

Trade Effects of Minimum Quality Standards with and without Deterred Entry

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Abstract

In a model of vertical product differentiation, duopolistic firms face quality-dependent costs and compete in quality and price in two segmented markets. Minimum quality standards, set uniformly or according to the principle of Mutual Recognition, can be used to increase welfare. The analysis includes entry deterrence by the choice of a particular standard. With identical costs, both industries remain in the market under either regulatory alternative. Mutual Recognition is the optimal policy choice for either region. With significantly different costs, the Full-Harmonization outcome includes only one firm and leads to a maximal sum of regional welfares.

• **JEL Classifications:** F12, F21, L13

• **Key Words:** product differentiation, oligopoly, trade, quality standards, entry.

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I. Introduction

With the recent establishment of the European Common Market, international coordination of national regulations has gained new importance. This is exemplified by the ongoing efforts to implement the directives on harmonization of standards put forth in the EC Commission's [1985] White paper. Currently, two alternatives to national (destination-oriented) treatment of product standards are prevalent within the EU. Full Harmonization (FH), where uniform standards are set for all member countries, is the goal of the directives contained in the Commission's White paper. In all other cases, as a rule the Country-of-Origin principle (or principle of Mutual Recognition (MR)) applies. This means that governments set standards for their national industries only while recognizing the adequacy of foreign standards on imported products.¹ However, support for the harmonization of standards, especially minimum standards concerning product quality, safety, or environmental protection, varies considerably within the EU. In part, this is based on the common belief that these standards, when binding for less advanced national industries but not for more advanced national industries, lead to increased market shares for the latter. Therefore, some of the economically weaker members in the EU fear economic disadvantages from harmonized standards. In contrast to uniform standards, the Country-of-Origin principle allows for national differences in the degree of regulation. In this case, the more advanced national industries might fear to be disadvan-

1. Full Harmonization, the main goal until the late 1970s, will be constrained to essential safety and health requirements. In all other cases, as a rule Mutual Recognition of national standards applies. As an exception, National Treatment (NT) can be applied in certain cases governed by the EEC Treaty Articles 100 and 36. The differences between the three arrangements are best illustrated using an example. Suppose a French and a German manufacturer of household appliances are selling their products in both national markets. Under FH, one standard set by the EU Council of Ministers applies in both countries. Under MR, German products are governed by German standards even if they are sold in France and French products need only meet French standards even if they are sold in Germany (the country-of-origin principle). Under NT, German standards must be met by all products sold in Germany including the French products while French standards must be met by all products sold in France including the German products.

tagged by higher standards imposed on them by their national governments. On the other hand, all consumers may benefit from increased product qualities caused by standards.

In this paper I compare the effects of the two alternative standard-setting arrangements on national welfare, industry profits and consumers' welfare using a two-country model of vertical product differentiation. The analysis captures some of the most important aspects of European markets. National industries bear quality-dependent product development costs, choose different quality levels, and compete by setting prices in two segmented national markets. Trade takes place, since both industries are present in both markets. Since increased differentiation in terms of quality decreases competition between rival products, higher quality products will coexist with lower quality products, even if all firms were identical. However, in the presence of technological differences, high-quality products will normally be provided by national industries with low product development costs. Without regulation, equilibrium qualities and prices will not be optimal due to imperfect competition. In response to quality standards, qualities rise, quality differentiation is reduced, and prices adjusted for quality fall. This tends to increase welfare while reducing industry profits. In addition, this analysis explicitly accounts for the possibility that standards are used to restrict market entry. The firm providing the lower product also has lower profits. A quality standard can be set such that this firm's profit opportunities are driven below zero forcing it to exit the market.

The basic features of the model applied here are well-known (Mussa/Rosen [1978], Gabszewicz/Thisse [1979], Shaked/Sutton [1982], Ronnen [1991], Motta [1993]). Ronnen uses this framework to demonstrate cases where quality standards improve welfare. He concludes that there exists a binding minimum quality standard such that all consumers are weakly better off, both firms have positive profits, and total welfare is increased. As a result of such a standard, profits of the high-quality provider must fall, whereas profits of the low-quality provider may even rise if the standard is set close to the equilibrium level of low quality without regulation. However, Ronnen starts from the assumption that the chosen order of qualities is already determined, *i.e.* it is a priori clear which of the firms offers the higher quality. Consequently, Ronnen analyzed firms' quality best

responses only in the vicinity of one existing equilibrium. However, with completely endogenous choice of quality, there exist up to two equilibria and each firm's quality best response is discontinuous and contains a high- and a low-quality branch, respectively. In this paper, I will demonstrate the derivation of complete quality best responses and the resulting equilibria.² In addition, since there is only one market, the analysis of the case of Mutual Recognition is not possible and there is no scope for a welfare analysis in the presence of more than one regulating government. Crampes and Hollander[1995] present a study where quality improvements fall on variable costs. They present results where all consumers lose through the imposition of a standard, contrary to Ronnen. However, this literature is still limited to the analysis of uniform standards in a single market. Similarly, the earlier literature lacks the elements of two-way trade and strategic interaction of governments.³ Only recently has the existing analysis been extended to include these features. Boom[1995] introduces National Treatment of standards into a two-country model. Contrary to Ronnen or Motta and Thisse, a relatively high standard imposed in one country can lead to market exit and a reduction of product variety in one country reducing consumers' welfare. But to my knowledge, none of this literature covers Mutual Recognition.⁴

The model employed in this paper extends the framework of Shaked/Sutton and Ronnen for the two-country case. I present a comparison between Full Harmonization and Mutual Recognition abstracting from differences in

2. These equilibria are in pure strategies. If there are two pure-strategy equilibria, there also exists at least one mixed-strategy equilibrium. However, the analysis of mixed-strategy equilibria is beyond the scope of this work. The emergence of multiple equilibria has also been acknowledged by, *e.g.*, Boom [1995] or Crampes/ Hollander [1995]. The question of selection between two asymmetric equilibria was recently addressed by Motta/Thisse/Cabrales [1995] who demonstrate how the risk dominance criterion can be utilized for this purpose in models of the type employed here.

3. See, *e.g.*, Leland [1979], Shapiro [1983], Besanko/Donnenfeld/White [1988] and Das/Donnenfeld [1989].

4. In addition, these studies have generally neglected the possibility that a standard may give firms providing high quality the ability to deter entry by potential suppliers of lower qualities.

5. National Treatment is not included in this analysis but has been treated elsewhere. See, *e.g.*, Boom [1995].

regional demand (market size).⁵ This allows for a better exposition of the effects of these standard arrangements on entry behavior, *i.e.* a more general exposition of the resulting welfare effects. Standards are initially analyzed assuming identical costs. This assumption is relaxed later on.

As in Ronnen, the effects of quality standards on industry competition are primarily driven by their influence on price competition and the qualities produced. Due to the duopoly situation and the nature of price and quality competition, an unregulated equilibrium results in qualities being too low, prices being too high and quality differentiation being too low when compared to a welfare-maximizing solution. When qualities produced become more similar, price competition intensifies. In response to quality standards, qualities rise, quality differentiation is reduced, and prices adjusted for quality fall. In the case of FH, a single standard is binding only for the low-quality provider. High quality rises also because qualities are strategic complements due to the effect of quality differentiation on price competition. Reduced quality differentiation results because increasing quality is increasingly costly. In the two-country case, FH consists of maximizing the sum of regional welfares subject to a single standard.⁶ Under MR, each government maximizes regional welfare subject to its own standard. While FH internalizes effects on welfare of the other region not considered under MR, it uses only one regulatory instrument as compared to two under MR. Consequently, we cannot declare one regulatory alternative superior to the other without further analysis.

Assuming that firms have identical cost functions, this analysis shows the following. Introducing MR yields the maximal sum of regional welfares, while introducing either regulatory alternative will increase the sum of regional welfares compared to no regulation. Under FH, *i.e.* when the objective is to maximize the sum of regional welfares, there exists one local maximum involving only one firm in the market and an increase of regional welfare in both regions compared to the unregulated case. The second and global maximum involves both firms remaining in the market. However, a fully harmonized standard that globally maximizes the sum of regional wel-

6. Maximizing the sum of regional welfares can be seen as the outcome of Nash-Bargaining between both governments.

fares will lead to a reduction of welfare in the region with the high-quality provider. The low-quality provider earns strictly positive profits, *i.e.* it is better off than under MR. MR leads to increases of both regional welfares compared to both the case without regulation and the Full-Harmonization case (global maximum).

Compared to cases with identical costs, as costs of the low-quality provider increase, the sum of regional welfares under MR and under FH (with both firms in the market) decreases, while the sum of regional welfares with only the high-quality provider in the market stays constant. The same holds for the regional welfare of the region with the low-quality provider. With a high enough cost differential, FH with only one firm in the market will lead to the highest sum of regional welfares. In this case maximizing welfare through a uniform standard involves giving up the viability of the low-quality provider. But this is now also in the interest of the region that loses its industry!

The remainder of the paper is organized as follows. Section II presents the model and market equilibria without minimum quality standards. Market equilibria with minimum quality standards are derived in Section III. A summary and main conclusions are presented in Section IV.

II. The Model in the Absence of Standards

A. Basics

In this section I develop a two-market, partial-equilibrium model of vertical product differentiation. The model describes a two-stage game with firms interacting simultaneously in both stages. To derive solutions, I will use the concept of subgame-perfect equilibrium, computing the solutions for each stage in reverse order. There are two separate regions, the “domestic region” (D) and the “foreign region” (F). Markets (and demands) in both regions are segmented but identical. There are two firms, the “domestic firm” (d) is located in the domestic region and the “foreign firm” (f) is located in the foreign region. If entry takes place, then the two firms produce distinct goods, sold at prices p_d and p_f , respectively. The two products carry a single quality attribute denoted by s_d and s_f , respectively. Either firm faces costs of quality development. There are no unit costs of production. Quality

development costs are increasing, convex (quadratic) functions of quality, the exact level of which depending on quality chosen and a quality cost parameter b . Total costs of firm i are then:

$$c_i = b_i s_i^2 \quad (1)$$

In each market, there is a continuum of consumers distributed uniformly over the interval $[0, t]$ with unit density. Each consumer purchases at most one unit of either firm d 's product or firm f 's product. The higher consumer i 's income parameter t_i , the higher is her (his) reservation price. Consumer i 's utility is given by equation (2) if good j is purchased. Consumers who do not purchase receive zero utility.

$$u_{ii} = s_j t_i - p_j \quad (2)$$

Firms d and f play a two-stage game⁷. In the first stage, firms determine qualities to be produced and incur costs c_i ($i = d, f$). In the second stage, firms choose prices simultaneously. Note that both firms choose their respective product quality from the same interval $[0, \infty)$. This also means that both firms' choice whether to be the low-quality or the high-quality provider is now endogenous. The resulting market equilibria will include some consumers in the lower segment of the interval $[0, t]$ not valuing quality enough to even buy from the low-quality provider.⁸ Because the markets are segmented and demands are identical across regions, each firm's profits are identical across regions. It follows also that consumer surplus is the same across regions. This greatly simplifies the following analysis and allows for dropping regional indices when deriving the main model components.

7. In this formulation, firm i not entering the market is equivalent to firm i choosing $s_i = 0$. The entry decision by firms is made simultaneously when choosing quality.

8. This guarantees an interior solution of the price game. If the distribution of consumers would not cover the entire interval $[0, t]$, but were instead of the form covering the interval $[t-1, t]$, then this would not necessarily be true. If t were large, the firms would cover the whole market. However, including this case would not change the qualitative results to be obtained.

B. Price Competition

To solve the game, consider first the demand faced by the high-quality and low-quality provider in each market, respectively. Let h and o stand for high and low quality, respectively. These demands are then given by:

$$q_h = t - \frac{(p_h - p_o)}{s_h - s_o} \quad (3a)$$

$$q_o = \frac{p_h - p_o}{s_h - s_o} - \frac{p_o}{s_o} \quad (3b)$$

Let $t_h = (p_h - p_o)/(s_h - s_o)$ and $t_o = p_o/s_o$. Consumers with $t_i = p_o/s_o$ will be indifferent between buying the low-quality product and not buying at all. Consumers with $t_i = (p_h - p_o)/(s_h - s_o)$ will be indifferent between buying either the high-quality or the low-quality product. Consumers with $t > t_i \geq t_h$ will buy high quality, consumers with $t_h > t_i \geq t_o$ will buy low quality, and consumers with $t_i < p_o/s_o$ will not buy at all.

Let $i = h, o$; let $j \neq i$. The profit function for firm i is given by $\Pi_i = p_i q_i(p_i, p_j, s_i, s_j) - c_i(s_i)$. Taken both qualities as given, the price reaction functions in each market are given as the solutions to the first order conditions. Solving the resulting equations for both prices, equilibrium prices are then given as:

$$p_h = \frac{2ts_h(s_h - s_o)}{4s_h - s_o}, \quad p_o = \frac{t(s_h - s_o)s_o}{4s_h - s_o} \quad (4)$$

Note that for all $s_h > s_o$, $t > t_h > t_o > 0$ will hold, *i.e.*, equation (4) is in fact an unconstrained price equilibrium.

Given the price equilibrium depicted above, demands and thus profits can be expressed in terms of qualities. For positive qualities s_i ($i = h, o$), these profit functions are:

$$\Pi_h = 2 \frac{4t^2 s_h^2 (s_h - s_o)}{(4s_h - s_o)^2} - b_h s_h^2 \quad (5a)$$

$$\Pi_o = 2 \frac{t^2 s_h (s_h - s_o) s_o}{(4s_h - s_o)^2} - b_o s_o^2 \quad (5b)$$

C. Market Equilibria without Quality Standards

To derive the firms' quality best responses, I need to investigate each firm's profit function, given the other firm's quality choice, and taking into account the behavior in the price-setting subgame. Since the choice of high or low quality as compared to the competitor is endogenous, a firm's profit function will be a composite function, consisting of a segment where low quality is chosen and another segment where high quality i 's chosen. Firm i 's profit as a function of own quality, s_i , is then given by:

$$\begin{aligned} \Pi_i &= 2 \frac{4t^2 s_i^2 (s_i - s_j)}{(4s_i - s_j)^2} - b_i s_i^2 \quad \text{for } s_i \geq s_j; \\ &= 2 \frac{t^2 s_i s_j (-s_i + s_j)}{(-s_i + 4s_j)^2} - b_i s_i^2 \quad \text{for } 0 < s_i \leq s_j; \\ &= 0 \quad \text{for } s_i = 0; \end{aligned} \tag{6}$$

where $i = d, f; j \neq i$.

Note that equation (6) reduces to the monopoly profits at $s_j = 0$, *i.e.*, when the other firm does not enter the market.

The following are properties of the regional revenue functions which will be used extensively in the rest of this paper. Let R_t and MR_t denote firm i 's revenue and marginal revenue functions, respectively, where $t = h, o$ specifies whether firm i provides high or low quality. The other firm's quality is denoted by s_j . These properties are verified in the appendix.

$$\frac{\partial R_h}{\partial s_i} \geq 0 \quad (7a); \quad \frac{\partial R_o}{\partial s_i} \geq 0 \quad \text{for } s_i \leq \frac{4s_j}{7} \quad (7b)$$

$$\frac{\partial R_h}{\partial s_j} < 0 \quad (7c); \quad \frac{\partial R_o}{\partial s_j} > 0 \quad (7d)$$

$$\frac{\partial MR_h}{\partial s_i} \leq 0 \quad (8a); \quad \frac{\partial MR_o}{\partial s_i} \leq 0 \quad (8b)$$

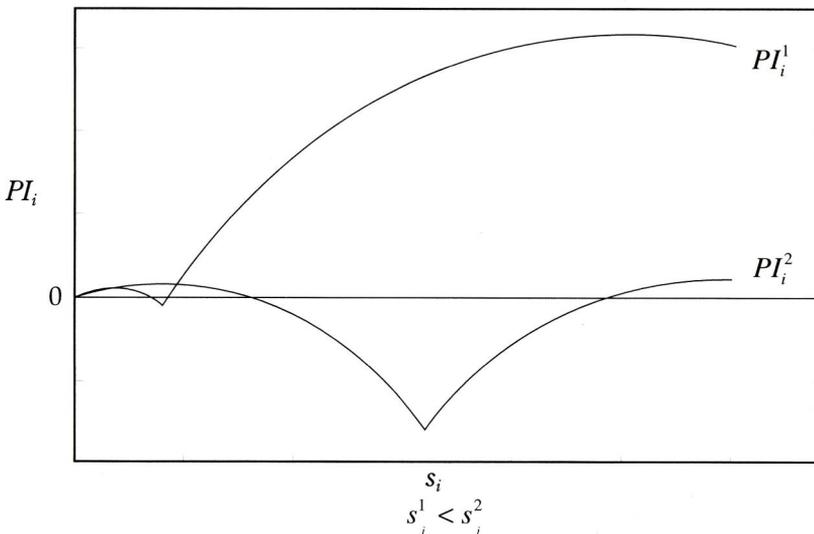
$$\frac{\partial MR_h}{\partial s_j} > 0 \quad (8c); \quad \frac{\partial MR_o}{\partial s_j} > 0 \quad (8d)$$

The economic content of these properties lies in the effects that quality choice has on price competition and marginal costs. I make use of these properties in establishing the shape of the profit function which, in turn, will

allow for the derivation of firm i 's quality best response. For any strictly positive quality chosen by the competitor, a firm can choose either a higher or a lower level of quality. The closer the two qualities are, however, the more are profits curtailed by price competition. If both qualities are identical, price equals marginal cost and profit is negative. This implies that an increase in the competitor's quality increases maximum profit in the low-quality segment while decreasing maximum profit in the high-quality segment. Redefine Π_h and Π_o as the expressions in the first and second line of the RHS of equation (6), respectively. Lemma 1 describes the shape of firm i 's profit function taking the competitor's quality as given. It also describes the change in local profit maxima when the competitor's quality changes. This is illustrated in Figure 1.

Lemma 1: Firm i 's profit as a function of own quality s_i consists of two strictly concave segments, the low-quality segment Π_o and the high-quality segment Π_h , connected at $s_i = s_j$ (where s_j is the competitor's quality). Each of these segments has a unique local maximum, say Π_o^{max} and Π_h^{max} for the low and the high-quality segment, respectively. As s_j approaches zero, $\Pi_h^{max} - \Pi_o^{max}$ approaches a positive limit. For any s_j , an increase in s_j will

Figure 1
Profit Functions



decrease $\Pi_h^{max} - \Pi_o^{max}$. There exists a unique switchpoint $s_j^* = (s_j \mid \Pi_h^{max} - \Pi_o^{max} = 0)$. At s_j^* , both local profit maxima are positive.

Proof: See the appendix.

Lemma 1 implies that firm i will earn higher profits as the high-quality provider for s_j between zero and the switchpoint s_j^* , while earning higher profits as the low-quality provider for $s_j > s_j^*$.

Hence, firm i 's switchpoint is that level of firm j 's quality where firm i is indifferent between being the high-quality and the low-quality provider. Profits along firm i 's quality best response are decreasing in s_j for $s_j < s_j^*$, increasing in s_j for $s_j > s_j^*$, and attain a minimum at the switchpoint. In the absence of fixed costs, profits along firm i 's quality best response are strictly positive for any $s_j > 0$. If s_j was to change from $s_j^* - \varepsilon$ to $s_j^* + \varepsilon$, firm i would switch from being the high-quality provider to being the low-quality provider. Hence, I can derive the shape of firm i 's quality best response. This is done in Lemma 2 and illustrated in Figure 2.

Lemma 2: a) Firm i 's quality best response consists of two segments satisfying the following conditions. For $0 \leq s_j < s_j^*$, firm i provides high quality. For $s_j > s_j^*$, firm i provides low quality. At $s_j = s_j^*$, firm i is indifferent between providing high or low quality. Profits along firm i 's quality best response are decreasing in s_j for $s_j < s_j^*$, increasing in s_j for $s_j > s_j^*$, and attain a minimum at the switchpoint.

b) Firm i 's quality best response is strictly increasing in s_j for all $s_j \neq s_j^*$.

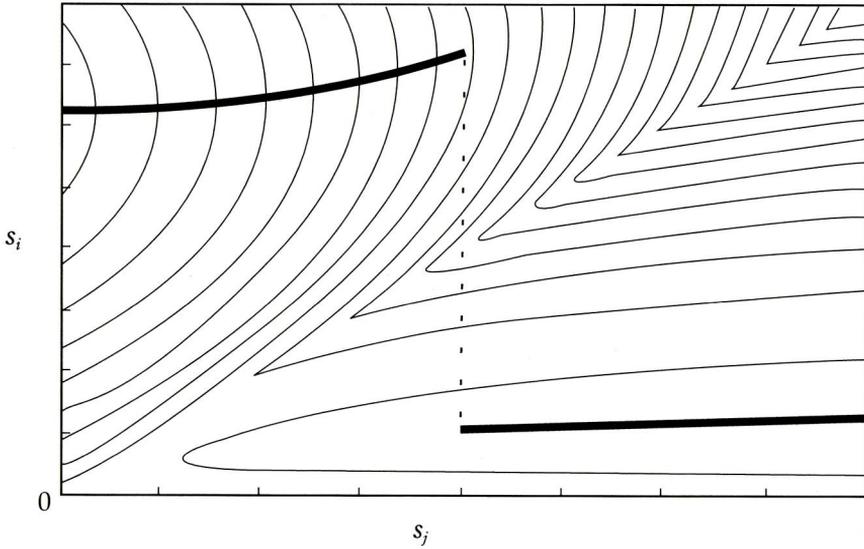
c) Firm i 's quality best response is strictly decreasing in b_i .

Proof: See the appendix.

The market equilibria in pure strategies without government intervention are simply given by the intersections of the quality best responses. Generally, there will be two pure-strategy equilibria as long as firms are not too different with respect to cost of providing quality.⁹ This is illustrated in Figure 3 for the case of identical firms.¹⁰ The ratio of high quality to low quality,

9. Note that in this case, there generally exists at least one non degenerate mixed-strategy equilibrium also.

Figure 2
Isoprofit Curves and Quality Best Response



s_h/s_o , is constant with respect to market size t but increases monotonically in b_o/b_h , the ratio of cost parameters.¹¹

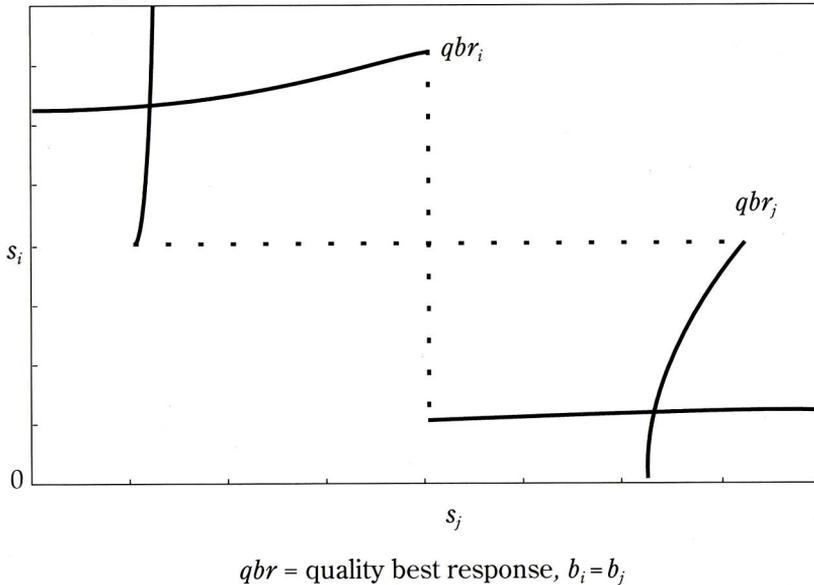
Consumer surplus for each equilibrium can be expressed in the following way:

$$CS_D = CS_F = \frac{t^2 s_h^2 (4s_h + 5s_0)}{2(-4s_h + s_0)^2} \tag{9}$$

Regional welfare is just the sum of regional consumer surplus and the profit of the firm located in that region. Total welfare is then the sum of the

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- 10. The existence of a unique quality equilibrium due to cost differences can be illustrated using Lemma 2(c) and Figure 3. In Figure 3, an increase in b_i would lead to a downward shift in qbr_i . If b_i/b_j gets sufficiently large, the intersection of qbr_i and qbr_j in the northwest corner of Figure 3 vanishes. Only one equilibrium with firm j providing high quality remains.
 - 11. An analytical solution for the equilibrium qualities can be calculated for any given ratio b_o/b_h . This involves solving the first-order conditions in equations (A.3a) and (A.3b) simultaneously. Note that t^2/b_h enters in a multiplicative way and therefore does not affect the calculations.

Figure 3
Quality Equilibria-Identical Firms



welfare in both regions.¹² Although welfare can only be calculated after determining which firm provides high quality and which provides low quality, some welfare results can be obtained that hold in either quality equilibrium. The qualities chosen in an unregulated equilibrium will generally not be optimal from the point of view of either government, since each government prefers higher quality levels than those chosen in a market equilibrium. The following properties of consumer surplus in either region will be used to show this. These properties are verified in the appendix. Let CS_I ($I = D, F$) denote region I 's consumer surplus function. Firms' qualities are denoted by s_h and s_o for high and low quality, respectively.

$$\frac{\partial CS_I}{\partial s_h} > 0 \text{ for } s_o < \frac{4s_h}{5} \quad (10a);$$

12. I denote regional welfare of region I as W_I ($I = D, F$) and total welfare as $W = W_D + W_F$. Alternatively, I can identify a region by the quality level its firm is selling, *i.e.* W_h is the regional welfare of the region with the firm providing high quality.

$$\frac{\partial CS_I}{\partial s_o} > 0 \quad (10b)$$

$$\frac{\partial^2 CS_I}{\partial s_h^2} = \frac{s_h^2}{s_o^2} \frac{\partial^2 CS_I}{\partial s_o^2} = -\frac{s_o}{s_h} \frac{\partial^2 CS_I}{\partial s_o \partial s_h} > 0 \quad (10c)$$

The expression in inequality (10a) is strictly positive for any pair of qualities chosen in a market equilibrium. This is so, since a market equilibrium requires the low-quality firm's marginal revenue to be positive, which is only the case if $s_o < 4s_h/7$. In both regions, an increase of either quality will lead to increases of consumer surplus at increasing rates. This leads to the result in Lemma 3.

Lemma 3: a) Given an unregulated quality equilibrium, regional welfare of both regions can be increased through an appropriate choice of increasing either or both qualities.

b) There exists a single standard that, if imposed in both regions, would increase welfare of both regions.

Proof: See the appendix.

Corollary 1: Starting from an unregulated quality equilibrium, gradually increasing low quality while letting the high-quality provider choose its quality best response will have the following effects on profits: a) the high-quality provider's profits will decrease monotonically; and b) the low-quality provider's profits are concave in low quality, *i.e.* they increase monotonically up to a single maximum and decrease monotonically thereafter.

Proof: See the appendix.

In the following section I extend the model introduced above to include the interaction of governments that use minimum quality standards as optimizing policy instruments. The two-stage industry game is preceded by a government stage where standards are set that will be constraints for the subsequent industry game. In contrast to the case without regulation, there is now the possibility, that only one firm stays in the market (*i.e.* offers a quality-level greater than zero).

III. Market Equilibria with Quality Standards

A. Full Harmonization

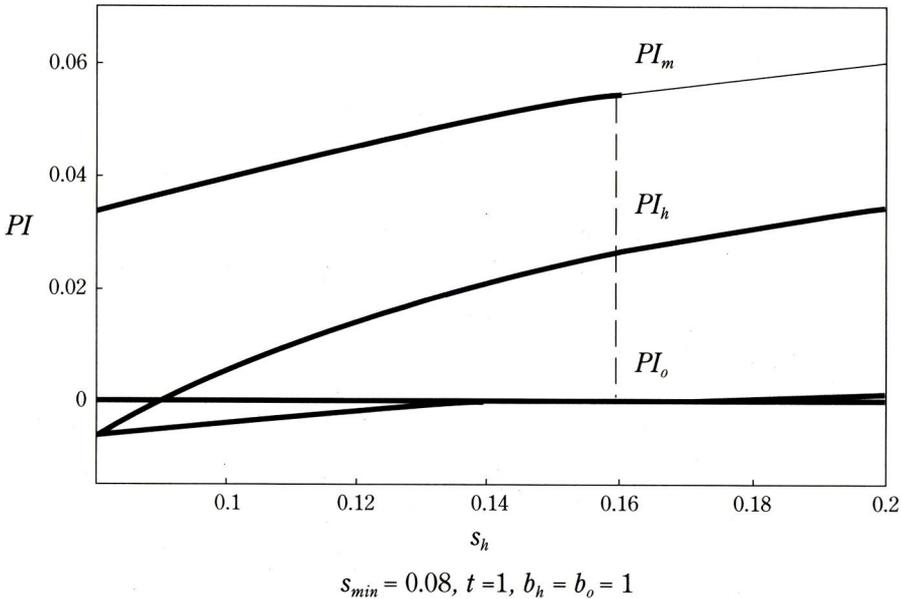
Under the standard-setting procedure of FH, both governments have agreed to set a single uniform standard that maximizes the sum of regional welfares of both regions. This standard will be binding for one of the two firms, namely the low-quality provider. This indicates that the standard-setting problem could be reduced to maximizing the sum of regional welfares with respect to low quality subject to firms' nonnegative-profit conditions and the constraint that the high-quality provider operates on its quality best response. This would lead to a duopoly solution. But since the low-quality provider faces a quality constraint, another condition needs to be satisfied if two firms are to remain in the market. Note that the high-quality provider may be able to deter entry of the low-quality provider by reducing quality differentiation, *i.e.* setting a quality lower than its (duopoly-) quality best response which, in turn, reduces the low-quality provider's profits to zero.¹³ This is illustrated by the numerical example in Figure 4.

In Figure 4, a uniform standard of $s_{min} = s_o = 0.08$ is set. If high quality is set close to s_{min} ($s_h < 0.16$), the low-quality provider is not able to make positive profits ($\Pi_o < 0$) and stays out of the market permitting the remaining firm to earn monopoly profits Π_m . But it may also be possible to earn higher duopoly-profits Π_h by choosing a higher quality. Generally, the high-quality provider will prefer to allow entry at low standards and to deter entry at high standards leading to a quality best response on a uniform standard of the type defined in Proposition 1 below. This is illustrated by the numerical example in Figure 5 where the best response to a standard consists of the segments shown in bold type.¹⁴ Figure 6 illustrates the derivation of this

13. Entry deterrence in the strict sense can occur when one firm is a leader, *i.e.* it moves first. Under simultaneous entry, a similar case arises then when the equilibrium solution involves one firm staying out. One firm "deters" entry, because the other firm correctly anticipates an equilibrium where it cannot attain positive profits. This scenario implicitly underlies any simultaneous-move market equilibrium involving less than the total number of potential entrants.

14. The case where a uniform standard is binding for the monopolist is not shown in Figures 5 and 6.

Figure 4
Profit Functions with a Uniform Standard



best response by showing the profits corresponding to the different segments. Consider a uniform standard set such that the low-quality provider's profits were just equal to zero at the high-quality provider's (duopoly-) quality best response. Clearly, the high-quality provider could prevent entry by the low-quality provider by setting its quality marginally lower than its optimal duopoly response, thereby increasing its profit. On the other hand, if a standard was set sufficiently high, entry of a low-quality provider would be blockaded, *i.e.* the remaining firm can set its quality as if it was a monopolist without the threat of entry.

However, deterring entry in the way described above is only possible, if the low-quality provider cannot profitably respond by setting a quality higher than the firm attempting to deter entry. Hence, quality must be set such that the competing firm can neither earn positive profits as the low-quality provider nor as the high-quality provider. I will refer to the former condition as the zero-profit condition (zpc) and to the latter as the no-leapfrogging condition (nlc).

Let $\Pi_i(s_h, s_o)$ [where $i = h, o$] be defined as in equations (5a) and (5b),

respectively. Let $\Pi_m(s'')$ be defined as in equation (A.5b) where $s_m = s''$. Let $qbr_h(s')$ be the solution to equation (A.3a) where $s_j = s'$. Let s_m be defined as in equation (A.5c). Denote a minimum quality standard as s_{min} .

Definition: $zpc: s \leq s_{zpc}(s') = s | \Pi_o(s, s') = 0;$
 $nlc: s \geq s_{nlc}$ where $s_{nlc} = s | \Pi_h(qbr_h(s), s) = 0$

Only if s_{min} is set such that $s_{zpc}(s_{min}) \geq s_{nlc}$, can entry by one firm be prohibited by the other firm's quality choice. Of course, entry will only be deterred, if the resulting monopoly profits are greater than those resulting from accommodating entry. In summary, the best response consists of the four segments: unrestricted high-quality best response, quality such that the other firm's profits are zero, monopoly quality, and quality bound by the standard, respectively. Proposition 1 presents a more formal definition.

Proposition 1: The high-quality provider's best response to a uniform quality standard consists of the following four segments:

- 1) $s_h = qbr_h(\text{Max}(s_{min}, s_o))$ for $s_{min} \leq s_1$,
- 2) $s_h = s_{zpc}$ for $s_1 \leq s_{min} < s_2$,
- 3) $s_h = s_m$ for $s_2 \leq s_{min} < s_m$,
- 4) $s_h = s_{min}$ for $s_{min} \geq s_m$;

where $s_1 = \text{Max}[s_{min} | \{\Pi_m(s_{zpc}(s_{min})) = \Pi_h(qbr_h(s_{min}), s_{min})\}$
 $s_{min} | \{s_{nlc} = s_{zpc}(s_{min})\}]$,
 $s_2 = s_{min} | \Pi_o(s_m, s_{min}) = 0$

Proof: Follows from discussion above.

The remaining condition is therefore that given a minimum quality standard, either nlc is not satisfied or the high-quality provider's duopoly profits must be greater than or equal to monopoly profits at that quality level that would lead to zero-profits by the constrained low-quality provider. Alternatively, the uniform standard could be set so high that only one firm can survive in the market. It follows that there are generally two generic¹⁵ local maxima, namely one with both firms serving the market and the other with

15. Actually, there are four local maxima, namely a) firm *d* offers high quality, b) firm *d* is a monopolist, firm *f* offers high quality, and d) firm *f* is a monopolist.

Figure 5
High-Quality Best Response with a Uniform Standard

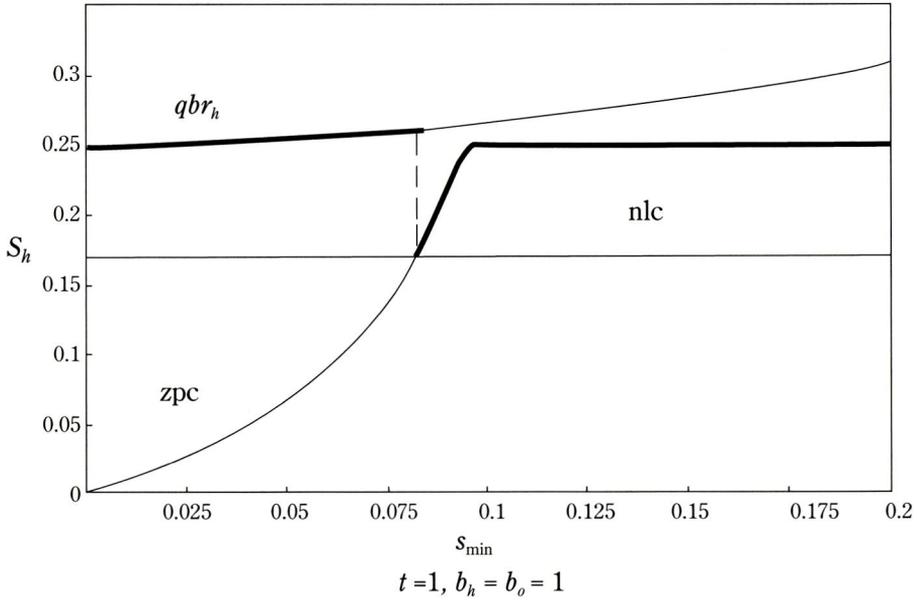
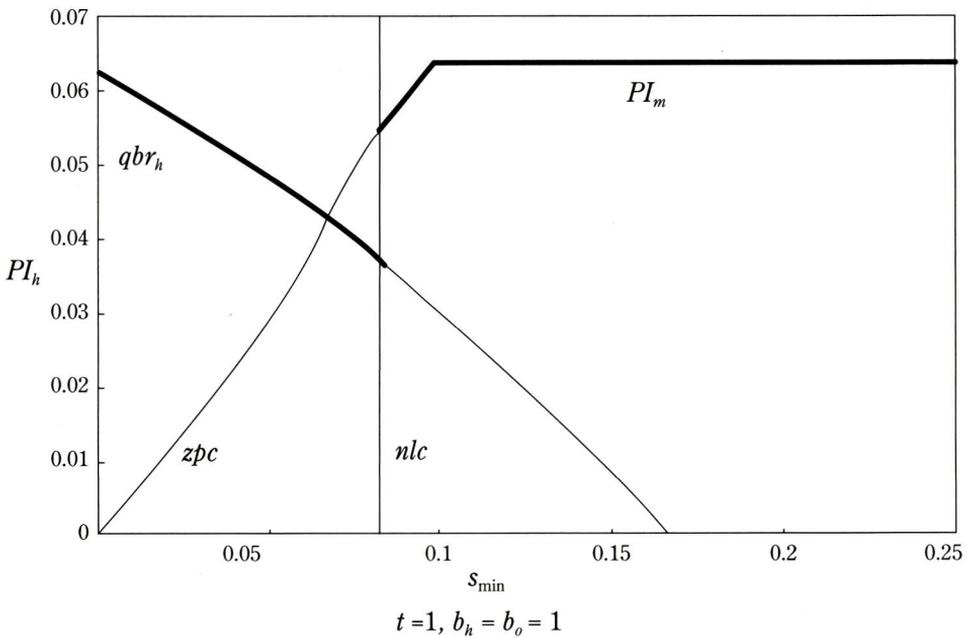


Figure 6
High-Quality Best Response Profits with a Uniform Standard



only one firm remaining in the market.

The calculation of the one-firm maximum is straightforward; it is done in the appendix. The calculation of the two-firm equilibrium involves the following steps. Let the high-quality provider's marginal quality best response be denoted by ds_h/ds_o . Differentiating the objective function with respect to s_o yields equation (11).

$$\frac{dW}{ds_o} = (MR_o - MC_o) + 2 \frac{\partial CS_l}{ds_o} + \frac{dR_h}{ds_o} + \frac{ds_h}{ds_o} \left\{ \frac{dR_o}{ds_h} + 2 \frac{\partial CS_l}{ds_h} \right\} \quad (11)$$

At unconstrained equilibrium qualities, this change is positive since marginal revenue minus marginal cost of quality is zero for both firms, $2\partial CS_l/\partial s_o + \partial R_h/\partial s_o > 0$, and the remaining terms on the RHS of equation (11) are all positive. However, as s_o is increased this change diminishes and eventually becomes negative. Differentiating equation (11) another time yields the following expression.

$$\begin{aligned} \frac{d^2W}{ds_o^2} = & \left(\frac{dMR_o}{ds_o} - 2b_o \right) + \frac{\partial^2 R_h}{ds_o^2} + 2 \frac{d^2 CS_l}{ds_o^2} + \frac{ds_h}{ds_o} \left(\frac{dMR_h}{ds_o} + 2 \frac{\partial^2 CS_l}{\partial s_h \partial s_o} \right) \\ & + \frac{\partial}{\partial s_o} \left(\frac{ds_h}{ds_o} \right) \left(\frac{dR_o}{ds_h} + 2 \frac{\partial CS_l}{\partial s_h} \right) < 0 \end{aligned} \quad (12)$$

It can be shown that the RHS of equation (12) is negative at the choice of s_o that sets the RHS of equation (11) equal to zero.¹⁶ When I simply assume that both firms will stay in the market, this objective function has a single extremum at which it is locally strictly concave. However, at that extremum, profits of the low-quality provider will generally not be nonnegative.¹⁷ Considering Corollary 1 and the previous discussion, it follows that the welfare maximum with two firms must involve lower qualities than those that could hypothetically be calculated by setting equation (11) equal to zero and those that would lead to zero-profits for the low-quality provider. This also implies that the RHS of equation (11) is positive for any standard leading to positive profits for the low-quality provider. Therefore, the Full-Harmonization solu-

16. This tedious but straightforward calculation yields a result equivalent to equation (A.10) in Lutz ([1993], Appendix A).

17. For identical costs, $\Pi_o = -0.00703433t^4/b$. It follows immediately that low-quality profits are negative for $b_o > b_h$.

tion with both firms in the market can be calculated as described in Proposition 2.

Proposition 2: The two-firm local maximum of the objective function under FH can be calculated by choosing a uniform standard $s_{min} = s_1$, *i.e.*

$$\text{Max}[s_{min} \mid \{\Pi_m(s_{zpc}(s_{min})) = \Pi_h(qbrh(s_{min}), s_{min})\}, s_{min} \mid \{s_{nlc} = s_{zpc}(s_{min})\}].$$

Proof. Follows from discussion above.

The examples presented above were calculated assuming identical firms, but all results are valid as long as firms' cost parameters are not too different. The influences of cost differences can be described using Figure 5. As the other firm's cost parameter rises (falls) relative to the high-quality provider's cost parameter, *nlc* falls (rises) and *zpc* becomes steeper (flatter). The high-quality provider's ability to deter entry rises (falls).

Consider the case where the other firm's cost parameter rises. Compared to the symmetry-case, the optimal uniform standard maintaining a duopoly must now be lower. The resulting welfare gain is then lower, too. However, the welfare gain from the optimal standard with only one firm in the market remains constant. It follows that setting a standard such that only one firm enters becomes the more attractive the higher the cost difference.¹⁸

The derivation of standards results for the case of MR is described in the next section.

B. Mutual Recognition

Under the standard-setting procedure of MR, governments noncooperatively set producer standards for their respective firms and recognize the adequacy of each other's standard.¹⁹ The two-stage industry game is now preceded by a stage where governments set their respective standards simultaneously. Each government maximizes regional welfare with respect to a minimum quality standard, taking the other government's standard as

18. The discussion of cost differences concentrates on the case where the high-quality-provider (or monopolist) is the low-cost firm. It is straightforward to show, that this is a necessary condition for optimality of a uniform standard.

19. Recall that each firm's product quality is governed by the regulation of the country of origin, regardless of destination.

given. Both firms will face binding standards. This means that each government maximizes regional welfare with respect to its own firm's quality subject to nonnegative profits to derive the regional standard best response. It also implies that the high-quality provider has no possibility to preempt entry by the low-quality provider. Differentiating region I 's objective function with respect to s_i yields equation (13).

$$\frac{dW_I}{ds_i} = (MR_i - MC_i) + \frac{\partial CS_I}{\partial s_i} \quad (13)$$

At the unregulated equilibrium, the RHS of equation (13) is positive for both regions since marginal consumer surplus is positive.²⁰ However, as s_i is increased this change diminishes and eventually becomes negative. In fact, it can be shown that, under this assumptions, each region's objective function either has a single maximum at which it is locally strictly concave or has a maximum where profits of the local firm just equal zero.²¹ It follows, that both regional governments have an incentive to set a binding minimum quality for their respective firm. In effect, either firm's quality is now set by its government. This means also, that the governments' standard best responses (to each other's standards) are of the same general shape as firms' quality best responses (illustrated in Figure 1). If costs are not too different, there exist two equilibria. Under large cost differences, only one equilibrium with the low-cost firm providing high quality remains.²²

I am now in the position to compare results under alternative regulatory arrangements. These results can be calculated provided the ratio of cost parameters is predetermined.²³ The next section presents results for identical cost cases.

20. Note also that the RHS of equation (13) is positive at $s_i = 0$. This means that a solution involving only one firm in the market cannot be optimal.

21. For an illustration of this procedure, see equations (A.12a) through (A.12c) in Lutz (1993, Appendix A).

22. Derivation is analogous to that of unregulated equilibria. See Section II.C and Footnotes 10 and 11.

23. All calculations for this paper were performed using the "Solve"-routine of Mathematica. Solutions are generally valid for any combination of market size t and cost parameters such that b_h/b_o is constant.

C. Regulatory Regimes with Identical Costs

With identical costs, MR is the optimal policy choice from the point of view of either government. It not only leads to a higher sum of regional welfares than FH but also makes each country better off compared to either FH or non-regulation (NR). FH produces a higher sum of regional welfares than NR, but the country which produces high-quality products has a welfare loss. The properties of the Mutual Recognition outcome are stated in Proposition 3 below.

Proposition 3: With identical costs, the introduction of MR yields maximal welfare for either region. Compared to NR, both qualities will rise, profits of either firm will fall, and consumer surplus in either region will rise.

Proof: See Table 1.²⁴

Regardless of the standards arrangement chosen, consumer surplus always rises in either region compared to the case without regulation.

Table 1
Outcomes under Different Regulatory Regimes-Identical Costs

	<i>NR</i>	<i>FH</i>	<i>FH_d</i>	<i>MR</i>
$s_h^*)$	0.25331	0.26018	0.37500	0.31625
$s_o^*)$	0.04823	0.08233	-	0.10060
$\Pi_h^{**})$	0.04888	0.03717	0.04688	0.02725
$\Pi_o^{**})$	0.00305	0.00152	-	0
$W_h^{**})$	0.09210	0.09068	0.09375	0.09246
$W_o^{**})$	0.04627	0.05504	0.04688	0.06521
$W^{**})$	0.13837	0.14572	0.14063	0.15767

Notes: $b_o = b_h = b$, *) Multiply values with t^2/b , **) Multiply values with t^4/b
NR=no regulation, *FH*=Full Harmonization, *FH_d*=*FH*/only one firm enters,
MR=Mutual Recognition

Under FH, *i.e.* when the objective is to maximize the sum of regional welfares, there exists one local maximum involving only one firm in the market

24. Solutions are generally valid for any $\{t, b_h, b_o\}$ such that $b_o/b_h = 1$.

and an increase of regional welfare in both regions compared to NR. The second and global maximum involves both firms remaining in the market. However, a fully harmonized standard that globally maximizes the sum of regional welfares will lead to a reduction of welfare in the region with the high-quality provider. It is noteworthy, that an agreement on introducing this kind of standard may necessitate a side-payment from the region with the low-quality provider to the region with the high-quality provider unless the viability of the low-quality provider is given up. However, if both firms remain in the market, then the low-quality provider earns strictly positive profits, *i.e.* it is better off than under MR.

MR leads to increases of both regional welfares compared to both NR and FH (global maximum). However, the region with the high-quality provider would be better off under FH with only one firm in the market, even though the sum of regional welfares remains higher under MR.

D. Regulatory Regimes with Different Costs

Compared to cases with identical costs, as costs of the low-quality provider increase, the sum of regional welfares under MR and under FH (with both firms in the market) decreases, while the sum of regional welfares with only the high-quality provider in the market stays constant. This is due to the effects higher costs have on the provision of low quality and on the resulting profits and consumer surplus. Due to increased costs, low quality is reduced and prices must be reduced also. Even though increased quality differentiation allows to ask a higher quality-adjusted price, profits of the low-quality provider are reduced as a result. Since consumers pay a higher quality-adjusted price, consumer surplus goes down. Consequently, if the low-quality provider's costs are very high, *i.e.* its cost function is convex enough, FH with only one firm in the market must maximize the sum of regional welfares.

Proposition 4: With a high enough cost differential, FH with only one firm in the market will lead to the highest sum of regional welfares.

Proof: Follows from the discussion above. This is shown for the case $b_o = 8b_h$ in Table 2.²⁵

25. Solutions are generally valid for any $\{t, b_h, b_o\}$ such that $b_o/b_h = 8$.

Table 2
Outcomes under Different Regulatory Regimes-Different Costs

	<i>NR</i>	<i>FH</i>	<i>FH_d</i>	<i>MR</i>
$S_h^*)$	0.25007	0.25029	0.37500	0.31257
$S_o^*)$	0.00757	0.01497	-	0.01523
$\Pi_h^{**})$	0.06057	0.05861	0.04688	0.05466
$\Pi_o^{**})$	0.00047	0.00002	-	0
$W_h^{**})$	0.09351	0.09327	0.09375	0.09714
$W_o^{**})$	0.03341	0.03467	0.04688	0.04248
$W^{**})$	0.12692	0.12794	0.14063	0.13962

$b_o = 8b_h = 8b$, *) Multiply values with t^2/b , **) Multiply values with t^4/b

NR=no regulation, *FH*=Full Harmonization, *FH_d*=*FH*/only one firm enters, *MR*=Mutual Recognition

In this example in Table 2, any chosen standards alternative will increase consumer surplus in either region compared to *NR*. Under *FH*, the global maximum involves only one firm in the market and increases regional welfare in both regions compared to *NR*. Not surprisingly, in this case maximizing welfare through a uniform standard involves giving up the viability of the low-quality provider. But this is now also in the interest of the region that loses its industry!²⁶ *MR* leads to increases of both regional welfares compared to *NR*. Compared to the *FH*-solution, it leads to a lower sum of regional welfares, higher welfare for the region with the high-quality provider, and lower welfare for the region with the low-quality provider.

IV. Summary and Conclusions

This paper has analyzed minimum quality standards in a partial-equilibrium model of vertical product differentiation and trade in which duopolistic firms face quality-dependent costs and compete in quality and price in two segmented markets. The two alternative standard-setting arrangements of Full Harmonization and Mutual Recognition were analyzed and compared.

25. Solutions are generally valid for any $\{t, b_h, b_o\}$ such that $b_o/b_h = 8$.

26. Note that W_o is maximized under *FH_d*.

The analysis explicitly accounts for the possibility that standards either create the power to deter entry for some firms or are directly used to restrict market entry.

In the benchmark case with identical product costs (*i.e.* identical technologies), Mutual Recognition is the optimal policy choice. Full Harmonization becomes a better alternative as differences in product costs become large. In this case, both countries will prefer a uniform minimum standard that permits only the low-cost industry to profitably exist. The country that loses its industry gains nevertheless since it profits from the availability of a superior product. However, under the condition that uniform standards must not induce exit of the low-quality industry, Mutual Recognition is always the preferable regulatory alternative.

Two main conclusions can be drawn from these results. First, the Country-of-Origin principle should be applied in cases where technological country differences are small or the exit of industries is not a (politically) desirable option. Second, countries should consider accepting uniform standards inducing exit of their national industries from some product markets if these industries face a large technological disadvantage.

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Appendix

A.1 Properties of the Revenue Functions

Let R_t and MR_t denote firm i 's regional revenue and marginal revenue functions, respectively, where $t = h, o$ specifies whether firm i provides high or low quality. The other firm's quality is denoted by s_j .

$$\frac{\partial R_h}{\partial s_i} = \frac{4t^2 s_i (4s_i^2 - 3s_i s_j + 2s_j^2)}{(4s_i - s_j)^3} \geq 0 \quad (\text{A.1a})$$

$$\frac{\partial R_o}{\partial s_i} = \frac{t^2 (7s_i - 4s_j) s_j^2}{(s_i - 4s_j)^3} \geq 0 \quad \text{for } s_i \leq \frac{4s_j}{7} \quad (\text{A.1b})$$

$$\frac{\partial R_h}{\partial s_j} = \frac{4t^2 s_i^2 (2s_i + s_j)}{(-4s_i + s_j)^3} < 0 \quad (\text{A.1c}); \quad \frac{\partial R_o}{\partial s_j} = \frac{t^2 s_i^2 (s_i + 2s_j)}{(-s_i + 4s_j)^3} > 0 \quad (\text{A.1d})$$

$$\frac{\partial MR_h}{\partial s_i} = \frac{-8t^2 s_j^2 (5s_i + s_j)}{(-4s_i + s_j)^4} \leq 0 \quad (\text{A.2a}); \quad \frac{\partial MR_o}{\partial s_i} = \frac{-2t^2 s_j^2 (7s_i + 8s_j)}{(s_i - 4s_j)^4} \leq 0 \quad (\text{A.2b})$$

$$\frac{\partial MR_h}{\partial s_j} = \frac{8t^2 s_i s_j (5s_i + s_j)}{(-4s_i + s_j)^4} > 0 \quad (\text{A.2c}); \quad \frac{\partial MR_o}{\partial s_j} = \frac{2t^2 s_i s_j (7s_i + 8s_j)}{(-s_i + 4s_j)^4} > 0 \quad (\text{A.2d})$$

A.2 First-Order Conditions and Slopes of Firms' Quality Best Responses

The first order conditions for the high and low quality branches of firms' quality best responses are given as:

$$(2s_i(16t^2 s_i^2 - 64b_i s_i^3 - 12t^2 s_i s_j + 48b_i s_i^2 s_j + 8t^2 s_j^2 - 12b_i s_i s_j^2 + b_i s_j^3))/ (4s_i - s_j)^3 = 0 \quad (\text{A.3a})$$

$$(2(b_i s_i^4 - 12b_i s_i^3 s_j - 7t^2 s_i s_j^2 + 48b_i s_i^2 s_j^2 + 4t^2 s_j^3 - 64b_i s_i s_j^3))/ (4s_j - s_i)^3 = 0 \quad (\text{A.3b})$$

The slopes of the high and low quality branches of firms' quality best responses are given as:

$$\left. \frac{ds_i}{ds_j} \right|_h = (8t^2 s_i s_j (5s_i + s_j)) / (256b_i s_i^4 - 256b_i s_i^3 s_j + 40t^2 s_i s_j^2 + \quad (\text{A.4a})$$

$$96b_i s_i^2 s_j^2 + 8t^2 s_j^3 - 16b_i s_i s_j^3 + b_i s_i^4) > 0$$

$$\left. \frac{ds_i}{ds_j} \right|_o = (2t^2 s_i s_j (7s_i + 8s_j)) / (b_i s_i^4 - 16b_i s_i^3 s_j + 14t^2 s_i s_j^2 + \quad (\text{A.4b})$$

$$96b_i s_i^2 s_j^2 + 16t^2 s_j^3 - 256b_i s_i s_j^3 + 256b_i s_i^4) > 0$$

Both slopes are positive, but less than one.

a. Proof of Lemma 1

The concavity properties of the profit function in equation (6) follow from concavity of revenues, since costs are convex. Revenues are concave by equations (A.1a), (A.1b), (A.2a) and (A.2b). The first-order conditions for local maxima are shown in equations (A.3a) and (A.3b). As s_j approaches

zero, Π_o^{max} approaches profits at $s_i = s_j = 0$ equaling 0, whereas Π_h^{max} approaches the monopoly profits. By equations (A.1c) and (A.1d), Π_h^{max} decreases and Π_o^{max} increases as s_i increases.

b. Proof of Lemma 2

a) By Lemma 1, for firm i , $(\Pi_h^{max} - \Pi_o^{max}) > 0$ for $s_j < s_j^*$, $(\Pi_o^{max} - \Pi_h^{max}) > 0$ for $s_j > s_j^*$, and $\Pi_h^{max} - \Pi_o^{max} = 0$ for $s_j = s_j^*$. By inequalities (A.1c) and (A.1d), Π_h^{max} decreases and Π_o^{max} increases as s_i increases.

b) At firm i 's quality best response, marginal revenue (of quality s_i) equals marginal cost. An increase in s_j increases marginal revenue while leaving marginal cost unchanged. Increasing s_i will decrease marginal revenue while increasing marginal cost until marginal revenue equals marginal cost again. See equation (1) and inequalities (A.2a) through (A.2d). The first order conditions for the quality best responses and the resulting slope expressions are shown in equations (A.3) and (A.4).

c) Starting at firm i 's quality best response, an increase in b_i increases marginal cost while leaving marginal revenue unchanged. Decreasing s_i will increase marginal revenue while decreasing marginal cost until marginal revenue equals marginal cost again.

c. Proof of Lemma 3

a) For any pair of qualities chosen in a market equilibrium, marginal profits of both firms are zero, whereas marginal consumer surplus in both regions with respect to both qualities is positive. In addition, an increase in high quality will increase low-quality profit and an increase in low quality will decrease high-quality profit less than consumer surplus increases, *i.e.* $2\partial CS_l/\partial s_o + \partial R_h/\partial s_o > 0$. See equations (A.1c), (A.1d), (A.7a) through (A.7e) and note that by equation (A.1b), $s_o < 4s_h/7$ is a necessary condition for low-quality marginal profits to be equal to zero.

b) If a standard were set slightly above low quality in the unregulated equilibrium, it would be binding for the low-quality provider, but not for the high-quality provider. Since by equation (A.3a), the high-quality provider's quality best response is increasing in low quality, both qualities will

$$\max_{s_o} (\text{Limit}_{s_h} PI_o) = \frac{t^4}{256b_o} \quad (\text{A.6c})$$

A.5 Properties of the Consumer Surplus Functions

Let CS_I ($I=D, F$) denote region I 's consumer surplus function. Firms' qualities are denoted by s_h and s_o for high and low quality, respectively.

$$\frac{\partial CS_I}{\partial s_h} = \frac{t^2 s_h (-8s_h^2 + 6s_h s_o + 5s_o^2)}{(-4s_h + s_o)^3} \quad (\text{A.7a}); \quad \frac{\partial CS_I}{\partial s_o} = \frac{ts_h^2 (28s_h + 5s_o)}{2(4s_h - s_o)^3} > 0 \quad (\text{A.7b})$$

$$\frac{\partial^2 CS_I}{\partial s_h^2} = \frac{t^2 s_o^2 (52s_h + 5s_o)}{(-4s_h + s_o)^4} \quad (\text{A.7c}); \quad \frac{\partial^2 CS_I}{\partial s_o^2} = \frac{t^2 s_h^2 (52s_h + 5s_o)}{(-4s_h + s_o)^4} > 0 \quad (\text{A.7d})$$

$$\frac{\partial^2 CS_I}{\partial s_o \partial s_h} = -\frac{t^2 s_h s_o (52s_h + 5s_o)}{(-4s_h + s_o)^4} < 0 \quad (\text{A.7e})$$

A.6 Full Harmonization with Deterred Entry

Let Π_m be firm i 's profit as a monopolist and CS_m be regional consumer surplus when only one product is offered. Equations (A.8a) through (A.8c) show regional consumer surplus, marginal world welfare, and optimal monopoly quality under FH when the standard is set so high that only one firm prevails. Equation (A.8d) shows regional consumer surplus, monopoly profits and welfare of the region with the monopoly firm when the standard is set according to equation (A.8c).

$$CS_m = \frac{s_m}{8} \quad (\text{A.8a}); \quad \frac{\partial W}{\partial s_m} = \frac{\partial(2CS_m + \Pi_m)}{\partial s_m} = 2\frac{1}{8} + t^2 - 2b_i s_m \quad (\text{A.8b})$$

$$CS_I = 0.046875 \frac{t^4}{b_i},$$

$$s_m = 0.375 \frac{t^2}{b_i} \quad (\text{A.8c}); \quad \Pi_m = 0.046875 \frac{t^4}{b_i}, \quad (\text{A.8d})$$

$$W_m = 0.09375 \frac{t^4}{b_i}$$

A.7 Derivation of the No-Leapfrogging Condition

This is derived by maximizing the high-quality isoprofit curve with

respect to low quality subject to profit equaling zero. For any $\{t, b_h, b_o\}$, I have $s_{nlc} = t^2 / (6b_o)$.