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How to Play Hotelling Game in a Square Town

by

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Introduction

We consider a model where a population of customers is spread out and uniformly distributed over a squared geographical area with density 1: two firms, located in the same space, sell a homogeneous product, whose unit cost is the same for each firm. Each firm has the aim of maximizing its own profit.

Following the classical "Main Street" model by Hotelling ([5]) and the paper by J.J.Gabszewicz and J.F.Thysse ([4]), we consider that, since the product is homogeneous, a customer will buy from the seller who quotes the lower full price (namely the mill price plus a "transportation cost ", which here will be merely quadratic).

Therefore the demand of a firm will depend on its location and price policy , as well as on the location and the price policy of the other firm. Moreover we suppose that each customer consumes exactly one unit of the commodity.

For such a model, we consider the problem of existence of a noncooperative price-location Nash equilibrium in pure strategies.

As it is well-known even in the one-dimensional model ([4]), no simultaneous price-location equilibrium can exist in pure strategies, if we don't allow the firms can locate outside the interval. Therefore we formulate the problem in terms of a two stage game; namely, price and location strategies are assumed to be played one at a time in a two-stage process. Locations are fixed in the first stage of the game , while prices are decided in the second stage.

In order to solve this problem in the one dimensional case , D'Aspremond, Gabsevich and Thysse introduced in [3] the maximal differentiation principle (m.d.p.). which is undoubtedly a very useful tool and has a great reputation: it provides indeed a very simple and effective description of this complicated problem.

Unfortunately, if we make even simple and quite natural alterations in the model (such as changing the number of the players or the shape of the town) the above mentioned principle is no longer valid. even if the sellers still need space out. in order to reduce the competition effects.

Therefore we are interested in a new formulation of the m.d.p.. with the aim of describing in a simple way the sides both of competition and of optimality which are implicit in the model.

In this paper we state two simple laws which allow us to solve the classical Hotelling problem in a square town, with easy algebraic calculations: we think these laws remain valid even if we suitably change the shape of the town.

Moreover, in the case of the square town we compute explicitly by routine calculations the profit functions and show that the price-location Nash equilibria obtained using usual analysis tools are the same we deduce directly and much more simply from the above mentioned laws.

1.Notations and description of the game.

Let $Q = \{(x, y) \in R^2 \, s.t. \, -1/2 \leq x \leq 1/2 \, ; \, -1/2 \leq y \leq 1/2\}$ be the unite square where consumers and sellers are located; the consumers are uniformly distributed. Firm 1 is located in a point $a = (a_1, a_2)$ and firm 2 in $b = (b_1, b_2)$: without loss of generality we can suppose $a_1 \leq b_1$, that is we agree upon naming "player 1" the one on the left side.We always consider the unit cost c is the same for each firm, so we can consider for semplicity c = 0; moreover we suppose the two sellers are located in different positions: otherwise, as in Bertrand [1], the unique price equilibrium is $p_1 = p_2 = 0$, so the profits of both firms are zero. This is not an admissible solution for the game, because in suitable different locations we know the sellers have positive profits.

Let p_1 and p_2 (belonging to $[0, +\infty[$) denote the mill price of 1 and 2 respectively and assume that the transportation costs are quadratic functions of the distance; therefore the full price payed by a consumer X = (x,y) who buys from firm 1 (resp. from firm 2) is

$$p^{(1)} = p_1 + t[(x - a_1)^2 + (y - a_2)^2]$$

$$(resp. \; p^{(2)} = p_2 + t[(x - b_1)^2 + (y - b_2)^2]$$

where t is a positive constant.

A consumer who is indifferent between the two firms is located in a position $(\bar{x}, \bar{y})$, such that

$$\bar{x}\,(a_1 - b_1) + \bar{y}\,(a_2 - b_2) = \frac{p_1 - p_2 - p_c}{2t} \quad (1.1)$$

where $p^c = t[(b_1^2 + b_2^2) - (a_1^2 + a_2^2)]$.

Let us notice that, if $a_1 = b_1$ (or $a_2 = b_2$), the demand function is analogous to the one-dimensional case; so in what follows we can suppose without loss of generality that $\alpha = b_1 - a_1 \neq 0$ and $\beta = b_2 - a_2 \neq 0$. The demand function of player 1 depends obviously on $(p_1, p_2, a_1, a_2, b_1, b_2)$, but here we wish to emphasize its dependence on $p_1 \in [0, +\infty[$ and consider the remaining variables like parameters; denoting $\frac{p_c}{t} = \gamma$, we obtain the following (1.2)

$$D_1(p_1, p_2, a, b) = \begin{cases} 1 & \text{if } 0 < p_1 \leq p_1^{(1)} \\ 1 - \dfrac{1}{8\alpha\,|\beta|}\left(\dfrac{p_1 - p_2}{t} + \gamma + \alpha + |\beta|\right)^2 & \text{if } p_1^{(1)} \leq p_1 \leq p_1^{(2)} \\ \dfrac{1}{2} - \dfrac{1}{2\alpha\,|\beta|}\, min\{\alpha, |\beta|\}\left(\dfrac{p_1 - p_2}{t} - \gamma\right) & \text{if } p_1^{(2)} \leq p_1 \leq p_1^{(3)} \\ \dfrac{1}{8\,\alpha\,|\beta|}\left(\dfrac{p_1 - p_2}{t} - \gamma - \alpha - |\beta|\right)^2 & \text{if } p_1^{(3)} \leq p_1 \leq p_1^{(4)} \\ 0 & \text{if } p_1 \geq p_1^{(4)} \end{cases}$$

where

$$\begin{aligned} p_1^{(1)} &= p_2 + p^c + t(-\alpha - |\beta|)\,\} \\ p_1^{(2)} &= p_2 + p^c + t\,min\{-\alpha + |\beta|, +\alpha - |\beta|\} \\ p_1^{(3)} &= p_2 + p^c + t\,max\{-\alpha + |\beta|, +\alpha - |\beta|\} \\ p_1^{(4)} &= p_2 + p^c + t\,(\alpha + |\beta|). \end{aligned}$$

It can be easily verified that D_1 is a decreasing differentiable function with respect to p_1, which is concave w.r.to p_1 in $[p_1^{(1)}, p_1^{(3)}]$ and convex in $[p_1^{(3)}, p_1^{(4)}]$.

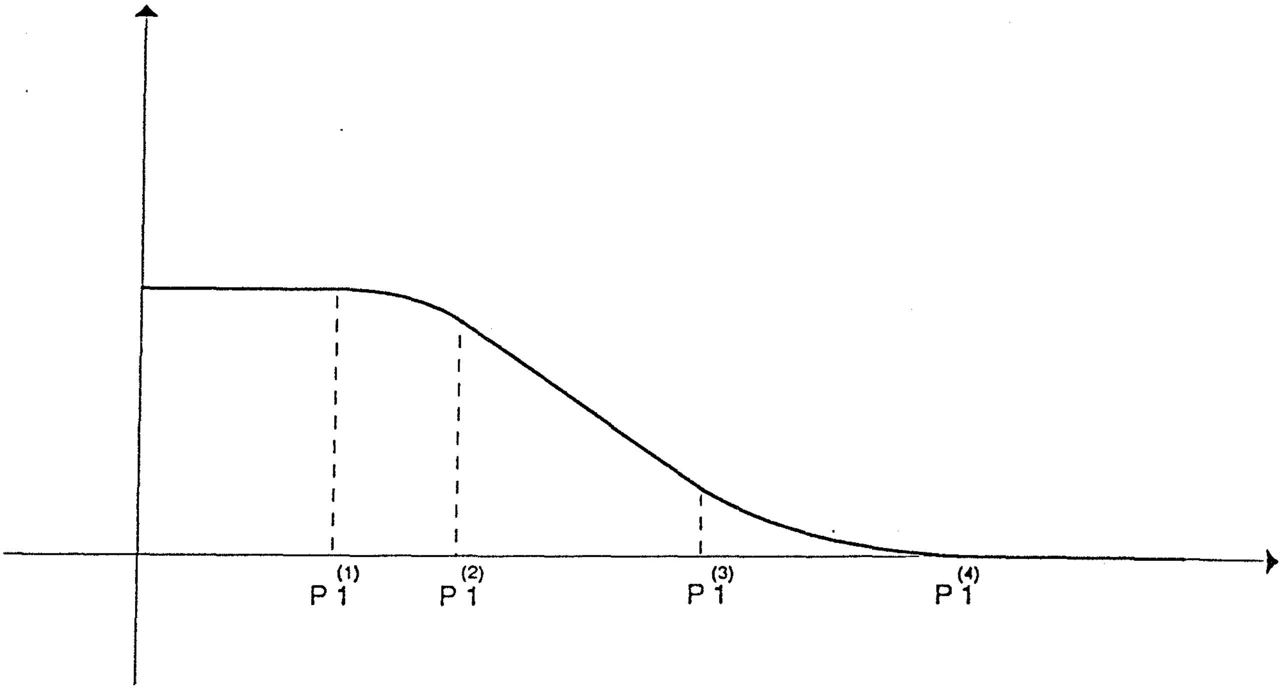


Fig.1

The demand function for player 2 is immediately computed, noticing that $D_1 + D_2 = 1$, as we supposed that each consumer buys one unit of the good.

2. The laws of equilibria.

As we recall in the introduction, we consider the game is played sequentially in a two-stage process: locations are fixed in the first stage, prices in the second one.

Note that here we assume the sequential game is correctly played: that is, when each player chooses his location, the decision on price is consequently already done, as each firm is supposed to play its optimal price, depending on the location choice made in the first stage.

Now we are able to state the laws of equilibria, which are stated in terms of price and demand variables; these are not directly controlled by the sellers, but are anyway significant from an economic point of view and express indeed a reaction of the market to the price policy of the sellers.

First Law :
Suppose the firms fix their respective locations in a and b ($a, b \in Q; a \neq b$). If the price vector (p_1, p_2) is a Nash equilibrium, then

$$p_1 D_2 = p_2 D_1. \qquad (2.1)$$

This law may be interpreted in different ways.
If we rewrite (2.1) as

$$p_1 (1 - D_1) = p_2(1 - D_2)$$

it becoms clear that, if (p_1, p_2) is an equilibrium, the amount of profit lost by seller 1, owing to his price p_1, must be equal to the amount of profit lost by seller 2.

Moreover, if we write the first law in a fractional way, we obtain

$$\frac{p_1}{p_2} = \frac{D_1}{D_2}.$$

Then $p_1 \geq p_2$ implies $D_1 \geq D_2$, i.e. in an equilibrium the seller who quotes the higher price has the gratest demand too: this is an apparently paradoxical consequence, but this actually happens when firm 1 is located better than firm 2.

When the profit functions are smooth enough (for instance, differentiable) , the first law can be directly deduced from optimality necessary conditions

$$\begin{cases} D_1 + p_1 \dfrac{\partial D_1}{\partial p_1} = 0 \\ D_2 + p_2 \dfrac{\partial D_2}{\partial p_2} = 0 \end{cases} \qquad (2.2)$$

by means of simple calculations, observing that the demand function (1.2) depends only on the price difference $p_1 - p_2$ and moreover $D_2 = 1 - D_1$: whence we have

$$\frac{\partial D_1}{\partial p_1} = \frac{\partial D_2}{\partial p_2}.$$

Such a smoothness can be obtained considering smooth and uniformly convex transportation cost functions (in our model, they are quadratic).

Finally, this law is stable w.r.to the shape of the town: we believe it remains valid in the case the town is convex, or even not convex, but with a suitable regular boundary.

When the sellers are more than two, we think that a corresponding formulation of the first law is still valid. After all, the first law seems us to be essentially stable either w.r.to the shape of the town and to the number of the players.

The second law of equilibria is, in some sense, complementary to the first one and is stated as follows:

Second Law

If the two firms are in an equilibrium w.r.to both prices and locations, then they get the same profit, i.e.

$$p_1 D_1 = p_2 D_2. \qquad (2.3)$$

This statement can not be directly deduced by necessary optimality conditions, but seems us quite reasonable; in fact, if $p_1 D_1 > p_2 D_2$ at any equilibrium (a, b, p_1, p_2), then the symmetry of the problem allows the players to choose also a different equilibrium where $\bar{p}_1 \bar{D}_1 < \bar{p}_2 \bar{D}_2$. That is , if $p_1 D_1 > p_2 D_2$, player 2 is not selecting his most preferred equilibrium.

Now, we show how to simply deduce from these laws the equilibria of the game. Denote by (a^*, b^*, p_1^*, p_2^*) a price-location equilibrium, which necessarily satisfies (2.1) , (2.2) and (2.3).

A direct consequence of the previous laws are the equalities

$$D_1^* = D_2^* \qquad\qquad p_1^* = p_2^* \qquad (2.4)$$

which are valid in every equilibrium position.

From the first of (2.4), we infer

$$D_1^* = D_2^* = \frac{1}{2} \; .$$

that is, the square is divided in two equal regions . This happens if the origin belongs to the indifference line, whose equation is (see (1.1))

$$(a_1^* - b_1^*)x + (a_2^* - b_2^*)y = \frac{p_1^* - p_2^* - p_c^*}{2t} \, . \quad (2.5)$$

Since from (2.4) we have $p_1^* = p_2^*$, the origin belongs to (2.5) iff

$$p_c^* = t[((b_1^*)^2 + (b_2^*)^2) - ((a_1^*)^2 + (a_2^*)^2)] = 0;$$

therefore

$$||a^*|| = ||b^*|| \quad (2.6)$$

that is a pair of locations which are an equilibrium must have the same distance from the centre of the town.

Let us compute $\frac{\partial D_1}{\partial p_1}$ in the point (a^*, b^*, p_1^*, p_2^*) (just to shorten the treatment, we consider here the case $\frac{b_2^* - a_2^*}{b_1^* - a_1^*} \leq 1$) and recall that from (2.4) we have $p_2^* = p_1^*$. It results:

$$\Delta D_1 = D_1(p_1, p_2^*) - D_1(p_1^*, p_2^*) = \frac{p_1 - p_2^*}{2t(a_1^* - b_1^*)} = \frac{p_1 - p_1^*}{2t(a_1^* - b_1^*)}$$

hence
$$\frac{\partial D_1}{\partial p_1}(p_1^*, p_1^*) = \frac{1}{2t(a_1^* - b_1^*)}.$$

From the first of (2.2) we deduce

$$p_1^* = t(b_1^* - a_1^*)$$

and consequently the profit corresponding to the equilibrium (a^*, b^*, p_1^*, p_2^*) is

$$\Pi_1^* = \frac{t}{2}(b_1^* - a_1^*) = \Pi_2^* \, ;$$

each firm gets the highest profit when $(b_1^* - a_1^*)$ is maximum, that is when

$$a_1^* = -\frac{1}{2} \text{ and } b_1^* = \frac{1}{2} \qquad (2.7).$$

(In the remaining case $\frac{b_2^* - a_2^*}{b_1^* - a_1^*} > 1$ we get $a_2^* = -\frac{1}{2}$ and $b_2^* = \frac{1}{2}$). Finally, the equilibrium locations may occur only if the sellers are situated on the opposite sides of the square, in positions that are symmetric w.r.to one axe or w.r.to the origin and the equilibrium prices are $p_1^* = p_2^* = t$.

Referring to Figure 2, the location pairs which are allowed to be equilibria by (2.6) and (2.7) are for instance the couples (a', b') or (a', b''), and (a_0, b'_0) or (a_0, b''_0).

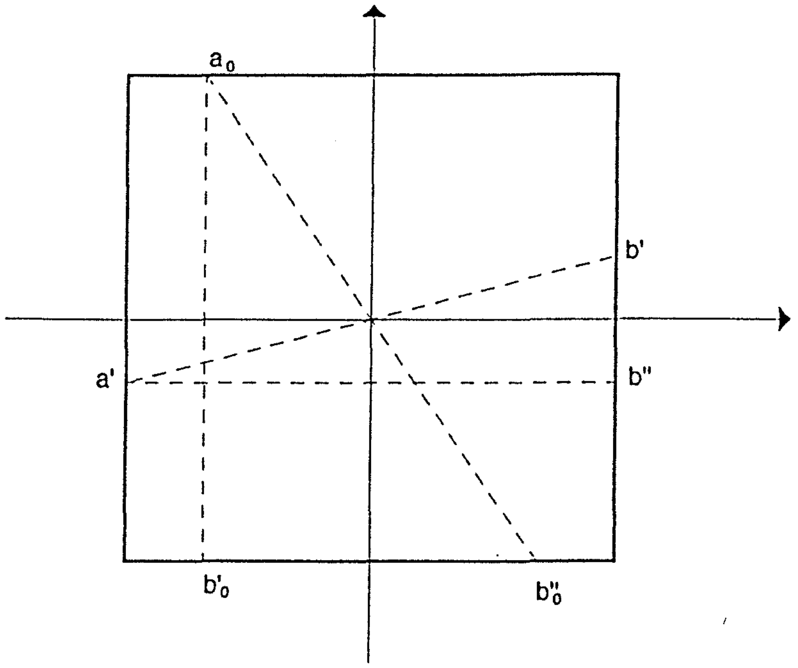


Fig.2

Notice that neither the pair (a', b') nor (a', b'') can be an equilibrium location, since a' isn't the best replay position for player 1 when 2 is located in b' (or in b").

To see this,observe that (Π_1 can be easily computed in this case : for the whole expression of Π_1 , see (3.2))

$$\Pi_1\left((-\frac{1}{2},0),(\frac{1}{2},b')\right) = \frac{1}{2t}\left[1 + \frac{1}{3t}(||b'||^2 - \frac{1}{4})\right]^2 >$$

$$\frac{1}{2t}\left[1 + \frac{1}{3t}(||b'||^2 - ||a'||^2)\right]^2 = \Pi_1\left((-\frac{1}{2},a'),(\frac{1}{2},b')\right)$$

hence player 1 increases his profit , moving to the intersection of the side $x = -\frac{1}{2}$ of the square with the x-axis.

Therefore, the only equilibrium pairs are located in the intersections of the axes with the opposite sides of the square, i.e.

$$(a^*, b^*) = ((-\frac{1}{2}, 0), (\frac{1}{2}, 0))$$

or

$$(a^*, b^*) = ((0, -\frac{1}{2}), (0, \frac{1}{2})).$$

3. **Direct computation of the equilibria**

In this section, our aim is to give exactly the expression of the profit function and obtain by direct calculations the price- location equilibrium we inferred by the laws in paragraph 2; we state here only the results of the required calculations, as the intermediate steps are tedious and not interesting.

Recalling (1.1) in paragraph 1, we obtain that the profit function for player i is

$$\Pi_i \; (a, b, p_1, p_2) = p_i \; D_i(a, b, p_1, p_2)$$

and we look for a price-location Nash equilibrium in pure strategies. Π_i is a differentiable and quasi-concave function w.r.to p_i (it is indeed concave in $[0, p_1^{(3)}]$ and decreasing if $p_1 \geq p_1^{(3)}$, therefore it is strictly quasi concave); moreover Π_i has a unique maximum in p_i.

As we specified in the introduction, the game is played sequentially: in order to solve it explicitly, we proceed as follows. We consider the choice about locations as prior to the decision on prices: that is the firms choose their locations simultaneously (first stage) and, given the locations, they choose prices simulataneously (second stage). For each choice of fixed positions a and b in Q we can consider the subgame depending only on prices (Π_1, Π_2) (where $\Pi_i = \Pi_i \; (a, b, p_1, p_2) = p_i \; D_i(a, b, p_1, p_2)$) and solve it firstly. Well-known theorems (see [2]) guarantee the existence and the uniqueness of a pair of equilibrium prices $(p_1^*(\bar{a}, \bar{b}), p_2^*(\bar{a}, \bar{b}))$ for each pair $\bar{a}$ and $\bar{b}$ in Q. Consider now an arbitrary pair a , b of points in Q and the corresponding payoffs obtained after having solved the second stage game

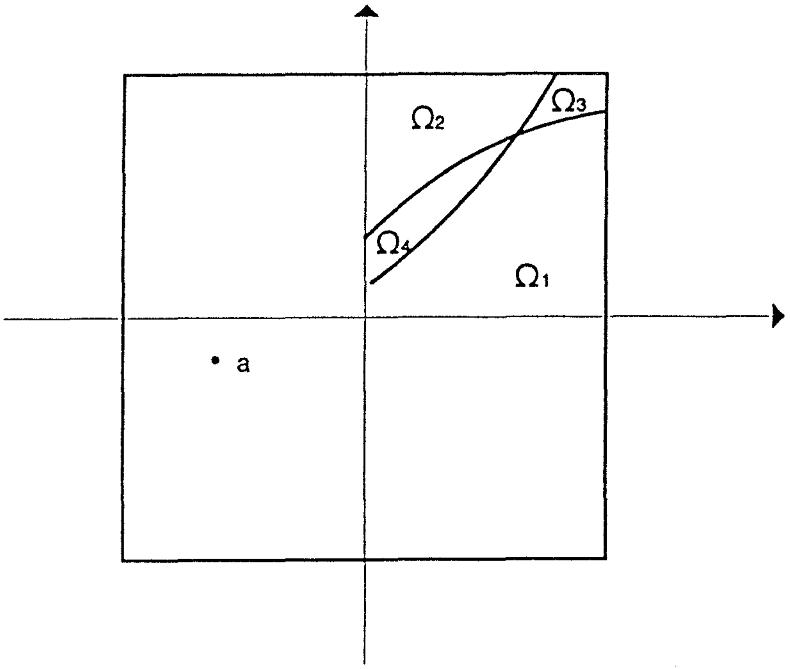
$$\Pi_i^* \; (a, b, p_1^*(a, b), p_2^*(a, b)) = p_i^*(a, b) \; D_i^*(a, b, p_1^*(a, b), p_2^*(a, b)). \qquad (3.1)$$

They are well defined (because of the second stage equilibrium prices are unique) and depend only on the positions a and b.

So, we can study location competition using the reduced-form profit functions (3.1) and compute a Nash equilibrium pair of locations (a^*, b^*) for the game (Π_1^*, Π_2^*). In such a way, we obtain the optimal quaterna $(a^*, b^*, p_1^*(a^*, b^*)p_2^*(a^*, b^*))$, which is the subgame perfect price-location equilibrium (see [4]).

More precisely, direct computation by usual analysis tools allow us to calculate the profit functions (3.1): to illustrate the result, let us consider for instance which is the expression of $\Pi_2^* \, (a, b, p_1^*(a, b), p_2^*(a, b))$ when the locations are such that $a = (a_1, a_2) \in Q_1 = [-\frac{1}{2}, 0] \times [-\frac{1}{2}, 0]$ and $b = (b_1, b_2) \in Q_2 = [0, \frac{1}{2}] \times [0, \frac{1}{2}]$, $a \neq b$ (the other cases can be handled similarly).

Consider the disks C_1 with center $(-\frac{3}{2}, \frac{3}{2})$ and radius $\sqrt{(a_1 + \frac{3}{2})^2 + (a_2 - \frac{3}{2})^2}$ and C_2 with center $(\frac{3}{2}, -\frac{3}{2})$ and radius $\sqrt{(a_1 - \frac{3}{2})^2 + (a_2 + \frac{3}{2})^2}$; their intersections with the square Q_2 split Q_2 into four parts , named Ω_i, as shown in the following Figure 3.



In each region, Π_i^* $(a, b, p_1^*(a,b), p_2^*(a,b))$, which we shortly indicate by Π_i^* , has different expressions, namely (3.2)

$$\Pi_1^* = \begin{cases} \frac{t}{2}\frac{1}{\alpha}(\alpha + \frac{1}{3}\gamma)^2 & \text{if} \quad b \in \Omega_1 \\ \frac{t}{2}\frac{1}{\beta}(\beta + \frac{1}{3}\gamma)^2 & \text{if} \quad b \in \Omega_2 \\ \frac{t}{8^3 2\alpha\beta}(\sqrt{(-\gamma+\alpha+\beta)^2 + 32\alpha\beta} - \gamma + \alpha + \beta)^3 + \\ \quad + \frac{t}{4}[\sqrt{(-\gamma+\alpha+\beta)^2 + 32\alpha\beta} - 3(-\gamma+\alpha+\beta)] & \text{if} \quad b \in \Omega_3 \\ \frac{t}{8^3 2\alpha\beta}(\sqrt{(\gamma+\alpha+\beta)^2 + 32\alpha\beta} + \gamma + \alpha + \beta)^3 & \text{if} \quad b \in \Omega_4 \end{cases}$$

$$\Pi_2^* = \begin{cases} \frac{t}{2}\frac{1}{\alpha}(\alpha - \frac{1}{3}\gamma)^2 & \text{if} \quad b \in \Omega_1 \\ \frac{t}{2}\frac{1}{\beta}(\beta - \frac{1}{3}\gamma)^2 & \text{if} \quad b \in \Omega_2 \\ \frac{t}{8^3 2\alpha\beta}(\sqrt{(-\gamma+\alpha+\beta)^2 + 32\alpha\beta} - \gamma + \alpha + \beta)^3 & \text{if} \quad b \in \Omega_3 \\ \frac{t}{8^3 2\alpha\beta}(\sqrt{(\gamma+\alpha+\beta)^2 + 32\alpha\beta} + \gamma + \alpha + \beta)^3 + \\ \quad + \frac{t}{4}[\sqrt{(\gamma+\alpha+\beta)^2 + 32\alpha\beta} - 3(\gamma+\alpha+\beta)] & \text{if} \quad b \in \Omega_4 \end{cases}$$

where α, β, γ have been defined in section 1.

One can show that, if $a \in Q_1$ and $b \in Q_2$, $(\nabla_a \Pi_1^*(a,b), \nabla_b \Pi_2^*(a,b)) \neq (0,0)$: in particular, if $b = (b_1, b_2)$ belongs to the region Ω_1 (resp. Ω_2) firm 1 increases its profit moving to the location $(b_1, 0)$ (resp. $(0, b_2)$). Moreover, it can be easily verified that, if the pair of locations $(\bar{a}, \bar{b}) = ((\bar{a}_1, \bar{a}_2), (\bar{b}_1, \bar{b}_2))$ is a Nash equilibrium, then the symmetric pair $(a_0, b_0) = (-\bar{b}, -\bar{a})$ is an equilibrium too.

Using the previous arguments , we can finally prove that the only two Nash equilibrium pairs of locations are $((-\frac{1}{2}, 0), (\frac{1}{2}, 0))$and $((0, -\frac{1}{2}), (0, \frac{1}{2}))$.

It is possible consider many other generalizations of the classical Hotelling model, more faithful to reality than the original one: among them, we have chosen here the ones which consider a flat town.

If the shape of the city is a plane geographical area, many not yet solved questions arise: for instance, there isn't any theorem which guarantees the existence of equilibria in locations or their uniqueness (except for the simplest situations); moreover no correct substitute of m.d.p.has been stated .

It may occur that the equilibrium positions are located on the boundary of the town (see the square town with two sellers, as we proved) but it may happen the equilibrium locations be in the interior (for example in the linear town with three players). In general, even for simple shapes (squares or circles), the lowest number of players such that at least one of the players has an internal equilibrium location is not known.

We intend to pursue further and answer some of these questions.

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