

$$U = \begin{cases} \theta s_i - p_i & \text{if he buys one unit of the good with quality } s_i \text{ at price } p_i, \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

4　As mentioned above, there is partial outsourcing in between the two polar organizational modes. For partial outsourcing see Shy and Stenbacka (2005).

In (6), θ represents consumers' taste parameter and consumers with a higher θ will be willing to pay more for a higher quality good. Since θ can be interpreted as the inverse of the marginal rate of substitution between income and quality, wealthier consumers have a lower marginal utility of income and therefore a higher θ.

Let $\hat{\theta}$ denote the marginal willingness to pay for quality defined for the consumer who is indifferent between buying the high-quality good at price p_{H} or the low-quality good at price p_{L}, i.e., $\hat{\theta} = (p_{\mathrm{H}} - p_{\mathrm{L}})/(s_{\mathrm{H}} - s_{\mathrm{L}})$. The consumer with index $\tilde{\theta}$ for which $\tilde{\theta}s_{\mathrm{L}} - p_{\mathrm{L}} = 0$ will be indifferent between buying the low-quality good and buying nothing at all, so $\tilde{\theta} = p_{\mathrm{L}}/s_{\mathrm{L}}$. We assume that a market is not covered. This assumption requires that $a < p_{\mathrm{L}}/s_{\mathrm{L}}$ and so enables us to compare equilibrium solutions under price and quantity competition. Moreover, demands for the high-quality and the low-quality firm are given by, respectively:

$$q_{\mathrm{H}} = b - \hat{\theta}, \tag{7}$$

$$q_{\mathrm{L}} = \hat{\theta} - \tilde{\theta}. \tag{8}$$

Let $\gamma = b/a$ and $\mu = s_{\mathrm{H}}/s_{\mathrm{L}}$ denote the degree of population heterogeneity (a, b) and the degree of product differentiation $(s_{\mathrm{L}}, s_{\mathrm{H}})$, respectively. By definition we have $\mu > 1$. The Nash equilibrium in price or quantity depends on these degrees.

First, each firm chooses the organizational production mode, then quality, and finally its price or quantity. The third stage equilibrium is a Nash equilibrium in price or quantity, taking each firm's choices of organizational production mode and quality as given by the preceding stages. Using this third stage solution, we can write the objective function of each firm as a function of the pair of quality levels chosen in the preceding stage.

In Table 1 $\pi_{i,j}$ is the payoff to firm i from the third stage of the game, given that both firms are in a state represented by the subscript j, which means a state where each firm chooses between the two alternative modes and thereby determines the shape of its cost function given in (2) or (3). $j = 1$ stands for the state in which both firms adopt vertical integration referred to as (K, K). $j = 2$ denotes the state where the high-quality firm chooses outsourcing while the low-quality firm chooses vertical integration referred to as (V, K). $j = 3$ means the state where the high-quality firm chooses vertical integration while the low-quality firm chooses outsourcing referred to as (K, V). $j = 4$ stands for the state in which both firms adopt outsourcing referred to as (V, V). We solve for a Nash equilibrium in that game. The solution concept is that of a subgame perfect equilibrium.

Table 1: Vertical Integration vs. Outsourcing

	Strategies	Low-Quality Firm: Vertical Integration (K)	Low-Quality Firm: Outsourcing (V)
High-Quality Firm	Vertical Integration (K)	$\pi_{\mathrm{H},1}$, $\pi_{\mathrm{L},1}$	$\pi_{\mathrm{H},3}$, $\pi_{\mathrm{L},3}$
	Outsourcing (V)	$\pi_{\mathrm{H},2}$, $\pi_{\mathrm{L},2}$	$\pi_{\mathrm{H},4}$, $\pi_{\mathrm{L},4}$

3. Choices of Organizational Production Mode and Quality: Bertrand Competition

In this section, in the first stage firms choose the organizational production mode, and in the second stage, quality, and they compete à la Bertrand in the marketing stage of the game. We first solve for Nash equilibria in the third stage. The solutions to this stage are then substituted into the payoff functions to produce $\pi_{i,j}$s in Table 1. When $j = 1$, letting i = H, then i = L in (4) produces the firms' profits corresponding to (K, K), i.e., (Π_{HK}, Π_{LK}). Similarly, when $j = 2$, we have the firms' profits corresponding to (V, K), i.e., (Π_{HV}, Π_{LK}). When $j = 3$, the firms' profits corresponding to (K, V) are (Π_{HK}, Π_{LV}). When $j = 4$, the firms' profits corresponding to (V, V) are (Π_{HV}, Π_{LV}).

3.1 Both firms choose vertical integration: (K, K)

First, differentiating Π_{HK} and Π_{LK} with respect to p_H and p_L, respectively, we have two first-order conditions from which a two-equation simultaneous system in unknowns p_H and p_L follows. Solving this system yields each firm's price that can be thought of as a function of qualities. Then, substituting these prices into each firm's profits and partially differentiating its profits with respect to its quality yields a first-order condition for each firm. Solving the two-equation system composed of the two first-order conditions leads to the determination of qualities.

We therefore have (see Motta, 1993 and Amacher et al., 2005):

$$s_{H,1} = 0.253311b^2/k; \quad s_{L,1} = 0.0482383b^2/k; \quad s_{H,1} - s_{L,1} = 0.205072b^2/k, \tag{9}$$

$$p_{H,1} = 0.107662b^3/k; \quad p_{L,1} = 0.0102511b^3/k; \quad p_{H,1}/p_{L,1} = 10.502468, \tag{10}$$

$$q_{H,1} = 0.524994b; \quad q_{L,1} = 0.262497b; \quad q_{H,1} + q_{L,1} = 0.787491b, \tag{11}$$

$$\pi_{H,1} = 0.0244386b^4/k; \quad \pi_{L,1} = 0.00152741b^4/k; \quad \pi_{H,1} + \pi_{L,1} = 0.0259660b^4/k, \tag{12}$$

$$\tilde{\theta}_1 = 0.212509b; \quad \hat{\theta}_1 = 0.475006b, \tag{13}$$

$$\gamma_1 > 4.705677; \quad \mu_1 = 5.251234, \tag{14}$$

where $\tilde{\theta}_1$, $\hat{\theta}_1$ and μ_1 stand for values of $\tilde{\theta}$, $\hat{\theta}$ and μ in the state of $j = 1$, respectively.[5]

5　Since $b - \tilde{\theta}_1 < 1$ has to hold true, we have $b < 1.269856$, in which case the degree of population heterogeneity represented by γ_1 is greater than 4.705677. In addition, if $\mu > 0.25$ and $\mu > 1.75$, then the second-order conditions for the high-quality and the low-quality firm are negative, respectively.

3.2 The high-quality firm chooses outsourcing while the low-quality firm adopts vertical integration: (V, K)

This subsection is concerned with the case in which the high-quality firm chooses outsourcing while the low-quality firm adopts vertical integration. Let $\beta \equiv k/v$. k and v are interpreted as efficiency parameters related to vertical integration and outsourcing, respectively. For example, higher values of k mean that vertical integration is a less efficient strategy for a firm. Thus, β is referred to as the efficiency ratio. β is small when the efficiency of vertical integration compared to that of outsourcing is high. Conversely, β is large when the efficiency of outsourcing compared to that of vertical integration is high.

The two first-order conditions for both firms fixing quality levels can be reduced to (see the Appendix for the derivation):

$$\beta = \frac{b\mu^3(4-11\mu+8\mu^2)(-20+81\mu-84\mu^2+32\mu^3)}{4(-1+\mu)(-1+4\mu)(2-3\mu+4\mu^2)(-4+23\mu-46\mu^2+24\mu^3)}. \tag{15}$$

If β were fixed at a certain value, we could determine a value of μ. Let $g^p(\mu)$ denote the right-hand side of this equation. This function is at first decreasing and then increasing in μ. However, there is a one-to-one correspondence between β and μ through $\beta = g^p(\mu)$ on the interval $[2.080460, +\infty)$. In this case, μ that can be thought of as a function of β and b is increasing in β.

For the moment we describe the following results in terms of μ:

$$s_{H,2} = \frac{4b(-1+\mu)(2-3\mu+4\mu^2)}{v(-4+23\mu-46\mu^2+24\mu^3)};\quad s_{L,2} = \frac{4b(-1+\mu)(2-3\mu+4\mu^2)}{v\mu(-4+23\mu-46\mu^2+24\mu^3)}, \tag{16}$$

$$p_{H,2} = \frac{8b^2(-1+\mu)^2(2-3\mu+4\mu^2)(4-11\mu+8\mu^2)}{v(-4+23\mu-46\mu^2+24\mu^3)^2};$$

$$p_{L,2} = \frac{4b^2(-1+\mu)^2(2-3\mu+4\mu^2)(4-11\mu+8\mu^2)}{v\mu(-4+23\mu-46\mu^2+24\mu^3)^2}, \tag{17}$$

$$q_{H,2} = \frac{4b\mu(1-4\mu+2\mu^2)}{-4+23\mu-46\mu^2+24\mu^3};\qquad q_{L,2} = \frac{b\mu(4-11\mu+8\mu^2)}{-4+23\mu-46\mu^2+24\mu^3};$$

$$q_{H,2} + q_{L,2} = \frac{b\mu(8-27\mu+16\mu^2)}{-4+23\mu-46\mu^2+24\mu^3}, \tag{18}$$

$$\pi_{H,2} = \frac{64b^3(-1+\mu)^2\mu(1-4\mu+2\mu^2)^2(2-3\mu+4\mu^2)}{v(-4+23\mu-46\mu^2+24\mu^3)^3};$$

$$\pi_{L,2} = \frac{2b^3(-1+\mu)(2-3\mu+4\mu^2)^2(4-15\mu+8\mu^2)(4-11\mu+8\mu^2)}{v(-1+4\mu)(-4+23\mu-46\mu^2+24\mu^3)^3}, \tag{19}$$

$$\tilde{\theta}_2 = \frac{b(-1+\mu)(4-11\mu+8\mu^2)}{-4+23\mu-46\mu^2+24\mu^3}; \quad \hat{\theta}_2 = \frac{b(-1+2\mu)(4-11\mu+8\mu^2)}{-4+23\mu-46\mu^2+24\mu^3}. \tag{20}$$

3.3 The high-quality firm chooses vertical integration while the low-quality firm adopts outsourcing: (K, V)

This subsection is concerned with the case in which the high-quality firm chooses vertical integration while the low-quality firm adopts outsourcing. The two first-order conditions for both firms leading to the determination of quality levels can be reduced to (see the Appendix for the derivation):

$$\beta = \frac{b(4-15\mu+12\mu^2)(8-42\mu+99\mu^2-104\mu^3+48\mu^4)}{2(-1+\mu)\mu(-7+4\mu)(-1+4\mu)(-2+19\mu-38\mu^2+24\mu^3)}. \tag{21}$$

Let $f^p(\mu)$ stand for the right-hand side of this equation. There is a one-to-one correspondence between β and μ through $\beta = f^p(\mu)$. In this case, μ can be thought of as a function of β and b,, and it is decreasing in β. For the moment we describe the following results in terms of μ:

$$s_{H,3} = \frac{2b(-1+\mu)\mu^2(-7+4\mu)}{v(-2+19\mu-38\mu^2+24\mu^3)}; \; s_{L,3} = \frac{2b(-1+\mu)\mu(-7+4\mu)}{v(-2+19\mu-38\mu^2+24\mu^3)}, \tag{22}$$

$$p_{H,3} = \frac{2b^2(-1+\mu)^2\mu^2(-7+4\mu)(4-15\mu+12\mu^2)}{v(-2+19\mu-38\mu^2+24\mu^3)^2};$$

$$p_{L,3} = \frac{2b^2(-1+\mu)^2\mu(-7+4\mu)(2-11\mu+8\mu^2)}{v(-2+19\mu-38\mu^2+24\mu^3)^2}, \tag{23}$$

$$q_{H,3} = \frac{b\mu(4-15\mu+12\mu^2)}{-2+19\mu-38\mu^2+24\mu^3}; \qquad q_{L,3} = \frac{2b\mu(1-2\mu+2\mu^2)}{-2+19\mu-38\mu^2+24\mu^3};$$

$$q_{H,3}+q_{L,3} = \frac{b\mu(6-19\mu+16\mu^2)}{-2+19\mu-38\mu^2+24\mu^3}, \tag{24}$$

$$\pi_{H,3} = \frac{b^3(7-4\mu)^2(-1+\mu)\mu^4(4-15\mu+12\mu^2)(4-13\mu+12\mu^2)}{v(-1+4\mu)(-2+19\mu-38\mu^2+24\mu^3)^3};$$

$$\pi_{L,3} = \frac{8b^3(-1+\mu)^2\mu^2(-7+4\mu)(1-2\mu+2\mu^2)^2}{v(-2+19\mu-38\mu^2+24\mu^3)^3}, \tag{25}$$

$$\tilde{\theta}_3 = \frac{b(-1+\mu)(2-11\mu+8\mu^2)}{-2+19\mu-38\mu^2+24\mu^3}; \quad \hat{\theta}_3 = \frac{b(-2+15\mu-23\mu^2+12\mu^3)}{-2+19\mu-38\mu^2+24\mu^3}. \tag{26}$$

3.4 Both firms choose outsourcing: (V, V)

In this case we obtain (see Motta, 1993 and Amacher et al., 2005)[6] :

$$s_{H,4} = 0.819521b/v; \quad s_{L,4} = 0.398722b/v; \quad s_{H,4} - s_{L,4} = 0.420798b/v, \tag{27}$$

$$p_{H,4} = 0.453313b^2/v; \quad p_{L,4} = 0.150020b^2/v; \quad p_{H,4}/p_{L,4} = 3.021676, \tag{28}$$

$$q_{H,4} = 0.279245b; \quad q_{L,4} = 0.344503b; \quad q_{H,4} + q_{L,4} = 0.623747b, \tag{29}$$

$$\pi_{H,4} = 0.0328129b^3/v; \quad \pi_{L,4} = 0.0242980b^3/v; \quad \pi_{H,4} + \pi_{L,4} = 0.0571108b^3/v, \tag{30}$$

$$\tilde{\theta}_4 = 0.376253b; \quad \hat{\theta}_4 = 0.720755b, \tag{31}$$

$$\gamma_4 > 2.657789; \quad \mu_4 = 2.055367. \tag{32}$$

3.5 Characterization of the Equilibria: price competition

In the first stage each firm chooses an organizational production mode, and in the second stage, its quality level. In this game, there are four possible outcomes as illustrated in Table 1: (K, K), (V, K), (K, V) and (V, V). We can use the following four lemmas to find out which pair(s) will be a Nash equilibrium (see the Appendix for proofs):

Lemma 1 *If* $0.411542b \leq \beta \leq 0.546074b$ $(=\beta^{*}_{12})$, *then we have* $\pi_{H,1} \geq \pi_{H,2}$. *Conversely, if* $0.546074b < \beta$, *then we obtain* $\pi_{H,1} < \pi_{H,2}$.

Lemma 2 *If* $\beta \leq 0.217161b$ $(= \beta^{**}_{13})$, *then we have* $\pi_{L,1} \geq \pi_{L,3}$. *Conversely, if* $0.217161b < \beta$, *then* $\pi_{L,1} < \pi_{L,3}$.

Lemma 3 *If* $\beta \in (0.411542b, 0.416891b)$ *or* $[0.411542b, 0.413810b]$, *then we have* $\pi_{L,2} \geq \pi_{L,4}$. *Conversely, if* $\beta > 0.416891b$, *then* $\pi_{L,2} < \pi_{L,4}$.

Lemma 4 *If* $\beta \leq 0.581924b$ $(= \beta^{**}_{34})$, *then we have* $\pi_{H,3} \geq \pi_{H,4}$. *Conversely, if* $0.581924b < \beta$, *then* $\pi_{H,3} < \pi_{H,4}$.

We therefore establish (see the Appendix for the proof):

Proposition 1 *Under price competition there are two subgame perfect equilibria of*

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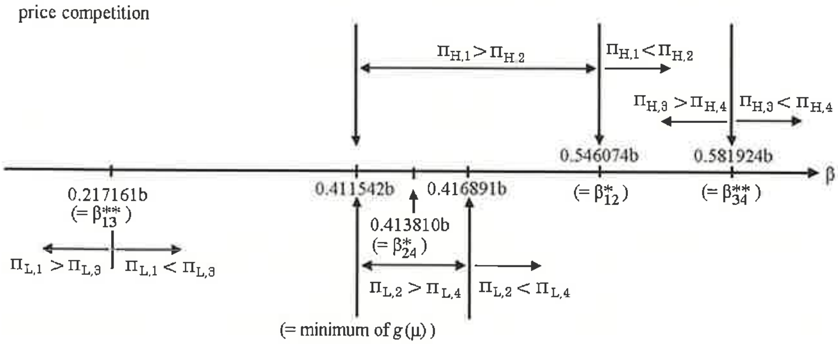
6 Since $b - \tilde{\theta}_4 < 1$ has to hold true, $b < 1.603213$, in which case $\gamma_4 > 2.657789$. In addition, if $\mu > 1$ and $\mu \in (1.75, 3.611555)$, then the second-order conditions for the high-quality and the low-quality firm are negative, respectively.

the game.
(i) *If* $0.217161b \leq \beta \leq 0.581924b$, then (K, V) *is a subgame perfect equilibrium of the game.*
(ii) *If* $0.581924b \leq \beta$, *then* (V, V) *is a subgame perfect equilibrium of the game.*

Figure 1: β and Payoffs: price competition



Note: The superscripts * and ** refer to the functions $g(\mu)$ and $f(\mu)$, respectively. The subscripts of β, 12, 13, 24, and 34, refer to two states, respectively. For example, 12 refers to the states, 1 and 2, simultaneously.

The first part of this proposition states that the high-quality firm chooses vertical integration while the low-quality firm chooses to outsource when the efficiency of in-house production compared to that of outsourcing is high, i.e., when β is small. This implies that low values of β will lead to the firms' asymmetric choices meaning intra-industry heterogeneity. The last part of the proposition shows that both firms choose to outsource when the efficiency of outsourcing compared to that of in-house production is high, i.e., when β is large. It should be noted that the other configurations, (K, K) and (V, K), are ruled out as subgame perfect equilibrium outcomes. Vertical integration is a dominated strategy for the low-quality firm.

We first focus on the percentage of the payoff to each firm to the total payoff in (K, K). The percentage of the high-quality firm's payoff to the total payoff is 94.12% while that of the low-quality firm's payoff to the total payoff is 5.88%. Thus, given the high-quality firm's choice of vertical integration, the low-quality firm's choice of vertical integration requires the efficiency of in-house production to be extremely high relative to that of outsourcing, which means that β is very small. Given the low-quality firm's choice of vertical integration, if β takes on intermediate values, then the high-quality firm chooses vertical integration. Therefore, they would not choose in-house production at equilibrium simultaneously.

Consider next whether the low-quality firm chooses vertical integration, given the high-quality firm's choice of outsourcing. In (V, V) the percentage of the high-quality firm's payoff to the total payoff is 57.45% while the low-quality firm's payoff to the total payoff is 42.55%. If β takes on intermediate values, then the low-quality firm chooses vertical integration. However, the interval in which β takes on those values is very narrow. Furthermore, very low values of β do not enable both firms to maximize profits in (V, K). On the other hand, given the low-quality firm's choice of in-house production, because the payoff to the high-quality firm is large in (K, K), only high values of β will lead it to choose outsourcing. That is, if the efficiency of outsourcing is rather high relative to that of in-house production, then the high-quality firm will choose outsourcing. This situation will lead the low-quality firm to choose outsourcing rather than vertical integration.

4. Choices of Organizational Production Mode and Quality: Cournot Competition

In this section, we deal with the case in which each firm chooses its quantity in the marketing stage of the game. In order to first solve for Nash equilibria in the third stage, we invert the demand system composed of (8) and (9). The inverse demand functions are given by, respectively:

$$p_{\mathrm{H}} = bs_{\mathrm{H}} - q_{\mathrm{H}}s_{\mathrm{H}} - q_{\mathrm{L}}s_{\mathrm{L}}, \tag{33}$$

$$p_{\mathrm{L}} = s_{\mathrm{L}}(b - q_{\mathrm{H}} - q_{\mathrm{L}}). \tag{34}$$

The solutions to this stage are then substituted into the payoff functions to produce $\pi_{i,j}$s in Table 1 as stated in the preceding section.

4.1 Both firms choose vertical integration: (K, K)

First, differentiating Π_{HK} and Π_{LK} with respect to q_{H} and q_{L}, respectively, we have two first-order conditions from which a two-equation simultaneous system in unknowns q_{H} and q_{L} follows. Solving this system yields each firm's quantity that can be thought of as a function of qualities. Then, substituting these quantities into each firm's profits and partially differentiating its profits with respect to its quality yields a first-order condition for each firm. Solving the two-equation system composed of the two first-order conditions leads to the determination of qualities.

We therefore have:

$$s_{H,1} = 0.251942b^2/k; \quad s_{L,1} = 0.0902232b^2/k; \quad s_{H,1} - s_{L,1} = 0.161719b^2/k, \tag{35}$$

$$p_{H,1} = 0.113584b^3/k; \quad p_{L,1} = 0.0247737b^3/k; \quad p_{H,1}/p_{L,1} = 4.584857, \tag{36}$$

$$q_{H,1} = 0.450834b; \quad q_{L,1} = 0.274583b; \quad q_{H,1} + q_{L,1} = 0.725417b, \tag{37}$$

$$\pi_{H,1} = 0.0194703b^4/k; \quad \pi_{L,1} = 0.00273233b^4/k; \quad \pi_{H,1} + \pi_{L,1} = 0.0222026b^4/k, \tag{38}$$

$$\tilde{\theta}_1 = 0.274583b; \quad \hat{\theta}_1 = 0.549166b, \tag{39}$$

$$\gamma_1 > 3.641889; \quad \mu_1 = 2.792429, \tag{40}$$

where $\mu_1, \tilde{\theta}_1$ and $\hat{\theta}_1$ represent values of $\mu, \tilde{\theta}$ and $\hat{\theta}$ in the state of $j = 1$, respectively.[7]

4.2 The high-quality firm chooses outsourcing while the low-quality firm adopts vertical integration: (V, K)

In this subsection, the high-quality firm chooses outsourcing while the low-quality firm adopts vertical integration. The two first-order conditions for both firms determining quality levels can be reduced to (see the Appendix for the derivation):

$$\beta = \frac{b\mu^2(1+4\mu)(-1+8\mu)^2}{4(-1+4\mu)(-5+12\mu)(1-2\mu+8\mu^2)}. \tag{41}$$

Let $g^q(\mu)$ denote the right-hand side of this equation. Since this function attains a minimum at $\mu = 0.970139$, there is a one-to-one correspondence between β and μ on the interval $[0.970139, +\infty)$ and μ is an increasing function of β.

We obtain the following results in terms of μ:

$$s_{H,2} = \frac{b(1-2\mu+8\mu^2)}{v\mu(-5+12\mu)}; \quad s_{L,2} = \frac{b(1-2\mu+8\mu^2)}{v\mu^2(-5+12\mu)}, \tag{42}$$

$$p_{H,2} = \frac{b^2(-1+2\mu)(-1+8\mu)(1-2\mu+8\mu^2)}{2v\mu^2(-5+12\mu)^2}; \quad p_{L,2} = \frac{b^2(-1+8\mu)(1-2\mu+8\mu^2)}{2v\mu^2(-5+12\mu)^2}, \tag{43}$$

$$q_{H,2} = \frac{4b(-1+\mu)}{-5+12\mu}; \quad q_{L,2} = \frac{b(-1+8\mu)}{2(-5+12\mu)}; \quad q_{H,2} + q_{L,2} = \frac{b(-9+16\mu)}{2(-5+12\mu)}, \tag{44}$$

7　Since $b - \tilde{\theta}_1 < 1$ has to hold true, $b < 1.378517$, which leads to the result that $\gamma_1 > 3.641889$. In addition, if $\mu > 0.666117$ and $\mu > 1.161438$, then the second-order conditions for the high-quality and the low-quality firm are negative, respectively.

$$\pi_{H,2} = \frac{16b^3(-1+\mu)^2(1-2\mu+8\mu^2)}{v\mu(-5+12\mu)^3}; \ \pi_{L,2} = \frac{b^3(1-8\mu)^2(-3+4\mu)(1-2\mu+8\mu^2)}{8v\mu^2(-1+4\mu)(-5+12\mu)^3}, \quad (45)$$

$$\tilde{\theta}_2 = \frac{b(-1+8\mu)}{2(-5+12\mu)}; \qquad \hat{\theta}_2 = \frac{b(-1+8\mu)}{-5+12\mu}. \quad (46)$$

4.3 The high-quality firm chooses vertical integration while the low-quality firm adopts outsourcing: (K, V)

This subsection focuses on the case in which the high-quality firm chooses vertical integration while the low-quality firm adopts outsourcing. The two first-order conditions for both firms leading to the determination of quality levels can be reduced to (see the Appendix for the derivation):

$$\beta = \frac{3b(3-8\mu+48\mu^2)}{4\mu(1+4\mu)(-1+12\mu)}. \quad (47)$$

Let $f^q(\mu)$ stand for the right-hand side of this equation. Since there is a one-to-one correspondence between β and μ through $\beta = f^q(\mu)$, μ can be thought of as a function of β and b, and it is decreasing in β. We describe the following results in terms of μ:

$$s_{H,3} = \frac{b\mu(1+4\mu)}{v(-1+12\mu)}; \qquad s_{L,3} = \frac{b(1+4\mu)}{v(-1+12\mu)}, \quad (48)$$

$$p_{H,3} = \frac{3b^2\mu(-1+4\mu)(1+4\mu)}{2v(-1+12\mu)^2}; \qquad p_{L,3} = \frac{b^2(1+4\mu)(1+8\mu)}{2v(-1+12\mu)^2}, \quad (49)$$

$$q_{H,3} = \frac{3b(-1+4\mu)}{2(-1+12\mu)}; \quad q_{L,3} = \frac{2b\mu}{-1+12\mu}; \quad q_{H,3}+q_{L,3} = \frac{b(-3+16\mu)}{2(-1+12\mu)}, \quad (50)$$

$$\pi_{H,3} = \frac{3b^3\mu(-3+4\mu)(1+4\mu)}{8v(-1+12\mu)^2}; \qquad \pi_{L,3} = \frac{4b^3\mu^2(1+4\mu)}{v(-1+12\mu)^3}, \quad (51)$$

$$\tilde{\theta}_3 = \frac{b(1+8\mu)}{2(-1+12\mu)}; \qquad \hat{\theta}_3 = \frac{b(1+12\mu)}{2(-1+12\mu)}. \quad (52)$$

4.4 Both firms choose outsourcing: (V, V)

In this case we obtain[8] :

8 Since $b - \tilde{\theta}_4 < 1$ has to hold true, $b < 2.160369$, in which case $\gamma_4 > 1.861795$. In addition, if $\mu > 0.401880$ and $\mu \in (0.25, 5.661687)$, then the second-order conditions for the high-quality and the low-quality firm are negative, respectively.

$$s_{H,4} = 0.738096b/v; \quad s_{L,4} = 0.585576b/v; \quad s_{H,4} - s_{L,4} = 0.152519b/v, \tag{53}$$

$$p_{H,4} = 0.433708b^2/v; \quad p_{L,4} = 0.314522b^2/v; \quad p_{H,4}/p_{L,4} = 1.378941, \tag{54}$$

$$q_{H,4} = 0.218556b; \quad q_{L,4} = 0.244328b; \quad q_{H,4} + q_{L,4} = 0.462884b, \tag{55}$$

$$\pi_{H,4} = 0.0352564b^3/v; \quad \pi_{L,4} = 0.0349566b^3/v; \quad \pi_{H,4} + \pi_{L,4} = 0.0702130b^3/v, \tag{56}$$

$$\bar{\theta}_4 = 0.537116b; \quad \hat{\theta}_4 = 0.781444b, \tag{57}$$

$$\gamma_4 > 1.861795; \quad \mu_4 = 1.260461. \tag{58}$$

4.5 Characterization of the Equilibria: quantity competition

We analyse whether each of four possible outcomes in Table 1 will be a Nash equilibrium. The four lemmas are given below (see the Appendix for proofs):

Lemma 5 *If* $0.416667b < \beta \leq 0.540551b$ $(= \beta^{\ddagger}_{12})$, *then we have* $\pi_{H,1} \geq \pi_{H,2}$. *Conversely, if* $0.540551b < \beta$, *then we obtain* $\pi_{H,1} < \pi_{H,2}$.

Lemma 6 *If* $\beta \leq 0.246262b$ $(= \beta^{\ddagger}_{13})$, *then we have* $\pi_{L,1} \geq \pi_{L,3}$. *Conversely, if* $0.246262b < \beta < 0.586364b$, *then* $\pi_{L,1} < \pi_{L,3}$

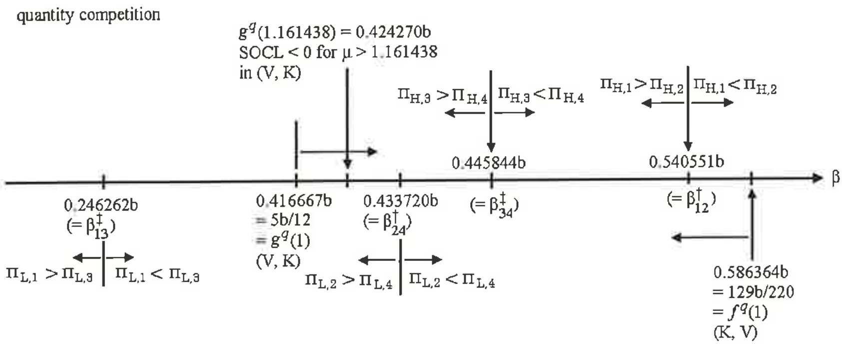
Lemma 7 *If* $0.424270b < \beta \leq 0.433720b$ $(= \beta^{\ddagger}_{24})$, *then we have* $\pi_{L,2} \geq \pi_{L,4}$. *Conversely, if* $0.433720b < \beta$, *then* $\pi_{L,2} < \pi_{L,4}$.

Lemma 8 *If* $\beta \leq 0.445844b$ $(= \beta^{\ddagger}_{34})$, *then we have* $\pi_{H,3} \geq \pi_{H,4}$. *Conversely, if* $0.445844b < \beta < 0.586364b$, *then* $\pi_{H,3} < \pi_{H,4}$.

We therefore establish (see the Appendix for the proof):

Proposition 2 *Under quantity competition there are two subgame perfect equilibria of the game.*
(i) If $0.246262b \leq \beta \leq 0.445844b$, *then* (K, V) *is a subgame perfect equilibrium of the game.*
(ii) *If* $0.445844b \leq \beta < 0.586364b$, *then* (V, V) *is a subgame perfect equilibrium of the game.*

Figure 2: β and Payoffs: quantity competition



Note: The superscripts † and ‡ refer to the functions $g^q(\mu)$ and $f^q(\mu)$, respectively. The subscripts of β, 12, 13, 24, and 34, refer to two states, respectively. For example, 12 refers to the states, 1 and 2, simultaneously.

Not only Proposition 1 but also Proposition 2 states that (K, V) and (V, V) are subgame perfect equilibria of the game, whereas (K, K) and (V, K) are ruled out as subgame perfect equilibrium outcomes. The same remarks as stated about Proposition 1 as to why (K, K) and (V, K) do not constitute subgame perfect equilibria apply to Proposition 2. However, the interval of β where (K, V) constitutes a subgame perfect equilibrium is narrower under quantity than under price competition. Furthermore, since $\mu > 1$ is supposed throughout the paper, β has an upper bound in (K, V). That is, (V, V) is a subgame perfect equilibrium when $0.445844b \leq \beta < 0.586364b$.

Consider why the interval of β on which (K, V) is a subgame perfect equilibrium outcome is narrower under quantity than under price competition. We first focus on a comparison between the percentage of the payoff to each firm to the total payoff in (K, K) under price competition and that under quantity competition. In (K, K) under quantity competition, the percentage of the high-quality firm's payoff to the total payoff is 87.69% while that of the low-quality firm's payoff to the total payoff is 12.31%. The percentage of the low-quality firm's payoff to the total payoff is much greater under quantity competition than under price competition. Thus, this percentage implies that given the high-quality firm's choice of vertical integration, the efficiency of outsourcing relative to that of vertical integration which is higher under quantity than under price competition allows (K, V) to be a subgame perfect equilibrium. This means that a lower bound of the interval of β where (K, V) is a subgame perfect equilibrium is greater under quantity than under price competition. An increase in the lower bound will, in turn, lead to a decrease in the corresponding degree of product differentiation μ through $f^q(\mu)$

Turn next to a comparison between the percentage of the payoff to each firm to the total payoff in (V, V) under price competition and that under quantity competition. In (V,

V) the percentage of the high-quality firm's payoff to the total payoff is 50.21% while that of the low-quality firm's payoff to the total payoff is 49.79%. These percentages are almost identical. Thus, given the low-quality firm's choice of outsourcing, the high-quality firm's choice of in-house production does not require its efficiency compared to that of outsourcing to be so high under quantity competition. This means that an upper bound of the interval of β where (K, V) is a subgame perfect equilibrium is lower under quantity than under price competition. Furthermore, this implies that in (K, V) the corresponding degree of product differentiation is lower under quantity than under price competition through $f^q(\mu)$.

In (K, V), under price competition $\mu_{13}^{**} = 4.862582$ and $\mu_{34}^{**} = 2.866840$ correspond to $\beta_{13}^{**} = 0.217161b$ and $\beta_{34}^{**} = 0.581924b$ through f^p, respectively, whereas under quantity competition $\mu_{13}^{\ddagger} = 2.725923$ and $\mu_{34}^{\ddagger} = 1.382835$ correspond to $\beta_{13}^{\ddagger} = 0.246262b$ and $\beta_{34}^{\ddagger} = 0.445844b$ through f^p, respectively. It should be noted that Cournot competition will give rise to less product differentiation at equilibrium than Bertrand competition, which will, in turn, lead to the result that the interval of β where (K, V) constitutes a subgame perfect equilibrium is narrower under quantity than under price competition.

5. Comparison: Bertrand vs. Cournot

This section deals with a comparison of firms' choices of the quality and organizational production mode in price and quantity competition. (K, V) and (V, V) are subgame perfect equilibria of the game both under price and under quantity competition.

Let us first turn to (V, V) in which equilibrium costs of quality improvement fall on variable costs instead of fixed costs. Motta (1993) shows that more product differentiation occurs under price than under quantity competition. He states that total profits are higher under quantity than under price competition. However, social surplus composed of the sum of consumer and producer surplus is higher under price than under quantity competition. These remarks apply to (V, V) in this paper, too. Also, it is worth adding that the degree of population heterogeneity γ under price competition is greater than 2.657789 while that under quantity competition is larger than 1.861795. This means that we reach these results on condition that the distribution of consumers' taste in markets should be broader in the sense of the higher degree of population heterogeneity under price than under quantity competition. Because Bertrand competition is harsher than Cournot competition, the former will give rise to more product differentiation than the latter. To put it another way, under price competition firms try to relax market competition by choosing qualities that are further apart from each other than under quantity competition. The higher degree of population heterogeneity will give the firms a broad scope for segmenting the market under price competition, too.

It can be seen from Propositions 1 and 2 that if β belongs to the interval [0.246262b, 0.445844b], then (K, V) constitutes a subgame perfect equilibrium of the game under price and under quantity competition. Suppose that β is in the interval. Table 2 (3) gives the equilibrium values obtained under price (quantity) competition when β is equal to $0.246262b$ and $0.445844b$, respectively.

Unlike (V, V), total profits are higher under price than under quantity competition in (K, V). Under price competition consumer surplus is equal to $0.177868b^3/v$ when β is equal to $0.246262b$, while if β is equal to $0.445844b$, then it is $0.113669b^3/v$. Consumer surplus under quantity competition equals $0.148062b^3/v$ and $0.0939828b^3/v$, respectively. Under price competition, therefore, social surplus is equal to $0.285849b^3/v$ when β is equal to $0.246262b$, while if β is equal to $0.445844b$, then it is $0.166547b^3/v$. Social surplus under quantity competition equals $0.254796b^3/v$ and $0.142414b^3/v$, respectively. These results are similar to those obtained in (K, K) where the firms incur fixed costs of quality improvement (see Motta, 1993, Table I).

Table 2 : Equilibrium Values under Price Competition[9]

$\beta = 0.246262b$		
High-quality Firm	Low-quality Firm	
$s_{H,3} = 1.030398b/v$	$s_{L,3} = 0.230204b/v$	$s_{H,3} - s_{L,3} = 0.800195b/v$
$p_{H,3} = 0.430782b^2/v$	$p_{L,3} = 0.0613694b^2/v$	$p_{H,3}/p_{L,3} = 7.019492$
$q_{H,3} = 0.538347b$	$q_{L,3} = 0.195066b$	$q_{H,3} + q_{L,3} = 0.733412b$
$\pi_{H,3} = 0.101179b^3/v$	$\pi_{L,3} = 0.00680245b^3/v$	$\pi_{H,3} + \pi_{L,3} = 0.107982b^3/v$
		$CS = 0.177868b^3/v$
		$SS = 0.285849b^3/v$
		$\tilde{\theta}_3 = 0.266588b$
		$\hat{\theta}_3 = 0.461653b$
		$\gamma_3 > 3.751113$
		$\mu_3 = 4.476031$

9 In Tables 2 and 3, let *CS* and *SS* denote consumer surplus and social surplus, respectively.

$\beta = 0.445844b$		
High-quality Firm	Low-quality Firm	
$s_{H,3} = 0.579239b/v$	$s_{L,3} = 0.180052b/v$	$s_{H,3} - s_{L,3} = 0.399188b/v$
$p_{H,3} = 0.220850b^2/v$	$p_{L,3} = 0.0424223b^2/v$	$p_{H,3}/p_{L,3} = 5.204924$
$q_{H,3} = 0.553136b$	$q_{L,3} = 0.211252b$	$q_{H,3} + q_{L,3} = 0.764388b$
$\pi_{H,3} = 0.0473407b^3/v$	$\pi_{L,3} = 0.00553756b^3/v$	$\pi_{H,3} + \pi_{L,3} = 0.0528783b^3/v$
		$CS = 0.113669b^3/v$
		$SS = 0.166547b^3/v$
		$\bar{\theta}_3 = 0.235612b$
		$\hat{\theta}_3 = 0.446864b$
		$\gamma_3 > 4.244266$
		$\mu_3 = 3.217073$

Table 3: Equilibrium Values under Quantity Competition

$\beta = 0.246262b$		
High-quality Firm	Low-quality Firm	
$s_{H,3} = 1.023256b/v$	$s_{L,3} = 0.375380b/v$	$s_{H,3} - s_{L,3} = 0.647876b/v$
$p_{H,3} = 0.479360b^2/v$	$p_{L,3} = 0.134991b^2/v$	$p_{H,3}/p_{L,3} = 3.551047$
$q_{H,3} = 0.468465b$	$q_{L,3} = 0.171922b$	$q_{H,3} + q_{L,3} = 0.640388b$
$\pi_{H,3} = 0.0956389b^3/v$	$\pi_{L,3} = 0.0110952b$	$\pi_{H,3} + \pi_{L,3} = 0.106734b^3/v$
		$CS = 0.148062b^3/v$
		$SS = 0.254796b^3/v$
		$\bar{\theta}_3 = 0.359612b$
		$\hat{\theta}_3 = 0.531535b$
		$\gamma_3 > 2.780773$
		$\mu_3 = 2.725923$

$\beta = 0.445844b$		
High-quality Firm	Low-quality Firm	
$s_{H,3} = 0.579181b/v$	$s_{L,3} = 0.418836b/v$	$s_{H,3} - s_{L,3} = 0.160345b/v$
$p_{H,3} = 0.252449b^2/v$	$p_{L,3} = 0.161994b^2/v$	$p_{H,3}/p_{L,3} = 1.558383$
$q_{H,3} = 0.435873b$	$q_{L,3} = 0.177354b$	$q_{H,3} + q_{L,3} = 0.613227b$
$\pi_{H,3} = 0.0352564b^3/v$	$\pi_{L,3} = 0.0131743b^3/v$	$\pi_{H,3} + \pi_{L,3} = 0.0484307b^3/v$
		$CS = 0.0939828b^3/v$
		$SS = 0.142414b^3/v$
		$\bar{\theta}_3 = 0.386773b$
		$\hat{\theta}_3 = 0.564127b$
		$\gamma_3 > 2.585498$
		$\mu_3 = 1.382835$

6. Conclusion

In this paper, we have used a vertically differentiated duopoly model to analyse how firms' choice of two types of organizational production mode, vertical integration and outsourcing, will influence their quality choice, pricing and profits. Among other things, we have defined conditions under which the asymmetric configuration, where the high-quality firm chooses vertical integration while the low-quality firm chooses outsourcing, is accepted as a subgame perfect equilibrium outcome. Moreover, we have shown that not only the other asymmetric configuration but also the symmetric configuration where both firms choose in-house production is ruled out as the subgame perfect equilibrium outcome. The other symmetric configuration where both firms choose outsourcing is the subgame perfect equilibrium.

Shy and Stenbacka (2003) provide an example exemplifying (V, V) as a subgame perfect equilibrium outcome. They suggest that it is a common business practice for competing product market firms to outsource production to a joint input producer in order to exploit economies of scale. Its good example is given by the competing mobile phone producers Ericsson and Nokia that outsource production to take place in Elcoteq's (a joint subcontractor) production facilities. It is a fact that in the mobile phone industry the unit price is much lower than in the LCD TV industry. This may imply that each final goods producer does not have a tendency to make a heavy investment in state-of-the-art production facilities and R&D, but he has an incentive to outsource production to a joint subcontractor in order to enable the whole industry to fully utilize economies of scale.

As already mentioned in our study, in real world LCD TV markets electronics manufacturers aiming for vertical integration coexist with electronics producers outsourcing the production of all or part of the inputs they need. This offers an example of the asymmetric equilibrium configuration (K, V).

Which of the two subgame perfect equilibrium outcomes takes place depends on what value the efficiency ratio β takes on. (K, V) occurs when β is small, i.e., when the efficiency of in-house production relative to that of outsourcing is high. (V, V) takes place when β is large, i.e., when the efficiency of outsourcing compared to that of in-house production is high. In Japan it is Sharp and Panasonic that have so far made massive investments in state-of-the-art facilities that carry out integrated production of large LCD TVs from manufacture of LCD panels to final assembly of TV sets. On the one hand, this will lead to an increase in the efficiency of in-house production relative to that of outsourcing, i.e., a reduction in β; on the other hand, it will allow them to utilize economies of scale more fully and so to reduce average cost. Furthermore, it is well known that they make a heavy investment in R&D for an improvement in the quality of products and the development of new products.

In the two equilibrium configurations we have also confirmed the earlier result that Cournot competition will give rise to less product differentiation at equilibrium than Bertrand competition. Furthermore, we have seen that social welfare is higher when firms compete in prices rather than in quantities.

Appendix

Derivation of (15). In the third stage, firms choose prices given the organizational production modes and quality levels. From the first-order conditions, $\partial\Pi_{\mathrm{HV}}/\partial p_{\mathrm{H}} = 0$ and $\partial\Pi_{\mathrm{LK}}/\partial p_{\mathrm{L}} = 0$, we can solve for each firm's price as a function of qualities:

$$p_{\mathrm{H}} = \frac{2s_{\mathrm{H}}[c(s_{\mathrm{H}}) + b(s_{\mathrm{H}} - s_{\mathrm{L}})]}{4s_{\mathrm{H}} - s_{\mathrm{L}}}; \quad p_{\mathrm{L}} = \frac{s_{\mathrm{L}}[c(s_{\mathrm{H}}) + b(s_{\mathrm{H}} - s_{\mathrm{L}})]}{4s_{\mathrm{H}} - s_{\mathrm{L}}}, \tag{59}$$

where $c(s_{\mathrm{H}}) = \frac{1}{2}vs_{\mathrm{H}}^2$.

Substituting these prices into Π_{HV} and Π_{LK} yields:

$$\Pi_{\mathrm{HV}} = \frac{s_{\mathrm{H}}^2[4b(s_{\mathrm{H}} - s_{\mathrm{L}}) + vs_{\mathrm{H}}(-2s_{\mathrm{H}} + s_{\mathrm{L}})]^2}{4(s_{\mathrm{H}} - s_{\mathrm{L}})(4s_{\mathrm{H}} - s_{\mathrm{L}})^2}, \tag{60}$$

$$\Pi_{\mathrm{LK}} = \frac{s_{\mathrm{L}}[v^2s_{\mathrm{H}}^5 + 4bvs_{\mathrm{H}}^3(s_{\mathrm{H}} - s_{\mathrm{L}}) + 4b^2s_{\mathrm{H}}(s_{\mathrm{H}} - s_{\mathrm{L}})^2 - 2ks_{\mathrm{L}}(s_{\mathrm{H}} - s_{\mathrm{L}})(-4s_{\mathrm{H}} + s_{\mathrm{L}})^2]}{4(s_{\mathrm{H}} - s_{\mathrm{L}})(4s_{\mathrm{H}} - s_{\mathrm{L}})^2}. \tag{61}$$

Differentiating (60) and (61) with respect to each firm's quality, given the other firm's quality, gives the first-order conditions:

$$s_H[16b^2(s_H - s_L)^2(4s_H^2 - 3s_H s_L + 2s_L^2) - 8bvs_H(s_H - s_L)^2(16s_H^2 - 12s_H s_L + 3s_L^2)$$
$$+v^2 s_H^2(48s_H^4 - 116s_H^3 s_L + 92s_H^2 s_L^2 - 31s_H s_L^3 + 4s_L^4)]/[4(s_H - s_L)^2(4s_H - s_L)^3] = 0, \quad (62)$$

$$[4b^2 s_H^2(4s_H - 7s_L)(s_H - s_L)^2 - 4ks_L(s_H - s_L)^2(4s_H - s_L)^3 + 4bvs_H^3(s_H - s_L)^2(4s_H + s_L)$$
$$+v^2 s_H^5(4s_H^2 + s_H s_L - 2s_L^2)]/[4(s_H - s_L^2)(4s_H - s_L)^3] = 0. \quad (63)$$

Define $s_L \equiv x$. By definition we have $s_H = \mu x$. Substituting these expressions into (62), we can solve for x as a function of μ:

$$x_2^* = \frac{4b(-1+\mu)}{v\mu(-1+2\mu)}; \quad x_2^{**} = \frac{4b(-1+\mu)(2-3\mu+4\mu^2)}{v\mu(-4+23\mu-46\mu^2+24\mu^3)}. \quad (64)$$

Evaluating the second-order condition for the high-quality firm at x_2^*, we obtain:

$$\frac{2bv\mu(1-4\mu+2\mu^2)^2}{(-1+2\mu)(1-5\mu+4\mu^2)} > 0 \quad \text{for} \quad \mu > 0.5,$$

while evaluating the second-order condition for the high-quality firm at x_2^{**} yields:

$$-\frac{2bv\mu(1-4\mu+2\mu^2)(-8+60\mu-123\mu^2+128\mu^3-78\mu^4+24\mu^5)}{(-1+\mu)^2(-1+4\mu)(2-3\mu+4\mu^2)(-4+23\mu-46\mu^2+24\mu^3)} < 0 \text{ for } \mu > 1.707107.$$

Thus, x_2^{**} in (64) is accepted as a 'solution'.

Substituting x_2^{**} into (63) and arranging terms leads to:

$$\frac{k}{v} = \frac{b\mu^3(4-11\mu+8\mu^2)(-20+81\mu-84\mu^2+32\mu^3)}{4(-1+\mu)(-1+4\mu)(2-3\mu+4\mu^2)(-4+23\mu-46\mu^2+24\mu^3)}. \quad (65)$$

Letting $\beta \equiv k/v$ and denoting the right-hand side of (65) by $g^p(\mu)$ leads to $\beta = g^p(\mu)$.

Derivation of (21). Solving the first-order conditions, $\partial\Pi_{HK}/\partial p_H = 0$ and $\partial\Pi_{LV}/\partial p_L = 0$, yields:

$$p_H = \frac{s_H[c(s_L) + 2b(s_H - s_L)]}{4s_H - s_L}; \quad p_L = \frac{2s_H c(s_L) + bs_L(s_H - s_L)}{4s_H - s_L}, \quad (66)$$

where $c(s_L) = \frac{1}{2}vs_L^2$.

Substituting these prices into Π_{HK} and Π_{LV} produces:

$$\Pi_{\mathrm{HK}} = \frac{s_{\mathrm{H}}^2[16b^2(s_{\mathrm{H}}-s_{\mathrm{L}})^2 + 8bvs_{\mathrm{L}}^2(s_{\mathrm{H}}-s_{\mathrm{L}}) + v^2s_{\mathrm{L}}^4 - 2k(s_{\mathrm{H}}-s_{\mathrm{L}})(-4s_{\mathrm{H}}+s_{\mathrm{L}})^2]}{4(s_{\mathrm{H}}-s_{\mathrm{L}})(4s_{\mathrm{H}}-s_{\mathrm{L}})^2}, \tag{67}$$

$$\Pi_{\mathrm{LV}} = \frac{s_{\mathrm{H}}s_{\mathrm{L}}[2b(s_{\mathrm{H}}-s_{\mathrm{L}}) + vs_{\mathrm{L}}(-2s_{\mathrm{H}}+s_{\mathrm{L}})^2]}{4(s_{\mathrm{H}}-s_{\mathrm{L}})(4s_{\mathrm{H}}-s_{\mathrm{L}})^2}. \tag{68}$$

Differentiating (67) and (68) with respect to each firm's quality, given the other firm's quality, gives the first-order conditions:

$$\begin{aligned}&-s_{\mathrm{H}}[4k(s_{\mathrm{H}}-s_{\mathrm{L}})^2(4s_{\mathrm{H}}-s_{\mathrm{L}})^3 + 16bvs_{\mathrm{L}}^3(s_{\mathrm{H}}-s_{\mathrm{L}})^2 + v^2s_{\mathrm{L}}^4(4s_{\mathrm{H}}^2+s_{\mathrm{H}}s_{\mathrm{L}}-2s_{\mathrm{L}}^2)\\&-16b^2(s_{\mathrm{H}}-s_{\mathrm{L}})^2(4s_{\mathrm{H}}^2-3s_{\mathrm{H}}s_{\mathrm{L}}+2s_{\mathrm{L}}^2)]/[4(s_{\mathrm{H}}-s_{\mathrm{L}})^2(4s_{\mathrm{H}}-s_{\mathrm{L}})^3] = 0,\end{aligned} \tag{69}$$

$$\begin{aligned}&s_{\mathrm{H}}[4b^2s_{\mathrm{H}}(4s_{\mathrm{H}}-7s_{\mathrm{L}})(s_{\mathrm{H}}-s_{\mathrm{L}})^2 - 4bvs_{\mathrm{L}}(s_{\mathrm{H}}-s_{\mathrm{L}})^2(16s_{\mathrm{H}}^2-12s_{\mathrm{H}}s_{\mathrm{L}}+s_{\mathrm{L}}^2)\\&+v^2s_{\mathrm{L}}^2(48s_{\mathrm{H}}^4-100s_{\mathrm{H}}^3s_{\mathrm{L}}+76s_{\mathrm{H}}^2s_{\mathrm{L}}^2-23s_{\mathrm{H}}s_{\mathrm{L}}^3+2s_{\mathrm{L}}^4)]/[4(s_{\mathrm{H}}-s_{\mathrm{L}})^2(4s_{\mathrm{H}}-s_{\mathrm{L}})^3] = 0.\end{aligned} \tag{70}$$

Substituting $s_{\mathrm{L}} = x$ and $s_{\mathrm{H}} = \mu x$ into (70), we can solve for x as a function of μ:

$$x_3^* = \frac{2b(-1+\mu)}{v(-1+2\mu)}; \quad x_3^{**} = \frac{2b\mu(-1+\mu)(-7+4\mu)}{v(-2+19\mu-38\mu^2+24\mu^3)}. \tag{71}$$

Evaluating the second-order condition for the low-quality firm at x_3^*, we have:

$$\frac{bv\mu(1-2\mu+2\mu^2)^2}{(-1+2\mu)(1-5\mu+4\mu^2)} > 0 \text{ for } \mu > 0.5,$$

while evaluating the second-order condition for the low-quality firm at x_3^{**} yields:

$$-\frac{bv\mu(1-2\mu+2\mu^2)(28-87\mu+102\mu^2-70\mu^3+24\mu^4)}{(-1+\mu)^2(-7+4\mu)(-1+4\mu)(-2+19\mu-38\mu^2+24\mu^3)} < 0 \text{ for } \mu > 1.75.$$

Thus, x_3^{**} in (64) is accepted as a 'solution'.

Substituting x_3^{**} into (69) and arranging terms gives:

$$\frac{k}{v} = \frac{b(4-15\mu+12\mu^2)(8-42\mu+99\mu^2-104\mu^3+48\mu^4)}{2(-1+\mu)\mu(-7+4\mu)(-1+4\mu)(-2+19\mu-38\mu^3+24\mu^4)}. \tag{72}$$

Letting $f^p(\mu)$ denote the right-hand side of (72) leads to $\beta = f^p(\mu)$.

Proof of Lemma 1. Consider first whether $\pi_{\mathrm{H},1} \geq \pi_{\mathrm{H},2}$. $\pi_{\mathrm{H},1}$ given by the first expression in (12) includes parameters b and k, while $\pi_{\mathrm{H},2}$ has parameters b and v and the degree of product differentiation μ. When the high-quality firm makes a comparison between $\pi_{H,1}$ in (K, K) and $\pi_{H,2}$ in (V, K), it faces $\beta = g^p(\mu)$ represented by (15). This equation relates k and v to μ. Using (15) enables us to express $\pi_{H,1}$ in terms of v rather than k.

Substituting $k = vg^p(\mu)$ into the first expression in (12) yields:

$$\pi_{H,1} = \frac{0.0977544b^3(-1+\mu)(-1+4\mu)(2-3\mu+4\mu^2)(-4+23\mu-46\mu^2+24\mu^3)}{v\mu^3(4-11\mu+8\mu^2)(-20+81\mu-84\mu^2+32\mu^3)}. \quad (73)$$

Let $R^p_{12}(\mu) \equiv \pi_{H,1}/\pi_{H,2}$. This ratio is given below:

$$R^p_{12}(\mu) = \frac{0.00152741(-1+4\mu)(-4+23\mu-46\mu^2+24\mu^3)^4}{\mu^4(-1+\mu)(4-11\mu+8\mu^2)(-20+81\mu-84\mu^2+32\mu^3)(1-4\mu+2\mu^2)^2}. \quad (74)$$

$\mu = 1.707107$ is an asymptotic line of $R^p_{12}(\mu)$. Because $\lim_{\mu\to 1.707107+} R^p_{12}(\mu) = +\infty$, $\lim_{\mu\to\infty} R^p_{12}(\mu) = 0$, $\lim_{\mu\to 1.707107+} dR^p_{12}(\mu)/d\mu = -\infty$ and $\lim_{\mu\to\infty} dR^p_{12}(\mu)/d\mu = 0$, $R^p_{12}(\mu)$ is positive and strictly decreasing in μ on (1.707107, +∞).[10] This implies that there exists a value of μ in the interval (1.707107, +∞) at which $R^p_{12}(\mu) = 1$, i.e., $\pi_{H,1} = \pi_{H,2}$. This value is $\mu^*_{12} = 3.287677$. Correspondingly, making use of $\beta = g^p(\mu)$ yields $\beta^*_{12} = 0.546074b$ at which $\pi^*_{H,2} = 0.0447532b^3/v$ is equal to $\pi_{H,1} = 0.0244386b^4/k$. Thus, $\pi_{H,1} \geq \pi_{H,2}$ for $\mu \leq \mu^*_{12}$, from which it follows that $\beta \leq \beta^*_{12}$. It should be noted that $g^p(\mu)$ attains a minimum $0.411542b$ at $\mu = 2.080460$. The above condition for $\pi_{H,1} \geq \pi_{H,2}$ is changed to $0.411542b \leq \beta \leq 0.546074b$. Conversely, if $0.546074b < \beta$, then $\pi_{H,1} < \pi_{H,2}$.

However, when μ is in the interval (1.585120, 2.255379), $\pi_{L,2} > \pi_{H,2}$. Find out whether $\pi_{H,1} > \pi_{L,2}$ for $\mu \in (1.585120, 2.255379)$, on which $\pi_{L,2}$ attains a maximum $0.0306901b^3/v$ at $\mu = 1.784800$. Because the second-order condition for the low-quality firm in (V, K) requires $\mu > 1.946960$, the maximum value of $\pi_{L,2}$ occurs at $\mu = 1.946960$ in [1.946960, 2.255379). It is $0.0286504b^3/v$. A value of β corresponding to $\mu = 1.946960$ is $0.416891b$ through $\beta = g^p(\mu)$, from which it follows that $\pi_{L,2} = 0.0119441b^4/k < 0.0244386b^4/k = \pi_{H,1}$ for $\mu \in [1.946960, 2.255379)$.[11] □

Proof of Lemma 2. Compare $\pi_{L,1}$ and $\pi_{L,3}$. Since the second expression in (12) includes parameters b and k, we use (21) relating k and v to μ. The low-quality firm's payoff $\pi_{L,1}$ can be rewritten as:

10 It should be noted that $\pi_{H,2}$ in (19) is positive and the second-order condition for the high-quality firm is negative for $\mu \in (1.707107, +\infty)$.

11 This question is closely related to the persistence of the high-quality advantage referred to by Lehmann-Grube (1997). In this case also we verify the persistence of the high-quality advantage.

$$\pi_{L,1} = \frac{0.00305482b^3(-1+\mu)\mu(-7+4\mu)(-1+4\mu)(-2+19\mu-38\mu^2+24\mu^3)}{v(4-15\mu+12\mu^2)(8-42\mu+99\mu^2-104\mu^3+48\mu^4)}. \quad (75)$$

Let $R^p_{13}(\mu) \equiv \pi_{L,1}/\pi_{L,3}$. We use $\pi_{L,3}$ given by the second expression in (25) to obtain:

$$R^p_{13}(\mu) = \frac{0.000381853(-1+4\mu)(-2+19\mu-38\mu^2+24\mu^3)^4}{(4-15\mu+12\mu^2)(8-42\mu+99\mu^2-104\mu^3+48\mu^4)(-1+\mu)\mu(1-2\mu+2\mu^2)^2}. \quad (76)$$

We have $\lim_{\mu\to 1+} R^p_{13}(\mu) = +\infty$, $\lim_{\mu\to\infty} R^p_{13}(\mu) = +\infty$, $\lim_{\mu\to 1+} dR^p_{13}(\mu)/d\mu = -\infty$ and $\lim_{\mu\to\infty} dR^p_{13}(\mu)/d\mu = 0.219947$. $R^p_{13}(\mu)$ attains a minimum 0.136995 at $\mu =$ 1.200335 where $d^2R^p_{13}(\mu)/d\mu^2 = 2.702819 > 0$. $R^p_{13}(\mu)$, then, is strictly increasing in $\mu \in (1.200335, +\infty)$. Therefore, there is a value of μ at which $R^p_{13}(\mu) = 1$, i.e., $\pi_{L,1} = \pi_{L,3}$. Its value is $\mu^{**}_{13} = 4.862582$. Making use of $\beta = f^p(\mu)$ leads to the result that we have $\beta^{**}_{13} = 0.217161b$ corresponding to μ^{**}_{13} and correspondingly $\pi^{**}_{L,3} = 0.00703356b^3/v$ $= 0.00152741b^4/k = \pi_{L,1}$. Because $\pi_{L,3}$ is positive and the second-order condition for the low-quality firm is negative for $\mu \in (1.75, +\infty)$, $\pi_{L,1} \geq \pi_{L,3}$ for $\mu \in [4.862582, +\infty)$. Using $\beta = f^p(\mu)$ yields $\pi_{L,1} \geq \pi_{L,3}$ for $\beta \leq 0.217161b$. Conversely, if $0.217161b < \beta$, then $\pi_{L,1} < \pi_{L,3}$. □

Proof of Lemma 3. $\pi_{L,2}$ is given by the second expression in (19) and $\pi_{L,4}$ by that in (30). Let $R^p_{24}(\mu)$ denote the ratio of the former to the latter:

$$R^p_{24}(\mu) \equiv \frac{82.311433(-1+\mu)(2-3\mu+4\mu^2)^2(4-15\mu+8\mu^2)(4-11\mu+8\mu^2)}{(-1+4\mu)(-4+23\mu-46\mu^2+24\mu^3)^3}. \quad (77)$$

Since $\mu = 1.261890$ is an asymptotic line of $R^p_{24}(\mu)$, $\lim_{\mu\to 1.261890+} R^p_{24}(\mu) = -\infty$. In addition, $\lim_{\mu\to\infty} R^p_{24}(\mu) = 0$. $R^p_{24}(\mu)$ attains a maximum 1.263072 at $\mu = 1.784800$ where $d^2R^p_{24}(\mu)/d\mu^2 = -11.773962 < 0$. $\pi_{L,2} > 0$ for $\mu > 1.553054$ and the second-order condition for the low-quality firm is negative for $\mu > 1.946960$. Because $d^2R^p_{24}(\mu)/d\mu^2 < 0$ on $(1.784800, +\infty)$, $R^p_{24}(\mu)$ is strictly decreasing in $\mu \in (1.946960, +\infty)$. Letting $R^p_{24}(\mu)$ be set equal to one, we have $\mu^*_{24} = 2.182609$ and correspondingly $\beta^*_{24} = 0.413810b$ through $\beta = g^p(\mu)$ where $\pi_{L,2} = \pi_{L,4}$. In this lemma the intervals of β, $(0.411542b, 0.416891b)$ and $[0.411542b, 0.413810b]$, correspond to those of μ, $(1.946960, 2.080460)$ and $[2.080460, 2.182609]$, respectively. Because $g^p(\mu)$ is at first decreasing and then increasing in $\mu \in (1.946960, +\infty)$, two values of μ correspond to a given value of β. For example, $\mu = 1.946960$ and 2.242880 correspond to $\beta = 0.416891b$. Since $\pi_{L,2}$ is decreasing in μ over $[1.946960, +\infty)$, the low-quality firm will choose the lower one from those two values corresponding to a given value of β. Therefore, if $\beta \in (0.411542b, 0.416891b)$ or $[0.411542b, 0.413810b]$, then $\pi_{L,2} \geq \pi_{L,4}$. Conversely, if $\beta >$ $0.416891b$, then $\pi_{L,2} < \pi_{L,4}$. □

Proof of Lemma 4. Compare $\pi_{H,3}$ and $\pi_{H,4}$. Let $R^p_{34}(\mu) \equiv \pi_{H,3}/\pi_{H,4}$:

$$R^p_{34}(\mu) = \frac{30.475844(7-4\mu)^2(-1+\mu)\mu^4(4-15\mu+12\mu^2)(4-13\mu+12\mu^2)}{(-1+4\mu)(-2+19\mu-38\mu^2+24\mu^3)^3}. \quad (78)$$

$R^p_{34}(\mu)$= 0 and $dR^p_{34}(\mu)/d\mu = 0$ at $\mu = 1.75$. In addition, $d^2R^p_{34}(\mu)/d\mu^2 = 3.625273 > 0$ at μ = 1.75. Furthermore, $\lim_{\mu\to\infty} R^p_{34}(\mu) = +\infty$ and $\lim_{\mu\to\infty} dR^p_{34}(\mu)/d\mu = 1.269827$. Since $R^p_{34}(\mu)$ is strictly increasing in $\mu \in [1.75, +\infty)$, there exists a value of μ at which $R^p_{34}(\mu)$= 1, i.e., $\pi_{H,3} = \pi_{H,4}$. This value is $\mu^{**}_{34} = 2.866840$ and correspondingly β^{**}_{34} = $0.581924b$ through $\beta = f^p(\mu)$, at which both firms' profits are $0.0328129b^3/v$. Therefore, if $\beta \leq 0.581924b$, then $\pi_{H,3} \geq \pi_{H,4}$. Conversely, if $0.581924b < \beta$, then $\pi_{H,3} < \pi_{H,4}$.[12] □

Proof of Proposition 1. From Table 1 we see that (K, K) is a Nash equilibrium when

$$\pi_{H,1} \geq \pi_{H,2} \quad \text{and} \quad \pi_{L,1} \geq \pi_{L,3}. \quad (79)$$

Lemmas 1 and 2 say that a sufficient condition to have $\pi_{H,1} \geq \pi_{H,2}$ is $0.411542b \leq \beta \leq 0.546074b$ while the condition for $\pi_{L,1} \geq \pi_{L,3}$ is $\beta \leq 0.217161b$. Then, these conditions are incompatible and thus (K, K) is not a Nash equilibrium.

Conditions for (V, K) to be a Nash equilibrium are:

$$\pi_{H,2} \geq \pi_{H,1} \quad \text{and} \quad \pi_{L,2} \geq \pi_{L,4}. \quad (80)$$

It follows from Lemma 1 that if $\beta \geq 0.546074b$, then $\pi_{H,2} \geq \pi_{H,1}$. Lemma 3 says that a sufficient condition for $\pi_{L,2} \geq \pi_{L,4}$ is $\beta \in (0.411542b, 0.416891b)$ or $[0.411542b, 0.413810b]$. These conditions are incompatible with each other. Thus, (V, K) is not a Nash equilibrium.

Similarly, if the following conditions are satisfied:

$$\pi_{H,3} \geq \pi_{H,4} \quad \text{and} \quad \pi_{L,3} \geq \pi_{L,1}, \quad (81)$$

then (K, V) is a Nash equilibrium. Lemma 2 says that a condition for $\pi_{L,1} \leq \pi_{L,3}$ is $\beta \geq 0.217161b$. Lemma 4 gives a sufficient condition for $\pi_{H,3} \geq \pi_{H,4}$, i.e., $\beta \leq 0.581924b$ ($= \beta^{**}_{34}$). Both lemmas therefore lead to the result that if $0.217161b \leq \beta \leq 0.581524b$, then (K, V) is a Nash equilibrium.

Turn to conditions under which (V, V) is a Nash equilibrium:

12 In (K, V), if $\mu > 1.75$, then $\pi_{H,3} > 0$ and $\pi_{L,3} > 0$. Moreover, the second-order condition for each firm is negative for $\mu > 1.75$.

$$\pi_{H,4} \geq \pi_{H,3} \quad \text{and} \quad \pi_{L,4} \geq \pi_{L,2}. \tag{82}$$

It follows from Lemma 4 that if $\beta \geq 0.581924b$, then $\pi_{H,3} \leq \pi_{H,4}$. Lemma 3 says that if $\beta \geq 0.416891b$, then $\pi_{L,2} \leq \pi_{L,4}$. Thus, if $\beta \geq 0.581924b$, then $\pi_{L,2} \leq \pi_{L,4}$ while $\pi_{H,3} \leq \pi_{H,4}$. This means that if $\beta \geq 0.581924$b, then (V, V) is a Nash equilibrium. □

Derivation of (41). From the first-order conditions, $\partial\Pi_{HV}/\partial q_H = 0$ and $\partial\Pi_{LK}/\partial q_L = 0$, we can solve for each firm's output as a function of qualities:

$$q_H = -\frac{2c(s_H) - b(2s_H - s_L)}{4s_H - s_L}; \quad q_L = \frac{c(s_H) + bs_H}{4s_H - s_L}, \tag{83}$$

where $c(s_H) = \frac{1}{2}vs_H^2$.

Substituting these quantities into Π_{HV} and Π_{LK} yields:

$$\Pi_{HV} = \frac{s_H[b(-2s_H + s_L) + vs_H^2]^2}{(4s_H - s_L)^2}, \tag{84}$$

$$\Pi_{LK} = \frac{s_L[s_H^2(2b + vs_H)^2 - 2ks_L(4s_H - s_L)^2]}{4(4s_H - s_L)^2}. \tag{85}$$

Differentiating (84) and (85) with respect to each firm's quality, given the other firm's quality, gives the first-order conditions:

$$[b^2(16s_H^3 - 12s_H^2 s_L + 4s_H s_L^2 - s_L^3) - 2bvs_H^2(16s_H^2 - 12s_H s_L + 3s_L^2) + v^2 s_H^4(12s_H - 5s_L)]/(4s_H - s_L)^3 = 0, \tag{86}$$

$$[-4ks_L(4s_H - s_L)^3 + s_H^2(4s_H + s_L)(2b + vs_H)^2]/[4(4s_H - s_L^3)] = 0. \tag{87}$$

Substituting $s_L = x$ and $s_H = \mu x$ into (86), we can solve for x as a function of μ:

$$x_2^* = \frac{b(-1 + 2\mu)}{v\mu^2}; \quad x_2^{**} = \frac{b(1 - 2\mu + 8\mu^2)}{v\mu^2(-5 + 12\mu)}. \tag{88}$$

Evaluating the second-order condition for the high-quality firm at x_2^*, we obtain:

$$\frac{8bv\mu(-1 + \mu)^2}{(-1 + 4\mu)^2(-1 + 2\mu)} > 0,$$

while evaluating the second-order condition for the high-quality firm at x_2^{**} yields:

$$-\frac{8bv(-1+\mu)\mu(5-3\mu+12\mu^2)}{(-1+4\mu)(-5+12\mu)(1-2\mu+8\mu^2)} < 0 \quad \text{for} \quad \mu > 1.$$

Thus, x_2^{**} in (88) is accepted as a 'solution'.

Substituting x_2^{**} into (87) and arranging terms leads to:

$$\frac{k}{v} = \frac{b\mu^2(1+4\mu)(-1+8\mu)^2}{4(-1+4\mu)(-5+12\mu)(1-2\mu+8\mu^2)}. \tag{89}$$

Letting $g^q(\mu)$ denote the right-hand side of (89) leads to $\beta = g^q(\mu)$.

Derivation of (47). Solving the first-order conditions, $\partial\Pi_{\mathrm{HK}}/\partial q_{\mathrm{H}} = 0$ and $\partial\Pi_{\mathrm{LV}}/\partial q_{\mathrm{L}} = 0$, yields:

$$q_{\mathrm{H}} = \frac{c(s_{\mathrm{L}}) + b(2s_{\mathrm{H}} - s_{\mathrm{L}})}{4s_{\mathrm{H}} - s_{\mathrm{L}}}; \quad q_{\mathrm{L}} = \frac{s_{\mathrm{H}}[-2c(s_{\mathrm{L}}) + bs_{\mathrm{L}}]}{s_{\mathrm{L}}(4s_{\mathrm{H}} - s_{\mathrm{L}})}, \tag{90}$$

where $c(s_{\mathrm{L}}) = \frac{1}{2}vs_{\mathrm{L}}^2$.

Substituting these quantities into Π_{HK} and Π_{LV} produces:

$$\Pi_{\mathrm{HK}} = \frac{s_{\mathrm{H}}\{-2ks_{\mathrm{H}}(4s_{\mathrm{H}} - s_{\mathrm{L}})^2 + [2b(2s_{\mathrm{H}} - s_{\mathrm{L}}) + vs_{\mathrm{L}}^2]^2\}}{4(4s_{\mathrm{H}} - s_{\mathrm{L}})^2}, \tag{91}$$

$$\Pi_{\mathrm{LV}} = \frac{s_{\mathrm{H}}^2 s_{\mathrm{L}}(b - vs_{\mathrm{L}})^2}{4(4s_{\mathrm{H}} - s_{\mathrm{L}})^2}. \tag{92}$$

Differentiating (91) and (92) with respect to each firm's quality, given the other firm's quality, gives the first-order conditions:

$$[-4ks_{\mathrm{H}}(4s_{\mathrm{H}} - s_{\mathrm{L}})^3 + 4b^2(16s_{\mathrm{H}}^3 - 12s_{\mathrm{H}}^2 s_{\mathrm{L}} + 4s_{\mathrm{H}}s_{\mathrm{L}}^2 - s_{\mathrm{L}}^3) + 4bvs_{\mathrm{L}}^4 - v^2 s_{\mathrm{L}}^4(4s_{\mathrm{H}} + s_{\mathrm{L}})]$$
$$/[4(4s_{\mathrm{H}} - s_{\mathrm{L}})^3] = 0, \tag{93}$$

$$\{s_{\mathrm{H}}^2(b - vs_{\mathrm{L}})[b(4s_{\mathrm{H}} + s_{\mathrm{L}}) - vs_{\mathrm{L}}(12s_{\mathrm{H}} - s_{\mathrm{L}})]\}/(4s_{\mathrm{H}} - s_{\mathrm{L}})^3 = 0. \tag{94}$$

Substituting $s_{\mathrm{L}} = x$ and $s_{\mathrm{H}} = \mu x$ into (94), we can solve for x as a function of μ:

$$x_3^* = \frac{b}{v}; \quad x_3^{**} = \frac{b(1+4\mu)}{v(-1+12\mu)}. \tag{95}$$

Since $x_3^* = b/v$ produces $\mu = bv/4k$, the second-order condition for the low-quality firm at x_3^* is :

$$\frac{2bv\mu^2}{(1-4\mu)^2} > 0,$$

while evaluating the second-order condition for the low-quality firm at x_3^{**} yields:

$$-\frac{2bv\mu^2(1+12\mu)}{(-1+4\mu)(1+4\mu)(-1+12\mu)} < 0 \quad \text{for} \quad \mu > 0.25.$$

Thus, x_3^{**} in (95) is accepted as a 'solution'.

Substituting x_3^{**} into (93) and arranging terms gives:

$$\frac{k}{v} = \frac{3b(3-8\mu+48\mu^2)}{4\mu(1+4\mu)(-1+12\mu)}. \tag{96}$$

Letting $f^q(\mu)$ denote the right-hand side of (96) leads to $\beta = f^q(\mu)$.

Proof of Lemma 5. Let $R_{12}^q(\mu)$ stand for the ratio of the first expression in (38) to that in (45). When the high-quality firm draws a comparison between $\pi_{H,1}$ and $\pi_{H,2}$, it faces $\beta = g^q(\mu)$ expressed by (41). Taking this equation into account, the ratio is written as follows:

$$R_{12}^q(\mu) = \frac{0.00486756(-1+4\mu)(-5+12\mu)^4}{\mu(1+\mu)(-1+\mu)^2(-1+8\mu)^2}. \tag{97}$$

$\lim_{\mu\to 1+} R_{12}^q(\mu) = +\infty$ and $\lim_{\mu\to\infty} R_{12}^q(\mu) = 0$. Moreover, $\lim_{\mu\to 1+} dR_{12}^q(\mu)/d\mu = -\infty$ and $\lim_{\mu\to\infty} dR_{12}^q(\mu)/d\mu = 0$. Since $d^2R_{12}^q(\mu)/d\mu^2 > 0$ on $(1, +\infty)$, $R_{12}^q(\mu)$ is positive and strictly decreasing in $\mu \in (1, +\infty)$. Thus, there exists a value of μ at which $R_{12}^q(\mu) = 1$, i.e., $\pi_{H,1} = \pi_{H,2}$. It is $\mu_{12}^\dagger = 2.107089$, which in turn produces $\beta_{12}^\dagger = 0.540551b$ through $\beta = g^q(\mu)$. $\pi_{H,2}^\dagger = 0.0360192b^3/v$ then is equal to $\pi_{H,1} = 0.0194703b^4/k$. Since $\mu = 5/12$ is an asymptotic line of $g^q(\mu)$, $\pi_{H,1} \geq \pi_{H,2}$ for β satisfying $0.416667b < \beta \leq 0.540551b$, from which it follows that $1 < \mu \leq 2.107089$. If $\beta > 0.540551b$, then $\pi_{H,1} < \pi_{H,2}$, in which case $\mu > 2.107089$. □

Proof of Lemma 6. Let R_{13}^q represent the ratio of the second part in (38) to that in (51). Moreover, taking (47) into account produces:

$$R_{13}^q(\mu) = \frac{0.000910776(-1+12\mu)^4}{\mu(3-8\mu+48\mu^2)}. \tag{98}$$

$R_{13}^q(\mu) = 0$ at $\mu = 1/12$ where $dR_{13}^q(\mu)/d\mu = 0$ and $d^4R_{13}^q(\mu)/d\mu^4 = 2039.6729 > 0$. $\lim_{\mu\to\infty} R_{13}^q(\mu) = +\infty$ and $\lim_{\mu\to\infty} dR_{13}^q(\mu)/d\mu = 0.393455$. $R_{13}^q(\mu)$ is positive and strictly increasing in $\mu \in (1/12, +\infty)$, which leads to the result that there exists a value of μ at which $R^q_{13}(\mu) = 1$, i.e., $\pi_{L,1} = \pi_{L,3}$. Its value is $\mu^\ddagger_{13} = 2.725923$, from which it follows that $\beta^\ddagger_{13} = 0.246262b$ and correspondingly $\pi^\ddagger_{L,3} = 0.0110952b^3/v = 0.00273233b^4/k = \pi_{L,1}$. It should be noted that $f^q(\mu)$ is decreasing in μ and so μ is decreasing in β. In (K, V) an upper bound of β is given by $f^q(1) = 129b/220 (= 0.586364b)$ which is an asymptotic line of $f^q(\mu)$. If $\beta \leq 0.246262b$ $(= \beta^\ddagger_{13})$, then $\pi_{L,1} \geq \pi_{L,3}$. Conversely, if $0.246262b < \beta < 0.586364b$, then $\pi_{L,1} < \pi_{L,3}$. □

Proof of Lemma 7. We derive a value of μ at which $\pi_{L,2} = \pi_{L,4}$ holds true. Define $R^q_{24}(\mu)$ to be the ratio of the second expression in (45) to that in (56) as follows:

$$R^q_{24}(\mu) = \frac{3.575858(1-8\mu)^2(-3+4\mu)(1-2\mu+8\mu^2)}{\mu^2(-1+4\mu)(-5+12\mu)^3}. \tag{99}$$

$\lim_{\mu\to\infty} R^q_{24}(\mu) = 0$ and $\lim_{\mu\to\frac{5}{12}+} R^q_{24}(\mu) = -\infty$. Because $dR^q_{24}(\mu)/d\mu = 0$, and $d^2R^q_{13}(\mu)/d\mu^2 = -12.153947 < 0$ at $\mu = 0.978574$, $R^q_{24}(\mu)$ attains a maximum 1.194499 there and thus is positive and strictly decreasing in $\mu \in (0.978574, +\infty)$. Therefore, there exists a value of μ at which $R^q_{24}(\mu) = 1$, i.e., $\pi_{L,2} = \pi_{L,4}$ holds true. Its value is $\mu^\dagger_{24} = 1.274575$, which correspondingly yields $\beta^\dagger_{24} = 0.433720b$ through $\beta = g^q(\mu)$. In (V, K) the second-order condition for the low-quality firm is negative for $\mu > 1.161438$. This inequality holds true for $\beta > 0.424270b$. If $0.424270b < \beta \leq 0.433720b$ $(= \beta^\ddagger_{24})$, then $\pi_{L,2} \geq \pi_{L,4}$. Conversely, if $0.433720b < \beta$, then $\pi_{L,2} < \pi_{L,4}$. □

Proof of Lemma 8. In order to find a value of μ and a corresponding value of β at which $\pi_{H,3} = \pi_{H,4}$, let $R^q_{34}(\mu)$ denote the ratio of the second expression in (51) to that in (56):

$$R^q_{34}(\mu) = \frac{10.636366\mu(-3+4\mu)(1+4\mu)}{(-1+12\mu)^2}. \tag{100}$$

$R^q_{34}(\mu)$ is equal to zero at $\mu = 3/4$ where $dR^q_{34}(\mu)/d\mu > 0$, and is positive for $\mu \in (3/4, +\infty)$. Moreover, $\lim_{\mu\to\infty} R^q_{34}(\mu) = +\infty$, $\lim_{\mu\to\infty} dR^q_{34}(\mu)/d\mu = 1.181818$, and $dR^q_{34}(\mu)/d\mu > 0$ for $\mu \in (3/4, +\infty)$. Thus, there exists a value of μ at which $\pi_{H,3} = \pi_{H,4}$ holds true. Its value is $\mu^\ddagger_{34} = 1.382835$ and then $\beta^\ddagger_{34} = 0.445844b$, at which both firms' profits are $0.0352564b^3/v$. Making use of (47) leads to the result that if $\beta \leq 0.445844b (= \beta^\ddagger_{34})$, then $\pi_{H,3} \geq \pi_{H,4}$. Conversely, if $0.445844b < \beta < 0.586364b$, then $\pi_{H,3} < \pi_{H,4}$. □

Proof of Proposition 2. Lemmas 5 and 6 say that a sufficient condition to have $\pi_{H,1} \geq \pi_{H,2}$ is $0.416667b < \beta \leq 0.540551b$ while the condition to obtain $\pi_{L,1} \geq \pi_{L,3}$ is $\beta \leq 0.246262b$, from which it follows that these conditions are incompatible. Thus, (K, K) is not a Nash equilibrium under Cournot competition, either.

Discuss the question of whether $\pi_{H,2} \geq \pi_{H,1}$ and $\pi_{L,2} \geq \pi_{L,4}$. Lemma 5 says that if

$\beta \geq 0.540551b$, then $\pi_{H,2} \geq \pi_{H,1}$. Lemma 7 gives a sufficient condition for $\pi_{L,2} \geq \pi_{L,4}$, i.e., $0.424270b < \beta \leq 0.433720b$. These conditions mean that a sufficient condition for $\pi_{H,2} \geq \pi_{H,1}$ is incompatible with that for $\pi_{L,2} \geq \pi_{L,4}$. Thus, (V, K) is not a Nash equilibrium.

Find a condition under which (K, V) is a Nash equilibrium. Lemma 6 says that a condition for $\pi_{L,1} \leq \pi_{L,3}$ is $0.246262b \leq \beta < 0.586364b$. Lemma 8 gives a sufficient condition for $\pi_{H,3} \geq \pi_{H,4}$, i.e., $\beta \leq 0.445844b$. Both lemmas mean that if $0.246262b \leq \beta \leq 0.445844b$, then $\pi_{L,1} \leq \pi_{L,3}$ and $\pi_{H,3} \geq \pi_{H,4}$, in which case (K, V) is a Nash equilibrium.

Finally, find out whether (V, V) is a Nash equilibrium. It follows from Lemma 7 that if $0.433720b \leq \beta$, then $\pi_{L,2} \leq \pi_{L,4}$. Lemma 8 says that if $0.445844b \leq \beta < 0.586364b$, then $\pi_{H,3} \leq \pi_{H,4}$. Thus, if $0.445844b \leq \beta < 0.586364b$, then $\pi_{H,3} \leq \pi_{H,4}$ while $\pi_{L,2} \leq \pi_{L,4}$. This means that if $0.445844b \leq \beta < 0.586364$b, then (V, V) is a Nash equilibrium. □

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