Location choices under quality uncertainty

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Abstract

We examine a linear city duopoly where firms choose their locations to maximize expected profits, uncertain about how consumers will assess the relative quality of their products. Equilibrium locations depend on the ratio of the expected quality superiority and the strength of horizontal differentiation. When this ratio is small, firms locate at opposite endpoints. As it becomes larger, agglomeration also emerges as an equilibrium with both firms choosing the same location within an interval around the center. Eventually, when the ratio is large enough, agglomeration becomes the only equilibrium and can occur at any point of the linear city.

Keywords: Location; Product differentiation; Quality uncertainty; Linear city

JEL classification: L13; L15

1. Introduction

Horizontal differentiation in the context of geographical locations or in that of product characteristics has been studied in an extensive and important literature (see e.g. Gabszewicz and Thisse, 1992 for a review). Hotelling’s (1929) classic model has suggested that firms’ competition for the in-between consumers implies minimal differentiation. Subsequent work has stressed an opposite incentive, with firms locating...
away from their rivals, to relax price competition (see e.g. d’Aspremont et al., 1979). While various aspects of the interaction of these two effects have been studied, including multi-dimensional contexts,\(^1\) the effect of uncertainty about a second characteristic on location decisions is not that well understood. In this paper, we show that equilibrium locations depend critically on quality uncertainty. For instance, a restaurant’s incentive to locate close to its rivals may depend critically on how likely it is that consumers will significantly favor one restaurant to another, for reasons other than their locations.

We set up a duopoly model where, in addition to their locations, products may differ with respect to their quality. Firms choose their locations without knowing how consumers will assess the relative quality of the products. After quality becomes revealed, firms choose their product prices and consumers, then, choose which product to purchase. Thus, the central question is how equilibrium horizontal differentiation is affected by aggregate quality uncertainty. When the possible quality difference is relatively low, the equilibria in our model are as in the d’Aspremont et al. (1979) model of pure horizontal differentiation; that is, firms locate at the endpoints. However, as relative quality uncertainty increases, agglomeration emerges as an equilibrium outcome, with the set of equilibrium locations becoming larger for a higher possible quality difference. By locating at the same point as its rival, a firm risks obtaining zero profit if its quality proves inferior, but takes full advantage of its superiority when its quality is higher than the rival’s. As the possible quality difference increases, the incentive to agglomerate dominates. Importantly, our model offers an economic rationale for agglomeration also at points other than the city center.

Previous work has also considered how enriching the description of consumers’ preferences beyond simply the horizontal dimension may lead to a modified set of equilibria. Probably the closest work to ours is by Rhee et al. (1992) where consumers’ preferences have both an observable (to the firms) component and an unobservable one. This work shows that, as uncertainty about their preferences (that is, the unobservable component) becomes more important, a tendency appears for firms to choose locations closer to the center. Our work differs in that we consider aggregate quality uncertainty, rather than heterogeneity in consumers’ preferences.\(^2\) In other words, one of the products will be viewed (with some probability) by all consumers as having higher quality. As a result, we need to calculate equilibrium profits for all possible locations and quality differences. Then, to evaluate the location incentives, we derive expected profits at each pair of locations by aggregating over all possible quality difference realizations. Like in the Rhee et al. (1992) study of unobserved consumers’ heterogeneity, our analysis shows that there are incentives for firms to move away from the extreme locations. However, there are also differences in our conclusions. Rhee et al. (1992) find that firms tend to locate at points symmetric around the center and that, as uncertainty about preferences increases, these points come closer to the center, eventually with the firms locating at the center.

\(^1\) See e.g. Economides (1989), Neven and Thisse (1990), Irmen and Thisse (1998) and Ansari et al. (1998).

\(^2\) Heterogeneity in consumers’ preferences has also been shown to tend to drive firms to central locations in de Palma et al. (1985).
center. In our model, as the ratio of the quality difference to the transportation cost increases, there appear equilibria where both firms choose the same location, at points that belong to an interval around the center; once this ratio exceeds a given threshold, agglomeration may occur at any point of the line.

The remainder of the paper is as follows. Section 2 sets up the model. Section 3 presents the equilibrium. Section 4 modifies the game so that firms choose locations sequentially. Section 5 concludes. The calculations underlying the locations equilibria are standard but relatively tedious (since several cases have to be distinguished); they are contained in an Appendix which is available upon request from the authors.

2. The model

Consider two firms, \( A \) and \( B \), each producing a single product in a (new) market. Firms locate their products on the \([0,1]\) line. Consumers are uniformly distributed on the line segment with transportation cost quadratic in distance. A consumer located at point \( w \) on the line and purchasing a unit of firm \( i \)'s product obtains surplus equal to

\[
u(w,i) = R - t(w - x_i)^2 + q_i - p_i,
\]

where \( x_i \) denotes the location of firm \( i \), and \( p_i \) and \( q_i \) its product's price and quality, respectively. Thus, products are differentiated both horizontally and vertically.

We assume that the basic reservation value, \( R \), is high enough and that each consumer purchases one unit of the product, the one that offers the highest net surplus—in other words, consistent to the main body of the product differentiation literature, the market is “covered”.

In order to capture the effect of relative quality uncertainty on location choices, we assume that the quality of product \( i \), \( q_i \), is a random variable, the realization of which firms ignore when they choose their locations. The timing of the game is as follows:

1. Firms simultaneously choose the locations of their products.
2. The quality difference, \( q_i - q_j \), is revealed and becomes common knowledge.
3. Firms simultaneously choose their product prices.
4. Having observed the firms’ locations and the product qualities and prices, each consumer purchases one unit of the product from one of the firms.

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3 The effect of uncertainty on location choices has been also studied in Balvers and Szerb (1996), but in a model that suppresses price competition and, thus, obtains very different results (risk aversion drives firms away from agglomeration). Gerlach et al. (2005) also study the effect of quality uncertainty on horizontal differentiation, but their focus and results are different, primarily because, in their model, firms with different qualities do not coexist in the market (thus, there is no need to calculate the firms’ expected profits for each and every given pair of possible quality differences).

4 The main body of these calculations is also contained in a working paper version of this work, Christou and Vettas (2004).
Each firm is risk neutral and seeks to maximize its expected profit and each consumer seeks to maximize his (net) surplus from the purchase.

The structure of the model is consistent with the view that location choices have longer run characteristics than pricing. It also captures the idea that these locations are costly to change after certain aspects of the products (quality) become revealed to the consumers.

For reasons of tractability, we further assume that the random variable \( q_i - q_j \) is uniformly distributed on some interval \([-h, h]\), \( h > 0 \). Implicit in this assumption is our treatment of firms as a priori symmetric. Note that the ratio \( h/t \) captures the importance of vertical (quality) differentiation relative to horizontal (location) differentiation. Since the quality difference is a random variable, the profits associated with each location pair are also random, at the time the location decisions are made. We assume that unit costs are zero.

3. Equilibrium

We proceed backwards, looking for a subgame perfect Nash equilibrium.

3.1. Price equilibrium

Since each firm, \( A \) or \( B \), can choose any location on the line, it is convenient to denote for the price competition part of the analysis the firms as 1 and 2, where firm 1 is to the left of 2 (\( x_1 < x_2 \)). When, subsequently, we turn to the location choices, we will allow each firm to choose a location to the left or the right of its rival (that is, allow each firm to assume the role of firm 1). Now, given the firms’ locations, their demand functions are as follows. Let \( z \) be the demand of firm 1—then, firm 2 has demand \( 1 - z \).

For \( z \in (0, 1) \), by solving equation (2), we obtain

\[
\frac{x_1 + x_2}{2} + \frac{p_2 - q - p_1}{2t(x_2 - x_1)}.
\]

Taking also into account the possibility that all consumers may choose one of the products, the firms’ profit functions are

\[
\pi_1 = p_1 z \quad \text{and} \quad \pi_2 = p_2 (1 - z),
\]
where
\[
    z = \begin{cases} 
        0 & \text{if } \frac{x_1 + x_2}{2} + \frac{p_2 - q - p_1}{2t(x_2 - x_1)} \leq 0 \\
        \frac{x_1 + x_2}{2} + \frac{p_2 - q - p_1}{2t(x_2 - x_1)} & \text{if } \frac{x_1 + x_2}{2} + \frac{p_2 - q - p_1}{2t(x_2 - x_1)} \in (0, 1) \\
        1 & \text{if } \frac{x_1 + x_2}{2} + \frac{p_2 - q - p_1}{2t(x_2 - x_1)} \geq 1.
    \end{cases}
\]

The equilibrium prices, as functions of locations and the realized \( q \), are as follows.\(^5\)

**Proposition 1.** For \( 0 \leq x_1 \leq x_2 \leq 1 \) the equilibrium prices are
\[
    p_1^* = \begin{cases} 
        t \left[ (x_2 - 1)^2 - (x_1 - 1)^2 \right] - q & \text{if } q < q_- \\
        \frac{1}{2} \left[ t \left( (x_2 + 1)^2 - (x_1 + 1)^2 \right) - q \right] & \text{if } q \in [q_-, q_+] \text{ if } q > q_+,
    \end{cases}
\]
and
\[
    p_2^* = \begin{cases} 
        0 & \text{if } q < q_- \\
        \frac{1}{2} \left[ t \left( (x_1 - 2)^2 - (x_2 - 2)^2 \right) + q \right] & \text{if } q \in [q_-, q_+] \text{ if } q > q_+,
    \end{cases}
\]

where
\[
    q_- = t \left[ (x_2 - 2)^2 - (x_1 - 2)^2 \right]
\]
and
\[
    q_+ = t \left[ (x_2 + 1)^2 - (x_1 + 1)^2 \right].
\]

Proposition 1 implies that there is a unique price equilibrium for each pair of locations and for each realization of the quality difference. It illustrates how, in equilibrium, a firm takes advantage of its product quality superiority. If the quality difference is small (and depending on the firms' locations) both firms make positive sales; otherwise, the high quality firm captures the entire market. The Proposition nests as special cases two extremes. When differentiation is only horizontal \((q = 0)\), we recover the d’Aspremont et al. (1979) characterization of price equilibria. When differentiation is only vertical \((x_1 = x_2)\), the firm selling the higher quality product charges a price equal to the quality difference, \( q \), and serves all consumers while the rival firm charges a price of zero.

### 3.2. Equilibrium locations

We now proceed to the first stage of the game, where firms choose their locations. Taking as given equilibrium pricing in the second stage (for any quality realization), each firm’s location should maximize its expected profit, given the location of its rival.

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5 Proposition 1 modifies and extends a result in Vettas (1999) to the case of arbitrary quality differences. The proof follows standard arguments and its details are available upon request.
We denote the expected profit function of firm $i$ by $E\pi_i(x_1, x_2)$, suppressing in the notation of the arguments the transportation cost parameter, $t$, and the quality difference parameter, $h$. The expectation is taken over the stochastic quality $q$. The expected profit function of firm 1 is

$$E\pi_1(x_1, x_2) = \int_{\min(-h, q_+)}^{q_-} \pi_i^m(x_1, x_2) dF + \int_{\max(-h, q_-)}^{\min(q_+, h)} \pi^c_1(x_1, x_2) dF,$$

(8)

where $F(x) = (x + h)/(2h)$ is the cumulative distribution function of the variable $q$ (since $q$ is uniformly distributed on $[-h, h]$). Depending on the quality realization, we can have either an interior solution (where both firms sell their products) or a corner solution (with only the high quality firm making positive sales). The function $\pi_i^m(x_1, x_2)$ denotes profit of firm 1 in the case that it only sells its product, and $\pi_i^c(x_1, x_2)$ denotes the profit of firm 1 when both firms sell their products. Specifically, by substituting the equilibrium prices from the relevant ranges of (5) and (6) into the profit function (3), we obtain

$$\pi_i^m(x_1, x_2) = -q + t \left[ (x_2 - 1)^2 - (x_1 - 1)^2 \right]$$

and

$$\pi_i^c(x_1, x_2) = \frac{1}{18(x_2 - x_1)} \left[ q + t \left[ (x_1 + 1)^2 - (x_2 + 1)^2 \right] \right].$$

(9)

The bounds of the integrals in (8) are set to be $\min\{-h, q_-\}$, $\max\{-h, q_-\}$ and $\min\{q_+, h\}$, to allow for the possibility that some type of price equilibria do not occur for some values of the parameters $(x_1, x_2, h, t)$. If, for example, $h$ is relatively low and the distance between the two firms’ locations is relatively large, that is, $q_-$ is low compared to $-h$, then even if $q$ equals $-h$, both firms sell their products in equilibrium regardless of the realized value of $q$.

Similarly, the expected profit function of firm 2 is

$$E\pi_2(x_1, x_2) = \int_{\max(-h, q_-)}^{\min(q_+, h)} \pi^c_2(x_1, x_2) dF + \int_{\min(q_+, h)}^{h} \pi^m_2(x_1, x_2) dF.$$

(10)

Since a firm can choose to locate either at the same location, to the left, or to the right of its rival, the expected profit functions of firms $A$ and $B$, over the entire range of locations, are

$$E\pi_i(x_i, x_j) = \begin{cases} E\pi_1(x_i, x_j) & \text{if } x_i \leq x_j \\ E\pi_2(x_j, x_i) & \text{if } x_i \geq x_j, \ i, j \in \{A, B\}. \end{cases}$$

(11)

A key characteristic of the functions $E\pi_1(x_1, x_2)$ and $E\pi_2(x_1, x_2)$ is that they are quasi-convex in $x_1$ and $x_2$, respectively, a property implying that they are maximized at the extrema of their domains.\(^6\) Since $E\pi_1(x_1, x_2)$ is quasi-convex in $x_1$, firm 1’s best response

\(^6\)In principle, the fact that the profit functions are not quasi-concave poses threats for the existence of equilibria. However in the present model there always exists at least one equilibrium.
is to locate either at 0 or at \(x_2\). Similarly, \(E\pi_2(x_1, x_2)\) achieves its maximum value either at point \(x_1\) or 1. It follows that, given the location of firm \(B\), firm \(A\)'s best response belongs to \(\{0, x_2, 1\}\), that is, either it chooses the same location as its rival or one of the endpoints.

Specifically, the best response correspondence of firm \(i\) given the location of firm \(j\), \(i, j=A, B\) is as follows:

- For \(h/t < r_1\)
  \[
  R_i(x_j) = \begin{cases} 
  1 & \text{if } x_j \leq 1/2 \\
  0 & \text{if } x_j \geq 1/2. 
  \end{cases}
  \]  \(12\)

- For \(h/t \in [r_1, r_2]\)
  \[
  R_i(x_j) = \begin{cases} 
  1 & \text{if } x_j \leq 1 - x^* \\
  x_j & \text{if } x_j \in [1 - x^*, x^*] \\
  0 & \text{if } x_j \geq x^*, 
  \end{cases}
  \]  \(13\)

where
\[
x^* = \arg_{x \in [0, 1]} \left\{ \frac{h^2 + 3x^2(2 + x)^2t^2}{54xt} = \frac{h}{4} \right\}.
\]  \(14\)

- For \(h/t > r_2\)
  \[
  R_i(x_j) = \{x_j\} \text{ for all } x_j \in [0, 1].
  \]  \(15\)

The values \(r_1\) and \(r_2\) are the solutions, with respect to \(x\), to the equation \((h^2 + 3x^2(2 + x)^2t^2)/(54xt) = h/4\) for \(x = 0.5\) and for \(x = 1\), respectively \((r_1 \approx 0.786\) and \(r_2 \approx 2.442\)). The explanation for the equality yielding these critical thresholds is as follows. The expected profit of a firm, if it is located at the same point as its rival, is \(E\pi(x, x) = h/4\), whereas \(E\pi(0, x)\) can be easily shown to be equal to \((h^2 + 3x^2(2 + x)^2t^2)/(54xt)\) and increasing in \(x\). Also, the difference \(E\pi_1(x, x) − E\pi_1(0, x)\) is increasing in \(h/t\), that is, the greater the maximum possible quality difference, the greater the incentive for a firm to locate at the same point as its rival. Thus, given the quasi-convexity of \(E\pi_1(x_1, x_j)\) with respect to \(x_i\) and the symmetry of the profit function \(E\pi_1(x_i, x_j)\) (that is, \(E\pi_1(x_i, x_j) = E\pi_1(1-x_j, 1-x_j)\)) a firm’s best response depends on the distance from its rival. Further, given the location of firm \(j\) at a point \(x \in [0.5, 1]\), the best response of firm \(i\) will be either at point 0, or at point \(x\); location at point 1 gives lower profit than location at point 0. For \(h/t < r_1\), \(E\pi_1(x, x) < E\pi_1(0, x)\), for every \(x\), and for \(h/t > r_2\), \(E\pi_1(x, x) > E\pi_1(0, x)\), for every \(x\). In the remaining case, when \(h/t \in (r_1, r_2)\), if firm \(j\) locates at a point \(x\), close enough to an endpoint, firm \(i\) would choose the opposite endpoint. For example, if firm 2 locates close enough to endpoint 1, so that \(x > x^*\), then \(E\pi_1(0, x) > E\pi_1(x, x)\) holds and the best response of firm 1 is to locate at point 0. On the other hand, if \(x \in (1-x^*, x^*)\), then \(E\pi_1(0, x) < E\pi_1(x, x)\), and the best response of firm \(i\) is to locate at the same point \(x\) as its rival. Finally, by implicit differentiation of the equality \((14)\) that defines \(x^*\), we observe that \(x^*\) is strictly increasing in \(h/t\). Thus, a higher value of \(h/t\) increases the attractiveness of locations near the center.
A diagrammatic illustration for the different cases discussed above is useful and also helps us derive the equilibrium locations. Fig. 1 presents the case $h/t \in [r_1, r_2]$. Observe that there is a continuum of location pairs at which the two best response correspondences intersect, that is, there is a continuum of location equilibria.

As $h/t$ approaches $r_1$, $x_B^*$ and $x_A^*$ approach 0.5 and the best response correspondence of firm $A$ becomes, in the limit, as shown in Fig. 2(a). Fig. 2(b) illustrates firm $B$'s best response correspondence. The two best response correspondences then cross only at the extreme points. As $h/t$ approaches $r_2$, $x_B^*$ and $1-x_A^*$ approach 1 and the best response correspondence of firm $A$, in the limit, becomes as shown in Fig. 2(c). For $h/t>N r_2$, the graphs of the best response correspondences of the two firms are identical and, hence, any point in the interval corresponds to a location equilibrium.

We summarize the previous analysis:

**Proposition 2.** The location equilibria are as follows: (i) for $h/t<r_1$ there are only two equilibrium location pairs, the extreme points $(x_A, x_B) = (0, 1)$ and $(x_A, x_B) = (1, 0)$, (ii) for $h/t \in [r_1, r_2]$ there is a continuum of equilibria $(x_A, x_B) = (x, x)$, with $x \in [x^*, 1-x^*]$ where $x^* \in [1/2, 1]$ is given by (14), as well as the two extreme points $(x_A, x_B) = (0, 1)$ and $(x_A, x_B) = (1, 0)$, and, (iii) for $h/t>r_2$ each location pair $(x_A, x_B) = (x, x)$, with $x \in [0, 1]$ is an equilibrium.
Thus, the firms tend to choose minimally differentiated locations if the expected gains of having a successful (high quality) product are sufficiently high. In other words, it pays to follow an aggressive product choice strategy if the expected value of the (possible) success is relatively high. Note that, when there are agglomeration equilibria, there is a continuum of these, in addition to the extreme locations equilibrium. Fig. 3 illustrates the set of equilibrium locations as a function of the ratio of the maximum possible quality difference to the transportation cost, \( h/t \). When \( h/t < r_1 \), there exist only equilibria with maximum horizontal differentiation. When \( h/t \in [r_1, r_2] \), in addition to the two equilibria with maximum differentiation, there also exist equilibria with minimum differentiation: agglomeration can occur at points that form a symmetric interval around the center of the city. The extent of locations where agglomeration equilibria exist increases with \( h/t \). For \( h/t > r_2 \) only equilibria with minimum differentiation exist and agglomeration may occur at any point in the city.

In models of horizontal differentiation, there are two forces, one pushing the firms close to each other and one pushing them in the opposite direction. In our formulation, which force dominates depends on the level of quality difference. When the expected quality advantage of a high quality firm is small, the price competition effect dominates and maximum horizontal differentiation is preferred. As the quality advantage one firm could gain over the other increases, a high quality firm tends to prefer locations closer to its rival. This fact is captured by the quasi-convexity of the profit functions: the expected profit \( E\pi_1(x_1, x_2) \) is maximized either at point 0 or at point \( x_2 \). This, in turn, is due to the fact that the profit \( \pi^m_1 (x_1, x_2) \), of a firm that has quality higher enough than its rival, is increasing in \( x_1 \). Moreover, the incentive of each firm to locate at the same point as its rival depends on the location of the latter. The closer the low quality firm is to the center, the greater is the incentive of the high quality firm to choose the same location. Essentially, the high quality firm prefers to take full advantage of its quality superiority by locating at the same point as its rival, only if the maximum horizontal differentiation it can achieve from the rival is relatively small. Taking expectations over quality realizations, the ratio of the expected profit under agglomeration to the one when choosing different locations is increasing in \( h/t \). Further, a higher \( h/t \) value supports
a greater range of locations at which there can exist equilibria with minimum horizontal differentiation.\footnote{Note that, as discussed in the Introduction, previous work has shown that uncertainty about the individual consumers’ preferences may lead to agglomeration at the city center. In particular, Rhee et al.’s (1992) Proposition 3 shows that for high uncertainty there is an equilibrium only at the center and for intermediate levels of uncertainty there is an equilibrium at the center, as well as “dispersed” equilibria with firms locating at equal distances from the center. In our analysis, under aggregate quality uncertainty, the set of equilibria is different. For high relative quality difference there can be agglomeration at any point on the interval, not only at the center. For intermediate values, we obtain both extreme location equilibria and also a continuum of agglomeration equilibria at points that belong to an interval around the center. These differences are because, under aggregate uncertainty, a firm expecting significant quality superiority finds it profitable to press its advantage by choosing the same location as its rival.}

Note that in the simultaneous location game, expected profits are not always maximized from the viewpoint of joint profit maximization. In particular, agglomeration equilibria are dominated in terms of profits by extreme locations equilibria and, if the firms could coordinate their decisions, they would like to avoid them. Partly motivated by this observation, we now turn to the study of sequential location choices.

4. Sequential location choices

Suppose now that the two firms make their location choices sequentially (and then firms compete in prices simultaneously, as before). This modification of the model allows us to understand better the firms’ location incentives. From the above analysis, we know that a follower’s best response is to locate either at an endpoint or at the same point as the first mover. Unlike the case of simultaneous location choices, however, now the firm that chooses its location first can effectively choose the location that maximizes its expected profit, knowing how its rival will respond (note that this location also maximizes the expected profit of its rival, since the expected profit functions take the same value in equilibrium). We have:

**Proposition 3.** When firms choose locations sequentially, the equilibrium locations are: (i) if $h/t < r_2$, $(x_A, x_B) = (0, 1)$ or $(x_A, x_B) = (1, 0)$, and, (ii) if $h/t > r_2$, $(x_A, x_B) = (x, x)$, for any $x \in [0, 1]$.

**Proof.** If either $h/t \geq r_2$ or $h/t < r_1$, the equilibrium locations are the same as in Proposition 2. Either firm wishes to locate at the same point as its rival (if $h/t \geq r_2$), or as far from each other as possible (if $h/t \leq r_1$). When $h/t \in [r_1, r_2]$, if the two firms end up located at the same point, each would have expected profit equal to $h/4$. If the two firms are located at the opposite endpoints, the expected profit of each firm would be $(t/2 + h^2/(54t))$. Straightforward calculations show that $h/4 < (t/2 + h^2/(54t)) \Leftrightarrow h/t < r_2$, implying that the firms prefer locating at the opposite endpoints. \( \square \)

5. Conclusions

We have studied how aggregate quality uncertainty affects the location choices of firms. We identify the ratio of the expected quality difference to horizontal differentiation as the
key parameter driving the results. For low values of this variable, we obtain maximum differentiation. For higher values, agglomeration equilibria also appear, around the center. Interestingly, agglomeration may occur not only at the center but also at points within a wider set of locations, symmetrically defined around the center. This set expands as the possible quality difference increases and, after a certain threshold, covers the entire linear city.

While we cannot claim full generality of our exact results (it is a common feature of the product differentiation literature that the equilibria may significantly depend on the model formulation), we believe the main conclusions from our analysis are more general than the specific model adopted: in industries where locations (or horizontal product characteristics) have to be chosen before uncertainty concerning the relative product quality is resolved, we expect firms to tend to locate closer to their rivals relative to industries where differentiation is essentially only horizontal, in which case the incentive to relax price competition tends to keep firms away from each other.

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