YARDSTICK COMPETITION AND QUALITY*

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Abstract

This paper explores the consequences for quality of introducing yardstick competition in duopoly when a verifiable quality indicator is available. Yardstick competition can be implemented by a menu of transfers that are linear in the cost differential between the two firms and in quality. Cost- and quality incentives are stronger in larger firms when improvements are highly valued by consumers and firms can significantly influence quality. Expenditures on quality improvement can increase or decrease following the introduction of yardstick competition. The crucial factor is the likelihood ratio of productivity between the two firms, not productivity differences.

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1 INTRODUCTION

The wave of regulatory reform that has swept over the industrialized countries in the last two decades has raised concern about the effect on quality of a stronger focus on cost minimization. During the Thatcher era, a whole range of public utilities (telecommunications, gas, electricity and water) were privatized in the United Kingdom. Academics were quick to identify the potential for firms of reducing quality as a response to pressure for reducing costs. Reductions in quality, it was argued, would have little effect on revenues owing to the firms' position as regional monopolies (see, e.g., Helm and Yarrow, 1988). The concern for quality was shared by the main architect behind the British reform, professor Stephen Littlechild, who in his report concerning the British water industry recognized the need for a joint regulation of prices and service (Littlechild, 1988). With the introduction of the Prospective Payment System (PPS) in US Medicare, observers perceived a danger that managers might devote most of their attention to reducing cost and that doctors might cut corners in medical treatment, e.g., by discharging patients prematurely, to reach ambitious cost targets (see, e.g., Johnson, 1984; Broyles and Rosko, 1985).

As suggested by these concerns, regulatory policies should be designed to balance quality and cost considerations. This paper studies the optimal regulation of quality and cost of two firms engaged in spatial competition. Two underlying factors that facilitate regulation are taken into account: quality indicators are available and performance is positively correlated among firms.

Quality indicators are available in many regulated industries. The British Drinking Water Inspectorate applies more than 50 microbiological, chemical and aesthetic parameters to measure the quality of tap water. The number, intensity and duration of outages form the basis of a quality indicator used in Sweden for regulating electricity distribution. Under the US Medicare system, utilization reviews are conducted to detect whether patients receive proper care. In England and Northern Ireland, the Quality Assessment Agency reviews universities and colleges based on student achievement and progression, curriculum design and organization.

The use of standardized technology implies that production cost is to some extent determined by factors common to all firms in the industry. In correlated environments, the regulator can draw inferences about single firms by comparing their performance to that of other firms in the industry. For example, a firm cannot convincingly argue to be a high-cost producer if comparable firms produce at low cost. Regulating firms on basis of relative performance is known as *yardstick competition* and is a powerful tool for extracting rents.[1] Two prominent examples of yardstick competition are the Prospective Payment System (PPS) used in US Medicare (Shleifer, 1985) and the regulation of English and Welsh water supply (Sawkins, 1995).

The ability to contract both on cost and a quality indicator provides the regulator with sufficient instruments to separate cost and quality regulation. Consequently, there is no underlying trade-off between cost and quality here. The optimal regulation can be implemented by a menu of transfers that are linear in the observed cost differential between the two firms and in quality. Cost efficiency dictates that the firm with the highest productivity should have the highest market share. As the scope for marginal cost reductions increases with firm size, the larger firm should have more high-powered cost incentives than the smaller firm. The larger firm should also have more high-powered quality incentives if the social value of quality is increasing in consumption, i.e., if quantity and quality are *net complements* (Laffont and Tirole, 1993). Quantity and quality are net complements here if consumers value quality improvement highly and firms have a significant

[1] The seminal papers on yardstick competition are Baiman and Demski (1980) and Holmstrom (1982). They are followed by Nalebuff and Stiglitz (1983), Demski and Sappington (1984), Mookherjee (1984), Shleifer (1985) and Cremér and McLean (1988). More recent contributions include Auriol and Laffont (1992), McAfee and Reny (1992), Auriol (1993), Dalen (1998), Sobel (1999) and Laffont and Martimort (2000).

influence on expected quality. In that case, a dollar spent on quality improvement raises the consumers' willingness to pay for the good by more than a dollar.[2]

Yardstick competition raises the efficiency of regulation by curbing informational rent. The scope for cost distortions due to rent extraction is smaller and both firms should ideally expand their production. This is impossible when market size is constant. All else equal, the social cost of distortions is smaller in firms at the tails of the productivity distribution because, on average, there is a smaller number of such firms. Thus, the tails are where yardstick competition has the largest impact on incentives. Hence, it is the firm with the lowest likelihood ratio which grows and therefore invests more in quality improvement when quantity and quality are net complements.

This is the first paper to analyze yardstick competition and quality, and only the second to go beyond the monopoly case in the analysis of optimal quality; see Sappington (2005) for a survey of quality regulation.[3] Auriol (1998) derives the optimal market structure when the quality delivered to consumers is an average of the quality produced by all firms in the industry; a leading example being the supply of gas by multiple producers in a common network. Producers can then free-ride on the quality of the competitors. I consider a setting where quality is a private good and study the effects of yardstick competition. Laffont and Tirole (1993) are the first to make the distinction between net complementarity and net substitutability in quality regulation. They derive linear

[2] Quantity and quality are *net substitutes* if a dollar spent on quality improvement raises the consumers' willingness to pay for the good by less than a dollar. Net substitutability follows if consumers either put little value on quality improvement or quality is essentially exogenous. In that case, the socially optimal expenditure on quality improvement is low, and quality is not an important issue.

[3] The seminal contribution is Lewis and Sappington (1991) which examines the effect on optimal monopoly regulation of verifiability, i.e., whether one can write contracts on quality. An abundance of health economics papers analyze quality and efficiency issues; see Chalkley and Malcomson (2000) for a survey. Most of them assume complete information. Those that incorporate incomplete information seldom go beyond comparing cost-plus to price-cap contracts. As a rule, monopoly is assumed, but Barros and Martinez-Giralt (2002) and Brekke et al. (2006) are exceptions using complete information. The above models cannot be used for analyzing the impact of yardstick competition or non-monopolies. More importantly, with incomplete contracts the results may be sensitive to the restrictions in the set of available contracts. The present paper avoids this problem by adopting a complete contracting framework, whereby an optimal regulation is derived. Finally, Dormont and Milcent (2005) construct a yardstick competition scheme à la Shleifer (1985), but with an exogenous quality dimension.

contracts in the monopoly case.

The remainder of this paper is organized as follows. Section 2 formulates the model. Section 3 derives the optimal regulatory policy and shows that it can be implemented by a menu of linear transfers. The qualitative properties of the regulatory contract are analyzed in Section 4. Finally, Section 5 concludes the analysis. All proofs are collected in an Appendix.

2 THE MODEL

I analyze a Hotelling model of spatial competition, augmented by a vertical quality dimension.

2.1 CONSUMERS

A continuum of consumers with unit measure is uniformly distributed on the unit interval, with one producer located at each end. Each consumer demands one unit at most. The consumer located at l obtains utility $\sigma_1^j - p_1^j - \gamma l$ upon buying from producer 1, $\sigma_2^j - p_2^j - \gamma(1-l)$ upon buying from producer 2 and 0 in case of no purchase. Let $\sigma_i^j \in \{\underline{\sigma}, \overline{\sigma}\}$, $\triangle\sigma = \overline{\sigma} - \underline{\sigma} > 0$, be a common knowledge indicator of the quality of the good produced by $i \in \{1,2\}$ in state j. This can be considered as a quality indicator published by the government. There are four quality states of the world. In state 1 both firms deliver a high quality product, $\sigma_1^1 = \sigma_2^1 = \overline{\sigma}$. In state 2 only firm 1 reaches the high quality, $\sigma_1^2 = \overline{\sigma}$, $\underline{\sigma} = \sigma_2^2$, whereas the opposite is true in state 3. Finally, both firms produce a low quality in state 4. Firm i charges p_i^j for a unit of the good in state $j \in \{1,2,3,4\}$, and γ is the (virtual) transportation cost and a measure of horizontal product differentiation. When both firms produce positive amounts, the demand for i's product is

$$q_i^j(\mathbf{p}^j) = \begin{cases} \frac{1}{\gamma}(\sigma_i^j - p_i^j) & \text{if } \frac{1}{\gamma}(\sigma_1^j - p_1^j + \sigma_2^j - p_2^j) \leq 1 \\ \frac{1}{2} + \frac{1}{2\gamma}(\sigma_i^j - p_i^j - \sigma_{-i}^j + p_{-i}^j) & \text{otherwise} \end{cases} \tag{1}$$

as a function of perceived quality and prices $\mathbf{p}^j = (p_i^j, p_{-i}^j)$. The consumer surplus is

$$\textstyle\sum_i V_i^j(\mathbf{p}^j) = \sum_i (\sigma_i^j - p_i^j - \frac{\gamma}{2} q_i^j(\mathbf{p}^j)) q_i^j(\mathbf{p}^j). \tag{2}$$

This paper focuses on the case where all consumers are served – the market is *fully covered*. Full market coverage is obtained if, e.g., the minimal quality $\underline{\sigma}$ is sufficiently high relative to the transportation cost γ. The assumption of full market coverage is realistic where universal service obligations apply, e.g., in water and electricity distribution, health care and elementary education. When all consumers are served, the market is one of duopoly. Comparatively few studies have focused on the optimal regulation of non-monopolistic industries, in particular as concerns quality regulation (an exception is Auriol, 1998). An *uncovered* market *de facto* characterizes a situation of *local monopoly* since small changes in the price or quality of one firm have no effect on the demand of the other. The effects of yardstick competition on costs and quality in local monopoly can be assessed by merging the yardstick competition results of Auriol and Laffont (1992) with the results on monopoly quality regulation by Laffont and Tirole (1993). Therefore, I skip a detailed analysis of this case.

2.2 FIRMS

The marginal production cost is constant and equal to $c_i = \beta_i + s_i - e_i$ for firm $i \in \{1, 2\}$. The regulator observes the marginal cost, but none of its components, β_i, s_i and e_i.

The exogenous productivity parameter $\beta_i = \alpha m + (1-\alpha)\varepsilon_i \in (\underline{\beta}, \overline{\beta}]$ consists of a common part m and an idiosyncratic part ε_i. *Industry-specific productivity* (ISP) is high ($m = \underline{m}$) with probability v and low ($m = \overline{m} > \underline{m}$) with probability $1 - v$. *Firm-specific productivity* (FSP) is continuously distributed on the interval $(\underline{\varepsilon}, \overline{\varepsilon}]$ with cumulative distribution $G(\cdot)$, where density $g = G' > 0$ is twice continuously differentiable. Further, I assume m, ε_1 and ε_2 to be stochastically independent. Finally, α is common knowledge and equal to $\alpha = (\overline{\varepsilon} - \underline{\varepsilon}) / (\overline{m} - \underline{m} + \overline{\varepsilon} - \underline{\varepsilon})$. Thus, β_i is distributed over two connected intervals as illustrated in Figure 1:

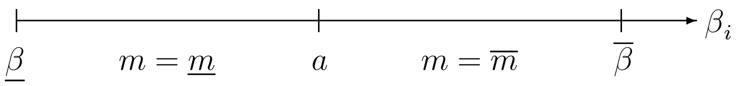

Figure 1: Productivity

When ISP is high, both firms have total productivity somewhere in the interval $(\underline{\beta}, a]$, with $\underline{\beta} = \alpha\underline{m} + (1-\alpha)\underline{\varepsilon}$ and $a = \alpha\underline{m} + (1-\alpha)\overline{\varepsilon}$. Conversely, low ISP implies both firms having total productivity in $(a, \overline{\beta}]$, with $a = \alpha\overline{m} + (1-\alpha)\underline{\varepsilon}$ and $\overline{\beta} = \alpha\overline{m} + (1-\alpha)\overline{\varepsilon}$. The marginal distribution of β_i on $(\underline{\beta}, \overline{\beta}]$ is a convolution of the distributions of m and ε_i. Denote by $f(\cdot)$ and $F(\cdot)$ the density function and cumulative distribution of β_i, respectively, and write $\mathbf{F}(\cdot)$ as the joint cumulative distribution of $\boldsymbol{\beta} = (\beta_i, \beta_{-i})$. The hazard rate F/f is non-decreasing by assumption.[4]

Firm i spends $s_i \in [0, \overline{s}]$ on quality improvement and reaches the high quality with probability $\theta(s_i)$, where $\theta(\cdot)$ is twice continuously differentiable, increasing and strictly concave, i.e., $\theta' > 0$, $\theta'' < 0$. The probability of state 1 is $\theta^1(\mathbf{s}) = \theta(s_1)\theta(s_2)$, the probability of state 2 is $\theta^2(\mathbf{s}) = \theta(s_1)(1 - \theta(s_2))$ and so forth, given expenditures $\mathbf{s} = (s_i, s_{-i})$.

The management of firm i devotes effort $e_i \in [0, \overline{e}]$ to cost containment and incurs a disutility of

[4] The stochastic structure described above was first utilized by Auriol and Laffont (1992). They show that a non-decreasing $(G + v/(1-v))/g$ and $vg(\overline{\varepsilon}) \geq (1-v)g(\underline{\varepsilon})$ are necessary and sufficient for global monotonicity of F/f. The structure has later been used for studying aspects of yardstick competition, such as investment incentives (Dalen, 1998) and collusion (Tangerås, 2002). See also Auriol (1993 and 2000).

effort, $\psi(\cdot)$, which is twice continuously differentiable, increasing and strictly convex, i.e., $\psi' > 0$, $\psi'' > 0$ and $\psi''' \geq 0$.

The operating profit of firm i in state j is $(p_i^j - c_i)q_i^j(\mathbf{p}^j)$. Firm i is risk neutral and receives a transfer t_i^j in state j which is net of operating profit. Therefore, i's rent is

$$u_i = \sum_j \theta^j(\mathbf{s})t_i^j - \psi(e_i). \tag{3}$$

2.3 WELFARE

Welfare equals consumer surplus plus industry rent minus the social cost of transfers

$$\sum_i \sum_j \theta^j(\mathbf{s})V_i^j(\mathbf{p}^j) + \sum_i u_i - (1+\lambda)\sum_i \sum_j \theta^j(\mathbf{s})(t_i^j - (p_i^j - c_i)q_i^j(\mathbf{p}^j)),$$

where $\lambda > 0$ is the shadow price on public funds. Using (3), welfare can be more conveniently restated as consumer surplus plus the social value of the operating profit minus the social cost of the firms' cost-containment efforts and industry rent

$$\sum_i \{\sum_j \theta^j(\mathbf{s})[V_i^j(\mathbf{p}^j) + (1+\lambda)(p_i^j - c_i)q_i^j(\mathbf{p}^j)] - (1+\lambda)\psi(e_i) - \lambda u_i\}.$$

2.4 REGULATION

By the Revelation Principle, the regulator can restrict herself to offering a menu of contracts which specifies a marginal cost target $c_i(\mathbf{b}) \geq 0$, four transfers $t_i(\mathbf{b}) = (t_i^1(\mathbf{b}), t_i^2(\mathbf{b}), t_i^3(\mathbf{b}), t_i^4(\mathbf{b})) \in \mathbb{R}^4$ net of operating profit and four prices $p_i(\mathbf{b}) = (p_i^1(\mathbf{b}), p_i^2(\mathbf{b}), p_i^3(\mathbf{b}), p_i^4(\mathbf{b})) \in \mathbb{R}_+^4$ for each possible productivity report $\mathbf{b} = (b_i, b_{-i}) \in (\underline{\beta}, \overline{\beta}]^2$. The regulatory contract chosen by each firm is common knowledge. The regulator maximizes expected welfare

$$\begin{aligned} EW = & \int_{\underline{\boldsymbol{\beta}}}^{\overline{\boldsymbol{\beta}}} \sum_i \{\sum_j \theta^j(\mathbf{s}(\boldsymbol{\beta}))[V_i^j(\mathbf{p}^j(\boldsymbol{\beta})) + (1+\lambda)(p_i^j(\boldsymbol{\beta}) - c_i(\boldsymbol{\beta}))q_i^j(\mathbf{p}^j(\boldsymbol{\beta}))] \\ - & (1+\lambda)\psi(e_i(\boldsymbol{\beta})) - \lambda u_i(\boldsymbol{\beta})\} d\mathbf{F}(\boldsymbol{\beta}), \end{aligned} \tag{4}$$

where

$$u_i(\boldsymbol{\beta}) = \sum_j \theta^j(\mathbf{s}(\boldsymbol{\beta}))t_i^j(\boldsymbol{\beta}) - \psi(e_i(\boldsymbol{\beta}))$$

is the equilibrium rent to firm i, subject to three sets of implementation constraints.

First, the regulator must provide each firm with the right incentives to spend the optimal amount on quality improvement $s_i(\boldsymbol{\beta})$ since these expenditures are unobservable to her. Assume that the two firms operate under the contract (b_i, β_{-i}), the vector of true types is $\boldsymbol{\beta} = (\beta_i, \beta_{-i})$ and that i believes that the competitor will spend the socially optimal amount $s_{-i}(\beta_{-i}, b_i)$ on quality improvement. Firm i spends s_i on quality improvement and exerts effort e_i to maximize

$$U_i(s_i, e_i, b_i, \beta_{-i}) = \sum_j \theta^j(s_i, s_{-i}(\beta_{-i}, b_i))t_i^j(b_i, \beta_{-i}) - \psi(e_i)$$

subject to meeting the required cost target $\beta_i + s_i - e_i = c_i(b_i, \beta_{-i})$. Firm i will provide the socially optimal quality expenditures $s_i(\boldsymbol{\beta})$ under truthful revelation of types if and only if

$$U_i(s_i(\boldsymbol{\beta}), e_i(\boldsymbol{\beta}), \boldsymbol{\beta}) \geq U_i(s_i, e_i, \boldsymbol{\beta}) \forall \boldsymbol{\beta} \in (\underline{\beta}, a]^2 \cup (a, \overline{\beta}]^2, \; \forall s_i - e_i = c_i(\boldsymbol{\beta}) - \beta_i. \tag{5}$$

Second, the firms must prefer truth-telling to lying

$$E[u_i(\boldsymbol{\beta})|\beta_i] \geq E[u_i(b_i, \beta_{-i}|\beta_i)|\beta_i] \; \forall (b_i, \beta_i) \in (\underline{\beta}, \overline{\beta}]^2, \tag{6}$$

where $u_i(b_i, \beta_{-i}|\beta_i)$ is the rent induced by i's optimal choice of s_i and e_i, and $E[\cdot|\beta_i]$ is the interim expectations operator over β_{-i} conditional on type β_i. The incentive compatibility constraint (6) on truth-telling states that the firm cannot strictly benefit from misrepresenting its type, conditional on its information about the other type, the expectation that the competitor truthfully reports its type and both firms' subsequent choice of expenditures on quality improvement. Third, the firms must prefer operating to shutting down

$$E[u_i(\boldsymbol{\beta})|\beta_i] \geq 0 \; \forall \beta_i \in (\underline{\beta}, \overline{\beta}], \tag{7}$$

where 0 is the reservation utility. To simplify matters, it is assumed that production by both firms is always socially optimal in equilibrium.

The marginal effect on the interim expected rent of a reduction in productivity is negative and equal to $dE[u_i(\boldsymbol{\beta})|\beta_i] = -dE[\psi'(e_i(\boldsymbol{\beta})|\beta_i]d\beta_i$.[5] Integrating gives the expected interim rent

$$E[u_i(\boldsymbol{\beta})|\beta_i] = E[\textstyle\int_{\beta_i}^{\overline{\beta}(\beta_{-i})} \psi'(e_i(x, \beta_{-i})dx|\beta_i] + E[u_i(\overline{\beta}(\beta_{-i}), \beta_{-i})|\overline{\beta}(\beta_i)],$$

where $\overline{\beta}(\beta_{-i}) = a$ for all $\beta_{-i} \leq a$ and $\overline{\beta}(\beta_{-i}) = \overline{\beta}$ for all $\beta_{-i} > a$ is the lower bound to i's productivity consistent with $-i$'s truthful report of β_{-i}. Conversely, the upper bound to i's productivity report consistent with $-i$'s truthful report of β_{-i} is $\underline{\beta}(\beta_{-i}) = \underline{\beta}$ for all $\beta_{-i} \leq a$ and $\underline{\beta}(\beta_{-i}) = a$ for all $\beta_{-i} > a$. Since expected rent is locally decreasing in β_i, (7) is satisfied if and only if $E[u_i(a, \beta_{-i})|a] \geq 0$ and $E[u_i(\overline{\beta}, \beta_{-i})|\overline{\beta}] \geq 0$. Rents are costly; see (4). Assuming that incentive compatibility is indeed met by $E[u_i(a, \beta_{-i})|a] = 0$ and $E[u_i(\overline{\beta}, \beta_{-i})|\overline{\beta}] = 0$, a standard integration by parts (see, e.g., Auriol and Laffont, 1992) yields the expected ex ante rent

$$\int_{\underline{\boldsymbol{\beta}}}^{\overline{\boldsymbol{\beta}}} u_i(\boldsymbol{\beta}) d\mathbf{F}(\boldsymbol{\beta}) = \int_{\underline{\boldsymbol{\beta}}}^{\overline{\boldsymbol{\beta}}} \psi'(e_i(\boldsymbol{\beta})) \tfrac{F(\beta_i) - \phi(\beta_i)F(a)}{f(\beta_i)} d\mathbf{F}(\boldsymbol{\beta}), \tag{8}$$

where $\phi(\beta_i)$ is an indicator function taking on the value of 1 for all $\beta_i > a$ and zero otherwise.

[5]The analysis is simplified by the fact that the distribution of β_{-i} is locally independent of β_i and equal to $G(\frac{\beta_{-i} - \alpha \underline{m}}{1-\alpha})$ for all $\boldsymbol{\beta} \in (\underline{\beta}, a]^2$ and $G(\frac{\beta_{-i} - \alpha \overline{m}}{1-\alpha})$ for all $\boldsymbol{\beta} \in (a, \overline{\beta}]^2$.

3 OPTIMAL REGULATION

Substitute (8) into (4) to obtain expected welfare

$$\begin{aligned} EW = & \int_{\underline{\boldsymbol{\beta}}}^{\overline{\boldsymbol{\beta}}} \sum_i \{ \sum_j \theta^j(\mathbf{s}(\boldsymbol{\beta}))[V_i^j(\mathbf{p}^j(\boldsymbol{\beta})) + (1+\lambda)(p_i^j(\boldsymbol{\beta}) - c_i(\boldsymbol{\beta}))q_i^j(\mathbf{p}^j(\boldsymbol{\beta}))] \\ - & (1+\lambda)\psi(e_i(\boldsymbol{\beta})) - \lambda\psi'(e_i(\boldsymbol{\beta}))\frac{F(\beta_i)-\phi(\beta_i)F(a)}{f(\beta_i)})\} d\mathbf{F}(\boldsymbol{\beta}) \end{aligned} \quad (9)$$

as a function of prices $\mathbf{p}(\boldsymbol{\beta})$, expenditures on quality improvement $\mathbf{s}(\boldsymbol{\beta})$ and effort $e_1(\boldsymbol{\beta})$ and $e_2(\boldsymbol{\beta})$.

3.1 POLICIES

First consider the regulation of prices. Suppose that prices are so low that a small change in the price or quality of one good affects the demand for both firms' products, i.e., $\frac{1}{\gamma}(\sigma_1^j - p_1^j + \sigma_2^j - p_2^j) > 1$ in some state j. This characterizes a situation of *market integration*. Welfare is affected through three channels by an increase in firm i's price:

$$\frac{\partial EW}{\partial p_i^j(\boldsymbol{\beta})} = -q_i^j(\mathbf{p}^j(\boldsymbol{\beta})) + (1+\lambda)[q_i^j(\mathbf{p}^j(\boldsymbol{\beta})) + (p_i^j(\boldsymbol{\beta}) - c_i(\boldsymbol{\beta}))\frac{\partial q_i^j(\mathbf{p}^j(\boldsymbol{\beta}))}{\partial p_i^j(\boldsymbol{\beta})} + (p_{-i}^j(\boldsymbol{\beta}) - c_{-i}(\boldsymbol{\beta}))\frac{\partial q_{-i}^j(\mathbf{p}^j(\boldsymbol{\beta}))}{\partial p_i^j(\boldsymbol{\beta})}].$$

First, consumers are hurt in proportion to the units purchased. The effect on firm i's profit is ambiguous; revenues go up, but the market share goes down. If the good is sold below the monopoly price, the first effect dominates. Third, the profit of the other firm increases with its market share. By adding the marginal price effects for the two firms, $\partial EW/\partial p_1^j + \partial EW/\partial p_2^j = \lambda > 0$, I find welfare to be increasing in prices in an integrated market.

In an integrated market of constant size, a small proportional increase in the prices of both goods has no impact on demand and incentives. It merely constitutes a transfer of income from consumers to the regulator. This income transfer is beneficial to society since it can be used to reduce distortionary taxation in other sectors of the economy.[6] In other words, the desire to

[6]Suppose that the regulator increases the price of both firms' goods by a small amount d. In the integrated

maximize the degree of self-financing on account of the firms leads to a softening of the competition.

The optimal market structure is *segmented*, which means that a small price increase or reduction in the quality has no effect on the demand for the competitor's product, i.e., $q_i^j(\mathbf{p}^j(\boldsymbol{\beta})) = \frac{1}{\gamma}(\sigma_i^j - p_i^j(\boldsymbol{\beta}))$. As the market is also fully covered, the optimal policy satisfies the additional constraint

$$\tfrac{1}{\gamma}(\sigma_1^j - p_1^j(\boldsymbol{\beta}) + \sigma_2^j - p_2^j(\boldsymbol{\beta})) = 1. \tag{10}$$

Letting $\chi^j(\boldsymbol{\beta})$ be the Lagrangian multiplier associated with (10), the optimal regulated price is given by the Ramsey relation

$$\frac{p_i^j(\boldsymbol{\beta}) - c_i(\boldsymbol{\beta})}{p_i^j(\boldsymbol{\beta})} = \frac{1}{-\frac{\partial q_i^j(\mathbf{p}^j(\boldsymbol{\beta}))}{\partial p_i^j(\boldsymbol{\beta})}\frac{p_i^j(\boldsymbol{\beta})}{q_i^j(\mathbf{p}^j(\boldsymbol{\beta}))}}\left(\frac{\lambda}{1+\lambda} + \frac{1}{\gamma(1+\lambda)}\frac{\chi^j(\boldsymbol{\beta})}{\theta^j(\mathbf{s}(\boldsymbol{\beta}))q_i^j(\mathbf{p}^j(\boldsymbol{\beta}))}\right). \tag{11}$$

The price is set above the marginal production cost to reduce the social cost of transfers. The mark-up is proportional to the inverse price elasticity of residual demand - the equilibrium mark-up in unregulated duopoly. The regulated price can either be higher or lower than the unregulated duopoly price, an issue to which I return below.

Next, consider optimal expenditures on quality improvement. Differentiation of expected welfare (9) gives the optimal expenditure $s_i(\boldsymbol{\beta})$ as a solution to

$$\begin{aligned}\textstyle\sum_j \frac{\partial \theta^j(\mathbf{s}(\boldsymbol{\beta}))}{\partial s_i(\boldsymbol{\beta})} \sum_h [V_h^j(\mathbf{p}^j(\boldsymbol{\beta})) + (1+\lambda)(p_h^j(\boldsymbol{\beta}) - c_h(\boldsymbol{\beta}))q_h^j(\mathbf{p}^j(\boldsymbol{\beta}))] + \mu_i^0(\boldsymbol{\beta}) \\ = (1+\lambda)\textstyle\sum_j \theta^j(\mathbf{s}(\boldsymbol{\beta}))q_i^j(\mathbf{p}^j(\boldsymbol{\beta})) + \overline{\mu}_i(\boldsymbol{\beta}),\end{aligned} \tag{12}$$

where $\mu_i^0(\boldsymbol{\beta})$ and $\overline{\mu}_i(\boldsymbol{\beta})$ are the Lagrangian multipliers of $s_i(\boldsymbol{\beta}) \geq 0$ and $s_i(\boldsymbol{\beta}) \leq \overline{s}$, respectively. The regulatory policy balances the impact on consumer and producer surplus associated with an increased likelihood of supplying a high quality product against a higher marginal production cost.

market, demand only depends on the relative price $|p_1^j - p_2^j|$, see (1), and is unaffected by the price increase. The firms' incentives (5), (6) and (7) are the same as before since they only depend on the transfers and marginal cost targets and these have not changed. The consumer surplus goes down by $d(q_1^j + q_2^j) = d$, whereas the social value of increased firm profit is $d(1+\lambda)(q_1^j + q_2^j) = d(1+\lambda) > d$.

Effort is set according to the familiar (see, e.g., Laffont and Tirole, 1993) expression

$$\psi'(e_i(\boldsymbol{\beta})) + \overline{\eta}_i(\boldsymbol{\beta}) - \eta_i^0(\boldsymbol{\beta}) = E^j[q_i^j(\boldsymbol{\beta})] - \tfrac{\lambda}{1+\lambda}\psi''(e_i(\boldsymbol{\beta}))\tfrac{F(\beta_i)-\phi(\beta_i)F(a)}{f(\beta_i)}, \tag{13}$$

where $\eta_i^0(\boldsymbol{\beta})$ and $\overline{\eta}_i(\boldsymbol{\beta})$ are the Lagrangian multipliers of $e_i(\boldsymbol{\beta}) \geq 0$ and $e_i(\boldsymbol{\beta}) \leq \overline{e}$, respectively. Firm i strikes a balance between marginal and fixed production cost by its choice of effort. The higher is expected production, the more profitable are investments in marginal cost reductions, and the higher is effort. Suppose that the regulator wants each firm to produce at the first-best level ($\psi'(e_i(\boldsymbol{\beta})) = E^j[q_i^j(\boldsymbol{\beta})]\ \forall \boldsymbol{\beta}$). The firm always has an incentive to choose the contract with the lowest expected production to save on effort. The regulator offsets this incentive by allowing higher transfers to firms with a larger production. However, the transfers can be reduced by downward distortions in effort. Small distortions only have a second-order effect, whereas the transfer reduction has a first-order effect. This rent correction is the last term in (13).

3.2 IMPLEMENTATION

Prices are observable and can be directly implemented. But managerial effort $e_i(\boldsymbol{\beta})$ and spending on quality improvement $s_i(\boldsymbol{\beta})$ are not observable. Instead, implementation must be based on observables such as the quality indicator σ_i^j and the production costs $\mathbf{c} = (c_i, c_{-i})$. Consider the linear transfer scheme

$$t_i^j(\mathbf{c}, \boldsymbol{\beta}) = y_i(\boldsymbol{\beta})(c_{-i} - c_i) + z_i(\boldsymbol{\beta})(\sigma_i^j - E^j[\sigma_i(s_i(\boldsymbol{\beta}))]) + T_i(\boldsymbol{\beta}), \tag{14}$$

intended for firm i when the two firms have productivity $\boldsymbol{\beta}$. By reimbursing a share $y_i(\boldsymbol{\beta}) \in [0,1]$ of the marginal *cost differential* $c_{-i} - c_i = (1-\alpha)(\varepsilon_{-i} - \varepsilon_i) + s_{-i} - s_i + e_i - e_{-i}$, the common cost component αm is filtered out. This yardstick scheme, originally studied by Auriol (2000), is augmented by a quality component $z_i(\boldsymbol{\beta}) \geq 0$, which rewards the firm based on the difference between the quality indicator σ_i^j and expected quality $E^j[\sigma_i(s_i(\boldsymbol{\beta}))] = \theta(s_i(\boldsymbol{\beta}))\triangle\sigma + \underline{\sigma}$.

To see how incentives are affected under (14), assume that the two firms operate under the contract (b_i, β_{-i}), where $b_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$ is consistent with β_{-i}, but i's type is, in fact, β_i. Firm i chooses expenditures s_i on quality improvement and managerial effort e_i to maximize:

$$\begin{aligned} U_i(s_i, e_i, b_i, \beta_{-i}) = &\ \textstyle\sum_j \theta^j(\mathbf{s}) t_i^j(\mathbf{c}, b_i, \beta_{-i}) - \psi(e_i) \\ = &\ y_i(b_i, \beta_{-i})(c_{-i} - c_i) + z_i(b_i, \beta_{-i}) \left(\theta(s_i) - \theta(s_i(b_i, \beta_{-i}))\right) \triangle\sigma \\ + &\ T_i(b_i, \beta_{-i}) - \psi(e_i). \end{aligned} \tag{15}$$

The marginal benefit of managerial effort is

$$\tfrac{\partial U_i}{\partial e_i} = y_i(b_i, \beta_{-i}) - \psi'(e_i).$$

If a small share of the costs is reimbursed ($y_i(b_i, \beta_{-i})$ is high), the firm is a residual claimant to most of its cost savings and has a strong incentive to cut costs; the cost incentives are *high-powered*. Conversely, the firm faces *low-powered* cost incentives if the regulator covers most of the costs ($y_i(b_i, \beta_{-i})$ is low). In particular, firm i exerts effort $e_i(b_i, \beta_{-i})$ independently of its true type β_i if $y_i(b_i, \beta_{-i}) = \psi'(e_i(b_i, \beta_{-i}))$.

The marginal incentive for investing in quality improvement is

$$\tfrac{\partial U_i}{\partial s_i} = z_i(b_i, \beta_{-i})\theta'(s_i)\triangle\sigma - y_i(b_i, \beta_{-i}).$$

The firm faces low-powered quality incentives if the transfer is independent of quality ($z_i(b_i, \beta_{-i}) = 0$) as it then has no incentive to spend anything on quality improvement. Conversely, the firm faces high-powered quality incentives if the transfer is sensitive to the quality indicator ($z_i(b_i, \beta_{-i})$ is high). A high-powered cost incentive has a negative effect on quality provision, but this negative effect can be mitigated by adjusting $z_i(b_i, \beta_{-i})$ accordingly. Specifically, firm i spends $s_i(b_i, \beta_{-i})$ on quality improvement independently of its true type β_i and on the power of the cost incentives if $z_i(b_i, \beta_{-i}) = y_i(b_i, \beta_{-i})/\theta'(s_i(b_i, \beta_{-i}))\triangle\sigma$.

Under truthful revelation of types, any $s_i(\boldsymbol{\beta})$ and $e_i(\boldsymbol{\beta})$ can be implemented by the appropriate choice of $y_i(\boldsymbol{\beta})$ and $z_i(\boldsymbol{\beta})$. The regulation satisfies (5). In particular, the firms can be induced to both produce efficiently and invest a great deal in quality improvement. Consequently, *there is no general trade-off between cost and quality* here. The ability to contract both on observed cost c_i and the quality indicator σ_i^j provides the regulator with sufficient instruments to separate cost and quality; see Laffont and Tirole (1993) for a similar result. Through the appropriate choice of the fixed compensation $T_i(\boldsymbol{\beta})$, it can be ensured that even (6) and (7) are satisfied, provided that the regulatory contract has a standard property:

Lemma 1 *Any regulatory policy where $e_i(\boldsymbol{\beta})$ is non-increasing in $\beta_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$ can be implemented by means of the linear transfer scheme (14) for the appropriate choice of $z_i(\boldsymbol{\beta})$, $y_i(\boldsymbol{\beta})$ and $T_i(\boldsymbol{\beta})$. Expected firm rent is given by (8).*

4 ANALYSIS OF THE OPTIMAL REGULATION

This section explores the qualitative properties of the optimal regulation and draws some implications for policy. Optimal regulation depends on whether the social value of consumption is increasing or decreasing in quality, i.e., whether quality and quantity are *net complements* or *net substitutes* (Laffont and Tirole, 1993). In the present model, net complementarity (net substitutability) arises if a dollar spent on quality improvement leads to an increase in expected quality which is worth more (less) than one dollar to the consumer, i.e., $k_i = \triangle\sigma\theta'(s_i) > 1$ $(k_i < 1)$ $\forall s_i$, and thereby raises (reduces) the optimal expected production

$$E^j[q_i^j(\boldsymbol{\beta})] = \tfrac{1}{2} + \tfrac{(1+\lambda)}{2\gamma(1+2\lambda)}(\triangle\sigma\theta(s_i(\boldsymbol{\beta})) - c_i(\boldsymbol{\beta}) - \triangle\sigma\theta(s_{-i}(\boldsymbol{\beta})) + c_{-i}(\boldsymbol{\beta})). \tag{16}$$

Proposition 1 *Assume that quantity and quality are either net complements or net substitutes. Then, the optimal regulation is given by (11), (12) and (13). The regulation has the following properties in the range of consistent productivity reports ($\forall \beta_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$): (i) managerial effort and expected production are increasing in the firm's own productivity and decreasing in the competitor's productivity; (ii) the firm spends more (less) on quality improvement the higher is its own productivity and the lower is the competitor's productivity when quality and quantity are net complements (net substitutes).*

The most interesting situation arises when quantity and quality are net complements. Note that k_i is low under two sets of circumstances. First, if $\overline{\sigma} \approx \underline{\sigma}$, the variation in quality is small. Second, if $\theta'(s_i) \approx 0 \ \forall s_i$, quality is essentially exogenous to the firms. The optimal expenditure on quality improvement is close to zero in both cases. For this reason, the remainder of the analysis focuses on net complementarity.

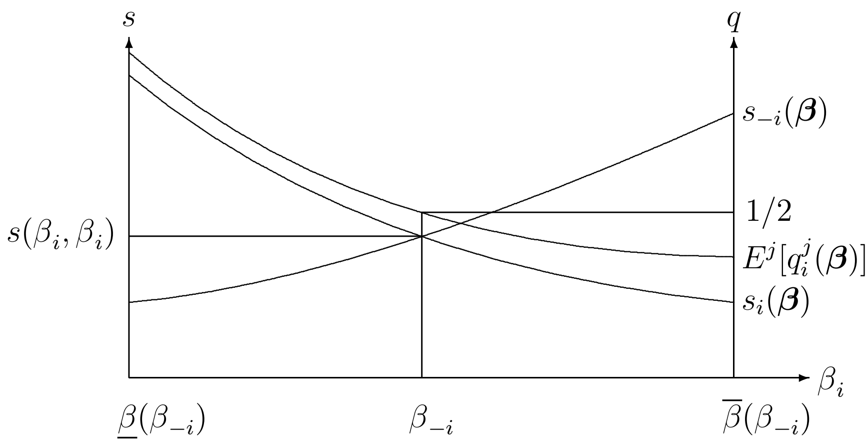

Figure 2: Production and expenditures on quality improvement

Figure 2 displays expected production in firm i and expenditures on quality improvement in both firms as a function of i's productivity β_i under net complementarity (effort can be depicted in the same way just by replacing s with e). Efficiency requires that the most productive firm has the largest market share ($E^j[q_i^j(\boldsymbol{\beta})] > 1/2$ if and only if $\beta_i < \beta_{-i}$). The larger is the firm's expected production, the larger is the scope for marginal cost reductions and quality improvement. Therefore, $E^j[q_i^j(\boldsymbol{\beta})]$, $s_i(\boldsymbol{\beta})$ and $e_i(\boldsymbol{\beta})$ are positively correlated under net complementarity. The regulator controls the firm's incentives by manipulating the power of the incentive scheme $y_i(\boldsymbol{\beta})$ and $z_i(\boldsymbol{\beta})$ in (14). Therefore, the following policy implication can be drawn:

Corollary 1 *The firm with the highest market share should have the most high-powered cost and quality incentives when quantity and quality are net complements.*

The regulatory schemes of the two firms are interdependent in duopoly; a change in productivity should affect the regulation of both firms, not just the firm where the change has taken place. An expansion in the production of firm i must necessarily come at the expense of the competitor's production when market size is constant. With lower production, marginal cost reductions and quality improvements are less desirable in firm $-i$.

Finally, (16) is higher than the unregulated duopoly quantity

$$E^j[q_i^{j(d)}(\boldsymbol{\beta})] = \frac{1}{2} + \frac{1}{6\gamma}(E^j[\sigma(s_i(\boldsymbol{\beta}))] - c_i(\boldsymbol{\beta}) - E^j[\sigma(s_{-i}(\boldsymbol{\beta}))] + c_{-i}(\boldsymbol{\beta}))$$

for the largest firm ($E^j[q_i^j(\boldsymbol{\beta})] > 1/2$). The unregulated duopoly price of the largest firm is too low; hence, it has a market share which is too low from the viewpoint of society. Thus, regulation accentuates the size differences between firms.

4.1 YARDSTICK COMPETITION

Firm rent stems from the informational advantage of the firm over the regulator. In particular, the firm can always secure itself a rent by picking a contract designed for a less productive firm. Yardstick competition increases the efficiency of the regulation by limiting informational rent. In particular, firm i cannot credibly pretend to have low Industry-specific productivity (ISP) if the other firm truthfully reveals itself as having a high ISP ($b_i > a$ and $\beta_{-i} \leq a$ are inconsistent). The associated reduction in informational rent reduces the need for effort distortions, which should ideally be followed by an output expansion since the marginal production cost is now lower. However, market size is constant and an output expansion in one firm must necessarily be followed by a corresponding output contraction in the other. The effect is ambiguous. To say more, I consider the linear-quadratic approximation[7]

$$\psi(e) = A + Be + \tfrac{r}{2}e^2,\ A \geq 0,\ B > 0 \text{ and } r > 0.$$

The model analyzed in this paper may yield multiple optimal policies. I restrict the attention to the policy that maximizes the expected production $E^j[q_i^j(\boldsymbol{\beta})]$ and expenditures on quality improvement $s_i(\boldsymbol{\beta})$ of firm i.

Proposition 2 *Assume disutility to be linear-quadratic, quantity and quality to be net complements or net substitutes and that $f(\beta_i) \leq f(\beta_{-i})$. Then, (i) the maximal expected production in firm i is higher under yardstick competition than separate regulation; and (ii) the maximal expenditure on quality improvement in firm i is higher (lower) under under yardstick competition than separate regulation when quantity and quality are net complements (net substitutes).*

[7]The key property of this specification is that all comparative statics effects working through the *third* derivative of the disutility function are eliminated.

In duopoly, the effect of yardstick competition does not, as might be expected, depend on the relative productivity of the two firms, but on the likelihood ratio $f(\beta_i)/f(\beta_{-i})$. The cost of informational rent is proportional to $F(\beta_i)$ and the cost of distorting effort is proportional to $f(\beta_i)$ for a firm with productivity β_i. The higher is F relative to f, the more profitable are distortions in effort. The monotone hazard rate assumption ensures that the cost of informational rent grows more quickly than the cost of distorting effort as productivity decreases. Yardstick competition leads to a proportional reduction $\lambda r F(a)$ in informational rent for all firms with a low ISP. Therefore, the firm with the lowest cost of distortions, i.e., the lowest f, faces the strongest increase in the power of the incentive system.

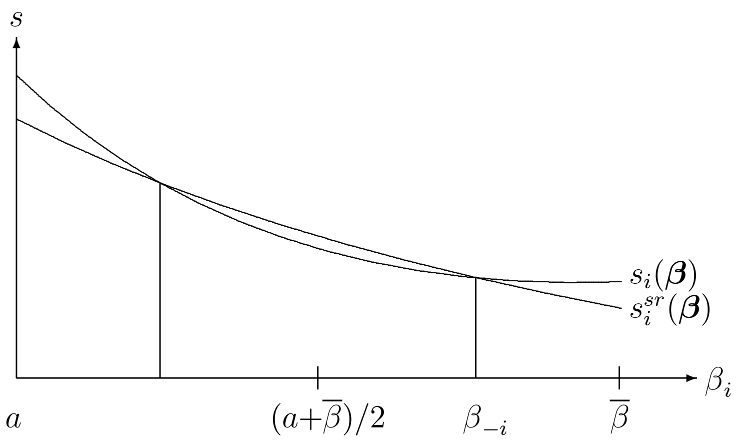

Figure 3: Effects of yardstick competition on quality improvement

Figure 3 displays the effect of yardstick competition on expenditures on quality improvement in firm i under the assumption that the distribution function f is quasi-concave and symmetric around the mean $(a+\overline{\beta})/2$ and quantity and quality are net complements. Let $s_i^{sr}(\boldsymbol{\beta})$ be optimal spending on quality improvement under separate regulation. The introduction of yardstick competition does not always have a negative impact on quality: expenditures on quality improvement go up at both tails of the distribution (this is where density is at its lowest). Therefore, firms with a very high productivity and firms with a very low productivity should be given more high-powered quality incentives.[8] Since expenditures on quality improvement are increasing in productivity, minimal expected quality goes up:

Corollary 2 *Assume disutility to be linear-quadratic, quantity and quality to be net complements and that* $f(\overline{\beta}) = \min_{\beta \in (a,\overline{\beta}]} f(\beta)$. *Then, the introduction of yardstick competition leads to an increase in the minimal expenditures on quality improvement* ($s_i(\overline{\beta}, \beta_{-i}) \geq s_i^{sr}(\overline{\beta}, \beta_{-i})$).

4.2 UNIVERSAL SERVICE OBLIGATIONS

Optimal regulation generally implies that expenditures on quality improvement are allowed to vary across firms as a function of their relative productivity; see Figure 2. It would then be expected that different firms offer products of different quality. In reality, uniform quality standards are common, in particular when it comes to elementary education and health care.[9] Maximizing expected welfare (9) under the additional constraint $s_1 = s_2 = s$ yields optimal expenditures on quality improvement

$$\triangle\sigma\theta'(s^{us}) - 1 + \mu^0 = \frac{(1+\lambda)}{\gamma(1+2\lambda)} (\triangle\sigma)^2 \theta'(s^{us})(\theta(s^{us}) - \tfrac{1}{2}) + \overline{\mu}$$

under a uniform quality standard. Quality spending is independent of productivity, which stems from full market coverage, constant marginal cost and the separability of s from e and β in the cost function. More interesting is the fact that spending under the uniform standard is exactly the same as optimal spending under symmetry, i.e., $s^{us} = s(\beta_i, \beta_i)$. Thus, the effects of imposing

[8] The regional monopoly case is simpler. Proposition 4.1 in Laffont and Tirole (1993) states that incomplete information leads to a lower level of quality in monopoly if and only if quantity and quality are net complements. Asymmetric information generally leads to downward distortions in monopoly effort and quantity. As yardstick competition reduces informational rent, see, e.g., Auriol and Laffont (1992), it follows that yardstick competition always leads to higher monopoly effort and production, but higher expenditures on quality improvement if and only if quantity and quality are net complements.

[9] In Sweden, for example, 2§ of the 1982 Health Care Act stipulates "health care on equal terms for the entire population" (my translation) as a fundamental objective.

a uniform quality standard are directly discernible from Figure 2. Under net complementarity, quality expenditures decrease in the most productive firm and increase in the less productive firm. Moreover, since quantity and quality are positively correlated, the most productive firm is comparatively smaller; see the Appendix. Thus, a uniform quality standard leads to a more even size distribution of firms in this model.

I round off the analysis by considering the effect of regulatory reform on consumer surplus. Would consumers be expected to vote in favour of or against yardstick competition or a uniform quality standard? The expected consumer surplus net of transportation cost at firm i is proportional to production in that firm:

$$E^j[\sigma_i^j - p_i^j(\boldsymbol{\beta})] = \gamma E^j[\tfrac{\sigma_i^j - p_i^j(\boldsymbol{\beta})}{\gamma}] = \gamma E^j[q_i^j(\boldsymbol{\beta})].$$

Consumers buying from the smallest firm receive a product of lesser quality in relation to the price they pay. The majority of consumers always buy from the larger firm and would therefore tend to oppose a uniform quality standard as this would lead to a reduction in the majority's expected consumer surplus. For the same reason, the majority would be expected to favour yardstick competition only if it would lead to increased differences in quality.

5 CONCLUSION

The complexity of optimal regulatory schemes makes them difficult to implement. Therefore, they can be criticized for being of limited practical relevance. Introducing quality concerns makes things even worse as the implications for regulation now depend on how consumers and firms value quantity relative to quality. Nonetheless, a few insights still emerge from the analysis. First, yardstick competition can be implemented by a menu of transfers that are linear in the cost differential between the two firms and in quality. Second, large firms should be given stronger incentives for cost containment and quality improvements than small firms when quality considerations are important (quality and quantity are net complements).

Holmstrom and Milgrom (1991) find cost minimization and quality provision to be irreconcilable targets. Economic agents assigned to do both will tend to put too much effort into cost reduction if quality is difficult to measure, but cost is not. The optimal compensation scheme should then be low-powered so as not to eradicate the incentives for quality provision. This conclusion is no longer valid if aspects of quality are contractible. Which is the most relevant case depends on the industry under consideration. Good quality indicators are easily constructed in utilities such as electricity distribution and water. In health care and education, quality may be too evasive a concept for good quality indicators to be constructed.

The majority of consumers would sometimes lose in terms of consumer surplus from a welfare improving policy such as yardstick competition. This happens in situations where it is socially optimal to reduce the quality of a good consumed by the majority for an increase in the expected quality of the good consumed by the minority. To the extent that consumers vote over regulatory policies, a regulation which entails a more even distribution of quality across firms might be difficult to implement.

Ai et al. (2004) analyze the impact of incentive schemes on a number of quality indicators in the US telecommunications industry. The evidence is mixed. Incentives have a negative impact on the number of trouble reports and a positive effect on consumer satisfaction, but delays in resolving reported service problems make the service quality lower. These results point to an important problem for the regulator. It is often relevant to consider quality as a multidimensional entity. If the regulator wants to take explicit account of quality incentives, she may have to balance different quality dimensions against each other. Optimal regulation with multidimensional quality is left to future research.

APPENDIX

Proof of Lemma 1.

Let $z_i(\boldsymbol{\beta}) = \psi'(e_i(\boldsymbol{\beta}))/\theta'(s_i(\boldsymbol{\beta}))\triangle\sigma$, $y_i(\boldsymbol{\beta}) = \psi'(e_i(\boldsymbol{\beta}))$ and

$$\begin{aligned} T_i(\boldsymbol{\beta}) = \; & \int_{\beta_i}^{\overline{\beta}(\beta_{-i})} \psi'(e_i(x,\beta_{-i}))dx + \psi'(e_i(\boldsymbol{\beta}))\left(c_i(\boldsymbol{\beta}) - c_{-i}(\boldsymbol{\beta})\right) \\ + \; & \psi(e_i(\boldsymbol{\beta})) + (1-\delta)(1-\phi(\beta_{-i}))\int_{\mathbf{a}}^{\overline{\boldsymbol{\beta}}} \frac{\psi'(e_i(\widehat{\boldsymbol{\beta}}))}{F(a)f(\widehat{\beta}_i)} d\mathbf{F}(\widehat{\boldsymbol{\beta}}), \end{aligned} \tag{17}$$

in (14), where $\boldsymbol{\beta}$ indicates that the contract is designed for firms whose true type is $\boldsymbol{\beta}$ and, recall, $\phi(\beta_{-i}) = 1$ for all $\beta_{-i} > a$ and zero otherwise. Parameter $\delta \in [0,1]$ is a measure of rent-extraction, where $\delta = 1$ under yardstick competition and $\delta = 0$ if the two firms are regulated as separate entities. As is easily verified, it is optimal for firm i to spend $s_i(b_i, \beta_{-i})$ on quality improvement and exert effort $e_i(b_i, \beta_{-i})$ independently of whether b_i is i's true type. Hence, i spends $s_i(\boldsymbol{\beta})$ on quality improvement and meets the cost target $c_i(\boldsymbol{\beta})$ if the firms operate under the designated contract $\boldsymbol{\beta}$. Firm i obtains the rent

$$u_i(b_i, \beta_{-i}|\beta_i) = \int_{b_i}^{\overline{\beta}(\beta_{-i})} \psi'(e_i(x,\beta_{-i}))dx + \int_{\beta_i}^{b_i} \psi'(e_i(b_i,\beta_{-i}))dx + (1-\delta)(1-\phi(\beta_{-i}))\int_{\mathbf{a}}^{\overline{\boldsymbol{\beta}}} \frac{\psi'(e_i(\widehat{\boldsymbol{\beta}}))}{F(a)f(\widehat{\beta}_i)} d\mathbf{F}(\widehat{\boldsymbol{\beta}})$$

if it has chosen $b_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$, but the true types are $\boldsymbol{\beta} = (\beta_i, \beta_{-i})$. The equilibrium rent is

$$u_i(\boldsymbol{\beta}) = \int_{\beta_i}^{\overline{\beta}(\beta_{-i})} \psi'(e_i(x,\beta_{-i}))dx + (1-\delta)(1-\phi(\beta_{-i}))\int_{\mathbf{a}}^{\overline{\boldsymbol{\beta}}} \frac{\psi'(e_i(\widehat{\boldsymbol{\beta}}))}{F(a)f(\widehat{\beta}_i)} d\mathbf{F}(\widehat{\boldsymbol{\beta}})$$

and non-negative. Hence, (7) is satisfied. The net benefit of choosing contract β_i over an arbitrary $b_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$ is

$$u_i(\boldsymbol{\beta}) - u_i(b_i, \beta_{-i}|\beta_i) = \int_{\beta_i}^{b_i} \left(\psi'(e_i(x,\beta_{-i})) - \psi'(e_i(b_i,\beta_{-i}))\right) dx.$$

Note that $u_i(\boldsymbol{\beta}) \geq u_i(b_i, \beta_{-i}|\beta_i)$ for any regulation where $e_i(\boldsymbol{\beta})$ is non-increasing in $\beta_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$. Thus, (6) is met for all consistent $b_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$. If $T_i(b_i, \beta_{-i}) = 0$ for all $b_i \notin (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$, firm i cannot profit from choosing an contract with inconsistent productivity either. Finally, the equilibrium expected rent is

$$\int_{\underline{\boldsymbol{\beta}}}^{\overline{\boldsymbol{\beta}}} u_i(\boldsymbol{\beta}) d\mathbf{F}(\boldsymbol{\beta}) = \int_{\underline{\boldsymbol{\beta}}}^{\overline{\boldsymbol{\beta}}} \psi'(e_i(\boldsymbol{\beta})) \frac{F(\beta_i) - \delta\phi(\beta_i)F(a)}{f(\beta_i)} d\mathbf{F}(\boldsymbol{\beta}) \tag{18}$$

after an integration by parts. Expected rent is equal to (8) for $\delta = 1$ and equal to equilibrium rent under separate regulation for $\delta = 0$. ■

Proof of Proposition 1.

The optimal prices and quantities do not directly depend on whether yardstick competition is applied or not. The only direct effect is on effort via informational rent; see (18). Hence, the optimal regulated quantity in state j is

$$q_i^j(\mathbf{e}, \mathbf{s}, \boldsymbol{\beta}) = \tfrac{1}{2} + \tfrac{(1+\lambda)}{2\gamma(1+2\lambda)}(\sigma_i^j - \sigma_{-i}^j + \beta_{-i} - \beta_i + s_{-i} - s_i + e_i - e_{-i}) \tag{19}$$

as a function of effort $\mathbf{e}$, expenditures $\mathbf{s}$ on quality improvement and productivity $\boldsymbol{\beta}$. Use $q_i^j = (\sigma_i^j - p_i^j)/\gamma$ (segmentation) and plug (18) into (4) to obtain welfare

$$\begin{aligned} W(\mathbf{e}, \mathbf{s}, \boldsymbol{\beta}, \delta) = & \textstyle\sum_i \{\sum_j \theta^j(\mathbf{s})[(1+\lambda)(\sigma_i^j - \beta_i - s_i + e_i) - \frac{\gamma(1+2\lambda)}{2} q_i^j(\mathbf{e}, \mathbf{s}, \boldsymbol{\beta})] q_i^j(\mathbf{e}, \mathbf{s}, \boldsymbol{\beta}) \\ - & (1+\lambda)\psi(e_i) - \lambda\psi'(e_i)\tfrac{F(\beta_i) - \delta\phi(\beta_i)F(a)}{f(\beta_i)}\}. \end{aligned}$$

The regulator maximizes W with respect to $(\mathbf{e}, \mathbf{s}) \in [0, \overline{e}]^2 \times [0, \overline{s}]^2$ for every $\boldsymbol{\beta}$ and subject to (5), (6) and (7). By Lemma 1, any regulatory policy with $e_i(\boldsymbol{\beta})$ non-increasing in $\beta_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$ can be implemented by means of a linear transfer scheme. I verify ex post that $e_i(\boldsymbol{\beta})$ has this property. The marginal welfare effects of effort e_i, quality expenditures s_i, productivity β_i and rent-extraction δ are, respectively,

$$\frac{\partial W}{\partial e_i} = \frac{\gamma(1+2\lambda)}{1+\lambda} + (\theta(s_i) - \theta(s_{-i}))\triangle\sigma - c_i + c_{-i} - \frac{2\gamma(1+2\lambda)}{1+\lambda}\left(\psi'(e_i) + \frac{\lambda}{1+\lambda}\psi''(e_i)\frac{F(\beta_i)-\delta\phi(\beta_i)F(a)}{f(\beta_i)}\right)$$
$$\frac{\partial W}{\partial s_i} = (k_i - 1)\left(\frac{\gamma(1+2\lambda)}{(1+\lambda)} + (\theta(s_i) - \theta(s_{-i}))\triangle\sigma - c_i + c_{-i}\right) + k_i\left(\frac{1}{2}\left(\overline{\sigma} + \underline{\sigma}\right) - E\sigma(s_i)\right)$$
$$\frac{\partial W}{\partial \beta_i} = -\left(\frac{\gamma(1+2\lambda)}{(1+\lambda)} + (\theta(s_i) - \theta(s_{-i}))\triangle\sigma - c_i + c_{-i} + \frac{2\gamma\lambda(1+2\lambda)}{(1+\lambda)^2}\psi'(e_i)\frac{d}{d\beta_i}\frac{F(\beta_i)-\delta\phi(\beta_i)F(a)}{f(\beta_i)}\right)$$
$$\frac{\partial W}{\partial \delta} = \frac{2\gamma\lambda(1+2\lambda)}{(1+\lambda)^2}\left(\psi'(e_i)\frac{\phi(\beta_i)F(a)}{f(\beta_i)} + \psi'(e_{-i})\frac{\phi(\beta_{-i})F(a)}{f(\beta_{-i})}\right)$$

where I have substituted in the functional form of $q_i^j(\mathbf{e}, \mathbf{s}, \boldsymbol{\beta})$ above, used $k_i = \triangle\sigma\theta'(s_i)$, and normalized by the constant $2\gamma(1+2\lambda)/(1+\lambda)^2$.

First assume quantity and quality to be net complements (this is equivalent to $\triangle\sigma\theta'(\overline{s}) > 1$ since $\overline{\theta}'' < 0$). Maximization of $W(\mathbf{e}, \mathbf{s}, \boldsymbol{\beta}, \delta)$ over $[0, \overline{e}]^2 \times [0, \overline{s}]^2$ is equivalent to maximization of $W^{(1)}(e_i, \widetilde{e}_{-i}, s_i, \widetilde{s}_{-i}, \widetilde{\boldsymbol{\beta}}, \delta) = W(e_i, -\widetilde{e}_{-i}, s_i, -\widetilde{s}_{-i}, -\widetilde{\boldsymbol{\beta}}, \delta)$ over $[0, \overline{e}] \times [-\overline{e}, 0] \times [0, \overline{s}] \times [-\overline{s}, 0]$. The domain of the choice variables is a compact sublattice in $\mathbb{R}^4$, and $\widetilde{\boldsymbol{\beta}} = (-\beta_i, -\beta_{-i}) \in (-\underline{\beta}(\beta_{-i}), -\overline{\beta}(\beta_{-i})]^2$ is a sublattice in $\mathbb{R}^2$. The function $W^{(1)}$ is C^2 with the assumption that ψ, θ and g are all twice continuously differentiable. The five rows of $DW^{(1)}$ contain the cross-partial derivatives of, in turn, $\partial W^{(1)}/\partial e_i$, $\partial W^{(1)}/\partial \widetilde{e}_{-i}$, $\partial W^{(1)}/\partial s_i$, $\partial W^{(1)}/\partial \widetilde{s}_{-i}$ and $\partial W^{(1)}/\partial \widetilde{\beta}_i$:

$$DW^{(1)} = \begin{pmatrix} \frac{\partial^2 W^{(1)}}{\partial e_i^2} & 1 & k_i - 1 & k_{-i} - 1 & 1 + \rho_i \\ 1 & \frac{\partial^2 W^{(1)}}{\partial \widetilde{e}_{-i}^2} & k_i - 1 & k_{-i} - 1 & 1 \\ k_i - 1 & k_i - 1 & \frac{\partial^2 W^{(1)}}{\partial s_i^2} & (k_1 - 1)(k_2 - 1) & k_i - 1 \\ k_{-i} - 1 & k_{-i} - 1 & (k_1 - 1)(k_2 - 1) & \frac{\partial^2 W^{(1)}}{\partial \widetilde{s}_{-i}^2} & k_{-i} - 1 \\ 1 + \rho_i & 1 & k_i - 1 & k_{-i} - 1 & \frac{\partial^2 W^{(1)}}{\partial \widetilde{\beta}_i^2} \end{pmatrix}.$$

All off-diagonal elements of $DW^{(1)}$ are strictly positive since $k_1 > 1$, $k_2 > 1$ and

$$\rho_i = \frac{2\lambda\gamma(1+2\lambda)}{(1+\lambda)^2}\psi''(e_i)\frac{d}{d\beta_i}\frac{F(\beta_i)-\delta\phi(\beta_i)F(a)}{f(\beta_i)} \geq 0.$$

Thus, $W^{(1)}$ is strictly supermodular (Vives, 2007). Maximization of the strictly supermodular

C^2 function $W^{(1)}$ on a compact sublattice yields a non-empty set of optimal policies where all equilibrium selections $e_i(\boldsymbol{\beta})$ and $s_i(\boldsymbol{\beta})$ are non-increasing in β_i, and $e_{-i}(\boldsymbol{\beta})$ and $s_{-i}(\boldsymbol{\beta})$ are non-decreasing in β_i for all $\beta_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$; see Theorems 10.3 and 10.7 in Sundaram (1996).

Next, consider the case of net substitutability (this is equivalent to $\triangle\sigma\overline{\theta}'(0) < 1$ since $\overline{\theta}'' < 0$). As is easily checked, the welfare function $W^{(2)}(e_i, \widetilde{e}_{-i}, \widetilde{s}_i, s_{-i}, \widetilde{\boldsymbol{\beta}}, \delta) = W(e_i, -\widetilde{e}_{-i}, -\widetilde{s}_i, s_{-i}, -\widetilde{\boldsymbol{\beta}}, \delta)$ is strictly supermodular, where now $\widetilde{s}_i = -s_i \in [-\overline{s}, 0]$. The set of optimal policies is non-empty, and for all $\beta_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$, the optimal policies have $e_i(\boldsymbol{\beta})$ and $s_{-i}(\boldsymbol{\beta})$ non-increasing in β_i, whereas $s_i(\boldsymbol{\beta})$ and $e_{-i}(\boldsymbol{\beta})$ are non-decreasing in β_i.

Finally,

$$\begin{aligned} E^j[q_i^j(\boldsymbol{\beta})] = {} & \tfrac{1}{2} + \tfrac{(1+\lambda)}{2\gamma(1+2\lambda)}[(\theta(s_i(\boldsymbol{\beta})) - \theta(s_{-i}(\boldsymbol{\beta})))\triangle\sigma \\ - {} & s_i(\boldsymbol{\beta}) + s_{-i}(\boldsymbol{\beta}) + e_i(\boldsymbol{\beta}) - e_{-i}(\boldsymbol{\beta}) + \beta_{-i} - \beta_i] \end{aligned} \tag{20}$$

is weakly decreasing in $\beta_i \in (\underline{\beta}(\beta_{-i}), \overline{\beta}(\beta_{-i})]$ both under net complementarity and net substitutability. Note first that $\theta(s_i(\boldsymbol{\beta}))\triangle\sigma - s_i(\boldsymbol{\beta})$ is weakly decreasing in β_i. Under net complementarity (substitutability), $\theta(s_i)\triangle\sigma - s_i$ increases (decreases) whenever s_i increases, whereas $s_i(\boldsymbol{\beta})$ is non-increasing (non-decreasing) in β_i. By a similar argument, $\theta(s_{-i}(\boldsymbol{\beta}))\triangle\sigma - s_{-i}(\boldsymbol{\beta})$ is weakly increasing in β_i both under net substitutability and net complementarity. Finally, $e_i(\boldsymbol{\beta})$ and $-e_{-i}(\boldsymbol{\beta})$ are both weakly decreasing in β_i, which completes the proof that $E^j[q_i^j(\boldsymbol{\beta})]$ is weakly decreasing in β_i in the consistent range, both under net substitutability and net complementarity. ■

Proof of Proposition 2.

Assume first that quality and quantity are net complements. Moreover, assume without loss of generality that $f(\beta_i) \leq f(\beta_{-i})$. Define two new variables, $\Sigma e = (e_i + e_{-i})/2 \in [0, \overline{e}]$ and $\Delta e = (e_i - e_{-i})/2 \in [-\overline{e}/2, \overline{e}/2]$. Note that $e_i = \Sigma e + \Delta e$ and $e_{-i} = \Sigma e - \Delta e$. Maximization of $W^{(3)}(\Delta e, \Sigma e, s_i, \widetilde{s}_{-i}, \boldsymbol{\beta}, \delta) = W(\Sigma e + \Delta e, \Sigma e - \Delta e, s_i, -\widetilde{s}_{-i}, \boldsymbol{\beta}, \delta)$ is equivalent to maximization of $W(\mathbf{e},\mathbf{s},\boldsymbol{\beta},\delta)$ over $[0,\overline{e}]^2\times[0,\overline{s}]^2$. The marginal welfare effects are $\frac{\partial W^{(3)}}{\partial\Delta e}=\frac{\partial W}{\partial e_i}-\frac{\partial W}{\partial e_{-i}}$, $\frac{\partial W^{(3)}}{\partial\Sigma e}=\frac{\partial W}{\partial e_i}+\frac{\partial W}{\partial e_{-i}}$, $\frac{\partial W^{(3)}}{\partial s_i}=\frac{\partial W}{\partial s_i}$, $\frac{\partial W^{(3)}}{\partial\widetilde{s}_{-i}}=-\frac{\partial W}{\partial s_{-i}}$ and $\frac{\partial W^{(3)}}{\partial\delta}=\frac{\partial W}{\partial\delta}$. The five rows of $DW^{(3)}$ contain the cross-partial derivatives of, in turn, $\partial W^{(3)}/\partial\Delta e$, $\partial W^{(3)}/\partial\Sigma e$, $\partial W^{(3)}/\partial s_i$, $\partial W^{(3)}/\partial\widetilde{s}_{-i}$ and $\partial W^{(3)}/\partial\delta$,

$$\frac{DW^{(3)}}{2}=\begin{pmatrix}\frac{\partial^2W^{(3)}}{\partial(\Delta e)^2} & r_{-i}-r_i & k_i-1 & k_{-i}-1 & \zeta_i-\zeta_{-i}\\ r_{-i}-r_i & \frac{\partial^2W^{(3)}}{\partial(\Sigma e)^2} & 0 & 0 & \zeta_1+\zeta_2\\ k_i-1 & 0 & \frac{\partial^2W^{(3)}}{\partial s_i^2} & (k_1-1)(k_2-1) & 0\\ k_{-i}-1 & 0 & (k_1-1)(k_2-1) & \frac{\partial^2W^{(3)}}{\partial\widetilde{s}_{-i}^2} & 0\\ \zeta_i-\zeta_{-i} & \zeta_1+\zeta_2 & 0 & 0 & \frac{\partial^2W^{(3)}}{\partial\delta^2}\end{pmatrix}$$

where

$$r_i=\tfrac{\gamma(1+2\lambda)}{1+\lambda}\left(\psi''(e_i)+\tfrac{\lambda}{1+\lambda}\psi'''(e_i)\tfrac{F(\beta_i)-\delta\phi(\beta_i)F(a)}{f(\beta_i)}\right),\ \zeta_i=\tfrac{\lambda\gamma(1+2\lambda)}{(1+\lambda)^2}\psi''(e_i)\tfrac{\phi(\beta_i)F(a)}{f(\beta_i)}.$$

The signs of the off-diagonal elements are ambiguous in general. Thus, the effects of yardstick competition are ambiguous. However, when disutility is linear-quadratic, i.e., $\psi(e)=A+Be+\frac{r}{2}e^2$, where $A\geq 0$, $B>0$ and $r>0$, it is possible to say more. First, $r_1=r_2$ and second,

$$\zeta_i-\zeta_{-i}=\tfrac{r\lambda\gamma(1+2\lambda)}{(1+\lambda)^2}\tfrac{\phi(\beta_i)F(a)}{f(\beta_i)f(\beta_{-i})}\left(f(\beta_{-i})-f(\beta_i)\right)\geq 0.$$

Hence, with linear-quadratic disutility, $W^{(3)}$ is supermodular (although not strictly). Then, for every set of equilibria $\Omega(\boldsymbol{\beta},\delta)$, there exists a maximal policy $(\Delta e^{\max},\Sigma e^{\max},s_i^{\max},\widetilde{s}_{-i}^{\max})$ where $s_i^{\max}\geq s_i\ \forall s_i\in\Omega(\boldsymbol{\beta},\delta)$ etc. and a minimal policy $(\Delta e^{\min},\Sigma e^{\min},s_i^{\min},\widetilde{s}_{-i}^{\min})$, in the sense that $s_i^{\min}\leq s_i\ \forall s_i\in\Omega(\boldsymbol{\beta},\delta)$ etc. The maximal and minimal policies are both non-decreasing in δ; see Theorem 10.7 in Sundaram (1996). Hence, when quantity and quality are net complements and $f(\beta_i)\leq f(\beta_{-i})$, $s_i^{\max}$, $\Delta e^{\max}$, $s_i^{\min}$, $\Delta e^{\min}$ weakly increase, whereas $s_{-i}^{\max}$ and $s_{-i}^{\min}$ weakly decrease when yardstick competition is introduced.

Next, assume that quality and quantity are net substitutes, but maintain the assumption that $f(\beta_i) \leq f(\beta_{-i})$. It is easily verified that $W^{(4)}(\Delta e, \Sigma e, \widetilde{s}_i, s_{-i}) = W(\Sigma e + \Delta e, \Sigma e - \Delta e, -\widetilde{s}_i, s_{-i})$ is supermodular when disutility is linear-quadratic. Hence, the maximal policy $(\Delta e^{\max}, \Sigma e^{\max}, \widetilde{s}_i^{\max}, s_{-i}^{\max})$ and minimal policy $(\Delta e^{\min}, \Sigma e^{\min}, \widetilde{s}_i^{\min}, s_{-i}^{\min})$ are non-decreasing in δ. It follows that there is a weak increase in $\Delta e^{\max}$, $s_{-i}^{\max}$, $\Delta e^{\min}$ and $s_{-i}^{\min}$ whereas there is a weak decrease $s_i^{\max}$ and $s_i^{\min}$ following the introduction of yardstick competition under net substitutability.

Finally,

$$E^j[q_i^{\max}] = \tfrac{1}{2} + \tfrac{(1+\lambda)}{2\gamma(1+2\lambda)} \left((\theta(s_i^{\max}) - \theta(s_{-i}^{\max}))\triangle\sigma - s_i^{\max} + s_{-i}^{\max} + \Delta e^{\max} + \beta_{-i} - \beta_i \right)$$

is weakly increasing in δ when disutility is linearly quadratic, $f(\beta_i) \leq f(\beta_{-i})$ and quantity and quality are either net complements or net substitutes. Note first that $\theta(s_i^{\max})\triangle\sigma - s_i^{\max}$ is weakly increasing in δ under the maintained assumptions. Under net complementarity (substitutability), $\theta(s_i)\triangle\sigma - s_i$ increases (decreases) whenever s_i increases, whereas $s_i^{\max}$ is non-decreasing (non-increasing) in δ. By a similar argument, $\theta(s_i^{\max})\triangle\sigma - s_i^{\max}$ is weakly decreasing in δ both under net substitutability and net complementarity. The fact that $\Delta e^{\max}$ is weakly increasing in δ completes the proof that $E^j[q_i^{\max}]$ is weakly increasing in δ both under net substitutability and net complementarity, provided that disutility is linearly quadratic and $f(\beta_i) \leq f(\beta_{-i})$. The proof that $E^j[q_i^{\min}]$ has the same property is analogous and is thus omitted. ■

The Effects of a Uniform Quality Standard.

As is directly observable from (20), expected quantity $E^j[q_i^{j(us)}(\boldsymbol{\beta})]$ under the uniform quality standard $s_1^{us}(\boldsymbol{\beta}) = s_2^{us}(\boldsymbol{\beta}) = s^{us}(\boldsymbol{\beta})$ is independent of the *amount* $s^{us}(\boldsymbol{\beta})$ spent on quality improvement. By implication, so is optimal effort $e_i^{us}(\boldsymbol{\beta})$, since it only depends on $\mathbf{s}$ via $E^j[q_i^{j(us)}(\boldsymbol{\beta})]$; see (13). To gauge the effects of a uniform quality standard on effort and production, one only has to study what happens to $E^j[\widehat{q}_i^j(\mathbf{s}, \boldsymbol{\beta})]$ defined in (16) and $\widehat{e}_1(\mathbf{s}, \boldsymbol{\beta})$, $\widehat{e}_2(\mathbf{s}, \boldsymbol{\beta})$ defined in (13), treating $\mathbf{s}$ as a pair of exogenous variables, where s_{-i} is fixed at $s_{-i}(\boldsymbol{\beta})$ and s_i varies between $s_i(\boldsymbol{\beta})$ and $s_{-i}(\boldsymbol{\beta})$. I only focus on net complementarity. Assume without loss of generality that $\beta_i < \beta_{-i}$, so that $s_i(\boldsymbol{\beta}) \geq s_{-i}(\boldsymbol{\beta})$. The effect on $\widehat{e}_i$ and $\widetilde{e}_{-i} = -\widehat{e}_{-i}$ follows from the third leading principal minor of $DW^{(1)}$; $\widehat{e}_i$ and $\widetilde{e}_{-i}$ are non-decreasing functions of s_i. Thus, $e_i(\boldsymbol{\beta}) \equiv \widehat{e}_i(s_i(\boldsymbol{\beta}), s_{-i}(\boldsymbol{\beta}), \boldsymbol{\beta}) \geq \widehat{e}_i(s_{-i}(\boldsymbol{\beta}), s_{-i}(\boldsymbol{\beta}), \boldsymbol{\beta}) \equiv e_i^{us}(\boldsymbol{\beta})$ and, similarly, $e_{-i}(\boldsymbol{\beta}) \leq e_{-i}^{us}(\boldsymbol{\beta})$. This result, and $\theta(s_i(\boldsymbol{\beta}))\triangle\sigma - s_i(\boldsymbol{\beta}) \geq \theta(s_{-i}(\boldsymbol{\beta}))\triangle\sigma - s_{-i}(\boldsymbol{\beta})$, which follows from net complementarity and $s_i(\boldsymbol{\beta}) \geq s_{-i}(\boldsymbol{\beta})$, imply that $E^j[q_i^{j(us)}(\boldsymbol{\beta})] \equiv E^j[\widehat{q}_i^j(s_{-i}(\boldsymbol{\beta}), s_{-i}(\boldsymbol{\beta}), \boldsymbol{\beta})] \leq E^j[\widehat{q}_i^j(s_i(\boldsymbol{\beta}), s_{-i}(\boldsymbol{\beta}), \boldsymbol{\beta})]$ $= E^j[q_i^j(\boldsymbol{\beta})]$.

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