points of the circle. The product at firm i's locations represent the basic product of firm i, its basic variety, but the latter can be redesigned by the firm in order to match the specific consumers' requirements bearing a unit constatnt customization cost t_i, so that the total customization cost is assumed to be linear in distance. In what follows, we shall call *variety* the basic product offered by the firm, and *version* the tailored product offered at each location. The parameter t_i synthesizes the technological properties of the customization activity or equivalently, according to Norman (2003) and Thisse and Vives (1988), the variable cost of redesigning the base product. The higher the technological parameter t_i, the higher are the customization costs incurred by the firm in the market.

We shall assume that each firm has access to a set of different customization technologies. This set is the same for all firms, which also share the same information technology. The customization technology adopted by a firm is always observable by its competitor. The competing firms are assumed to be able to offer individually tailored goods such that all the varieties of a basic product are offered; moreover they are assumed to be able to discriminate perfectly among consumers, by setting a price schedule $p(x)$ for each variety depending on consumers' location x, where x is the distance of a consumer from the generic firm i. This price charged to the consumers includes the cost associated with product customization, so that the mill price at each location is the price corrected for the customization cost - the transportation cost of adapting the firm's base product to consumers' needs.

In order to focus on the role of transportation costs, we assume that the basic variety is produced at zero variable costs. However, firms bear a set-up cost F to enter the market. This cost may be either constant and independent of the customization cost, or decreasing in the latter. In the first case the choice of a more efficient customization technology is costless for the firm; in the second efficiency in customization imposes higher set-up costs.

3 Pricing customization

It is within the above framework that the following three-stage game is analysed: firms are assumed to decide first their entry into the market, and then to engage a customization cost competition and a price competition. At each stage of the game firms' choices are simultaneous. The game is solved by backward induction. We solve first the price stage of the game, then we deal with the optimal choice of the customization cost. The optimal number of firms is determined, in the third stage, by a standard zero profit condition. To start with, we consider a situation in which the set-up costs are exogenous and independent of the customization technology.

3.1 The case with fixed set-up costs

3.1.1 The price stage

At the price stage we assume that n firms are on the circle, therefore a firm is $\frac{1}{n}$ far from its neighbours. The customization cost which firm i bears to deliver the product with attributes x is equal to $t_i x$, while the same variety is delivered by the adjacent firms at a cost equal to $t_{i-1}\left(\frac{1}{n} - x\right)$. The equilibrium in prices is an optimal price schedule for each firm, that holds for all possible values of the customization parameter.

Following a Bertrand argument, since consumers buy from the firm charging the lowest delivery price, at each point x price competition among firms results in a delivered price that cannot be higher than the transportation cost to buy the product of the closest rival firm. As demonstrated by Lederer and Hurter (1986) in their influential work, the $\frac{1}{n}$ consumers between two firms on the circle will be charged by firm i with a price infinitesimally lower than $p_i(x) = t_{i-1}\left(\frac{1}{n} - x\right)$ if $t_i x < t_{i-1}\left(\frac{1}{n} - x\right)$, and $p_i(x) = t_i x$ if $t_i x > t_{i-1}\left(\frac{1}{n} - x\right)$. Formally, $p_i^*(x) = \max\left\{t_i x, t_{i-1}\left(\frac{1}{n} - x\right)\right\}$.

Figure 1 shows the optimal price schedule of firm i under the assumption that the neighbouring firms have the same customization cost.

It is easy to check that the distance between firm i and the indifferent consumer between firm i and its (identical neighbours) is $\frac{t_{i-1}}{n(t_i+t_{i-1})}$. Notice that, differently from the traditional Hotelling model, the highest prices are actually paid to firm i by those among its customers who are located at a lower distance, while the indifferent consumer pays the lowest price.

Notice also that in the presence of symmetric customization costs, the market share of each firm at equilibrium will be obviously equal to $\frac{1}{n}$ and profits accruing to each firm are:

$$\pi_i = 2\int_0^{\frac{1}{2n}} \left(\frac{t}{n} - 2tx\right) dx - F = \frac{t}{2n^2} - F$$

clearly increasing in t.

Given this positive relationship between t and the level of profits, we now investigate the technological stage of the game in which firms optimally choose their customization costs.

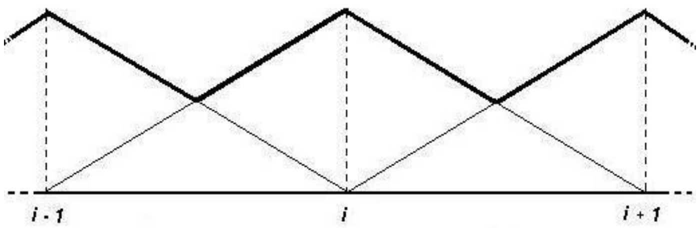

Figure 1: The optimal price schedule

3.1.2 The technological game and the cost paradox

Assume now that firms may choose the customization costs, by adopting a cost-reducing technology configuration. The technology switching is assumed to be costless. More precisely we assume that each firm may choose any t in the admissible range $[t_{\min}, t_{\max}]$. The existence of a lower bound may be seen as a technological constraint. The existence of an upper bound must be imposed in order to ensure that market is fully covered for reasonable values of the consumers' reservation utility.

The simultaneous choice of the customization cost may therefore be seen as a sort of technological competition among firms. Consider the optimal behaviour of firm i, given the behaviour of its adjacent rivals, firm $i-1$ and firm $i+1$. If the latter behave identically, i.e. $t_{i+1} = t_{i-1}$, profits of firm i may be written as:

$$\pi_i = 2\int_0^{\frac{t_{i-1}}{n(t_i+t_{i-1})}} \left(t_{i-1}\left(\frac{1}{n} - x\right) - t_i x\right) dx - F \tag{1}$$

Inspection of the profit function (1) shows that for all possible values of t_{i-1}, profits of firm i are monotonically decreasing in t_i. The intuition behind this result is the following: the firm's profits at each served location are the difference between the rival's customization cost at that location and its own customization cost: a cost reduction is profitable for a firm because it increases the mill price without affecting prices. Moreover, by reducing t_i firm i increases its market share. As a result, choosing the lowest possible

t is a dominant strategy for each firm. Therefore, imposing the symmetry condition, the Nash equilibrium in customization costs is $t_i = t_{i-1} = t_{\min}$.

Proposition 1 *When technology switching is costless, firms behaving non cooperatively choose the minimum level of the customizaton cost technologically available, $t = t_{\min}$.*

Notwithstanding the fact that the choice of a higher level of the technological parameter would soften price competition in the last stage of the game, firms choose to lower them. Notice that this is consistent with the cost paradox first discussed by Nelson (1957). [6] When firms may costlessly choose the customization cost, the production technology game is a prisoner's dilemma. The equilibrium profits are:

$$\pi_i = 2 \int_0^{\frac{1}{2n}} \left(\frac{t_{\min}}{n} - 2t_{\min} x \right) dx - F$$

Given the positive relation between profits and the customization cost, firms would clearly benefit from a cooperative and simultaneous increase of t. Indeed, the non-cooperative and the cooperative solution are the two corner solutions, $t_{\min}$ in the former case, $t_{\max}$ in the latter.

3.1.3 The entry stage

The equilibrium number of firms is determined by the technological parameter $t_{\min}$. The zero profit condition entails[7]:

$$n^* = \sqrt{\frac{1}{2} \frac{t_{\min}}{F}}$$

The equilibrium number of firms is increasing in $t_{\min}$ and (obviously) decreasing in F. At equilibrium customers of firm i face the following price schedule:

$$p_i^* \left(x \right) = t_{\min} \left(\frac{\sqrt{2F}}{\sqrt{t_{\min}}} - x \right)$$

[6] The cost paradox has been examined in the literature under different types of competition. For an interesting analysis of the cooperative attitude aimed at limiting price competition, see Kline (2000) where the effects of a Research Joint Ventures are considered.

[7] This result is consistent with that obtained by Bhaskar and To (2000).

which is increasing in $t_{\min}$ for all x served by i at equilibrium. Notice finally that the lower the minimum customization cost, the lower the number of firms and the lower the price paid for the customized product by each customer.

Therefore, an interesting feature which emerges in this set-up is that a concentrated market structure is consistent with low prices: both may be a consequence of a technological competition which translates into lower prices and reduces profits. In this sense, the model is consistent with a widely observed feature of digital markets, where products are customizable at very low costs, a few number of basic varieties are produced (the number of firms is low), each of them offered in many different versions (the market share of each firm is wide) at low prices. On the contrary, in markets where the customization technology is more costly we should expect that a great number of varieties be actually offered, each of them in a few versions, at high prices.

The result that the availability of efficient customization technologies and the technological competition lead to a more concentrated market structure, with a reduction of the number of basic varieties sold at low prices in many different versions, has been derived here under the simplified assumption that efficiency in versioning is indeed costless. Under this assumption the technological competition has a corner solution. In the next section we verify the robustness of this result by reformulating the game in a situation in which the adoption of low cost customization technologies imposes significant costs to the firms.

3.2 The case with endogenous set-up costs

Let us assume now that the choice of the customization technology is costly for the firm. The idea we want to capture is that the possibility of customizing the basic product at low cost requires higher investments, which can be assimilated to higher fixed costs expenditure that reduce marginal customization costs (Schwartz, 1989). In order to be able to offer different versions of the basic product at low cost, firms must afford heavier sut-up costs. With this modification, the analysis of customization gets significantly close to that of flexibility in production. As Norman (2003) argues: 'the adoption of flexible manufacturing imposes penalties with respect to the additional set-up costs that are necessary to establish such flexible systems' (p.420). Flexibility is in this case defined as the ability of a production technology to transfer the input factors from the fixed to the variable category (Stigler, 1939 and Roller and Tombak, 1990).

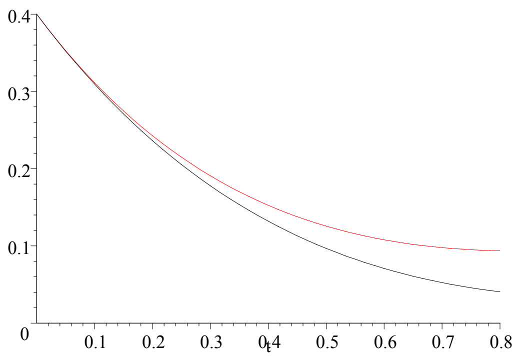

Figure 2: The shape of the set-up cost function

Therefore, in this section we modify the above framework by assuming that the set-up costs faced by any firm i depend on the chosen level of the customization cost. In other words the set-up costs are no more exogenous, but determined by the optimal choice of the customization parameter. A useful specification of the set-up cost function is the following:

$$S_i(F, b, t_i) = F - te^{-bt_i} \tag{2}$$

defined for $t_i \in \left[t_{\min}, \frac{1}{b}\right]$, and $F > \dfrac{e^{-1}}{b}$. This function is decreasing in t_i in the given interval, so that set-up cost savings occur as t_i grows. The upper bound on t_i is set for analytical convenience, but indeed it will turn out to be not binding. It is interesting to notice the role of the parameter b: as it increases, the set-up cost function becomes flatter, so that higher values of b imply a lower sensitivity of set-up costs with respect to changes in the customization technology. Figure 2 shows the different shape taken by the S_i function for different values of b.

The solution of the price stage of the game is clearly not affected by the endogeneization of set-up costs, which rather affects the technological stage.

3.2.1 The technological game revisited

Given the above formulation of the set-up costs, the profits of firm i can be rewritten as

$$\pi_i\left(t_i, t_{i-1}, b, n\right) = 2\int_0^{\frac{t_{i-1}}{n\left(t_i + t_{i-1}\right)}} \left(t_{i-1}\left(\frac{1}{n} - x\right) - t_i x\right) dx - F + t_i e^{-bt_i} \tag{3}$$

The first order conditions for firm i evaluated under symmetry entail the following solution:

$$t_i^* = -\frac{\Phi\left(\frac{1}{4n^2}e\right) - 1}{b} \tag{4}$$

where $\Phi(z)$ obeys $\Phi(z)\, e^{\Phi(z)} = z$ and is the so called LambertW function.[8]

As examples of this solution, one may check that for $b = 1$ and $n = 2$ the optimal value is $t_i \simeq 0.85329$; for $b = 0.8$ and $n = 2$, $t_i \simeq 1.0666$. It is possible to verify that $t_i < \frac{1}{b}$ for all values of b and n, so that the upper bound imposed to t_i is not binding. Moreover, t_i is clearly decreasing in b: for a given number of firms, as b increases, making the set-up cost function flatter, firms switch to more efficient customization technologies. This result is indeed intuitive: the lower is the marginal increase in set-up costs required by a marginal decrease in t_i, the higher is the incentive of firms to adopt the technologies allowing a cheaper customization.

3.2.2 The entry stage

By substituting (4) into (3), we obtain the maximum profit at the second stage of the game as a function of b and n:

$$\begin{aligned}\pi_i^*(b, n) &= -\frac{1}{2}\frac{\Phi\left(\frac{1}{4n^2}e\right) - 1}{bn^2} - F + \\ &\quad -\frac{\Phi\left(\frac{1}{4n^2}e\right) - 1}{b}\exp\left(\Phi\left(\frac{1}{4n^2}e\right) - 1\right)\end{aligned}$$

In order to analyse the third stage of the game which determines the equilibrium number of firms, it is useful to rewrite the zero profit condition in the following way:

$$h(b, n) = F$$

[8] The SOC for a maximum are satisfied at these value of t_i.

where

$$h(b,n) = -\frac{1}{2}\frac{\Phi\left(\frac{1}{4n^2}e\right)-1}{bn^2} + \\ -\frac{\Phi\left(\frac{1}{4n^2}e\right)-1}{b}\exp\left(\Phi\left(\frac{1}{4n^2}e\right)-1\right)$$

The analytical solution of the above zero profit condition is rather cumbersome. It is possible to check, however, that this solution exists for economically meaningful values of n and to analyse its qualitative properties.

Notice first that for $n = 1$, $h(b,n) = \frac{0.601\,09}{b}$; moreover, $\lim_{n\to\infty} h(b,n) = \frac{1}{b}e^{-1}$ and $\frac{\partial}{\partial n}h(b,n) < 0$ for $n \geq 1$. Therefore, for all values of $F \in \left(\frac{0.601\,09}{b}, \frac{1}{b}e^{-1}\right)$, there exists a unique solution for n, with $1 < n < \infty$.

The equilibrium number of firms is decreasing in b. Indeed, implicit differentiation of the zero profit condition gives

$$\frac{dn}{db} = -\frac{\frac{\partial h}{\partial b}}{\frac{\partial h}{\partial n}}$$

which is negative, since $\frac{\partial h}{\partial b} < 0$ for all $n > 1$.

The economic implications of the above analytical findings are easily stated. As discussed above, parameter b may be seen as an inverse index of the cost incurred by firms when they try to gain more efficiency in their customization technology. As b increases, firms are induced to choose optimally a more efficient customization technology - provided it is actually available ($t_i^* > t_{\min}$) - notwithstanding the fact that this makes price competition tougher. Profits are reduced and a lower number of firms enters the market. This reduction in the number of firms induces a further reduction in prices, given the properties of price competition in this discriminatory price setting.

This confirms the sharp result obtained in the fixed cost case. There, the number of basic varieties and the price of the various versions of these basic varieties was related to the availability of cheap customization technologies (the level of $t_{\min}$). Here, they depend on the marginal cost of gains in customization efficiency. However, the analysis of the endogenous set-up costs case may well explain some properties of the markets of the so-called information goods. These goods are easily customizable, in the sense that firms may cheaply move towards customized production. The increasing customization of these products has been accompanied by a progressive reduction of the number of basic varieties offered and a decrease in prices (as an example, one may quote many software applications).

3.2.3 An explanation of mass-customization

The growing adoption of the competitive strategy of personalization has led to the phenomenon known as mass customization. In Vulkan's (2003) words:

> 'Mass customization occurs where firms can offer at the same constant marginal costs without having to incur additional fixed costs on every differentiated brand they offer' (p.48)

Indeed, mass customization is a concept born in the late 1980's and is now considered a new frontier in business competition.[9] In the last years, the ability of firms to offer high volumes of designed products at reasonably low costs (da Silveira et al, 2001) has induced a change in production patterns from the so-called mass standardization to mass customization.

The results obtained in the current work may explain mass customization as the outcome of optimal technological and pricing strategies of firms operating in an imperfectly competitive setting. The technological feasibility of tailoring goods is a necessary, but not sufficient condition for widespread customization. In a monopoly setting, highly personalized products always lead to higher prices and profits (due to the additional surplus extraction allowed by price discrimination); on the contrary, in a imperfectly competitive environment this positive effect on profits may be outweighted when customization increases the intensity of price competition. The equilibrium outcome is a reduction of prices. The paper suggests that it's competition in customization costs that leads firms to offer tailored goods at a low cost. This is a relatively recent phenomenon. While customized products have always been attractive to consumers, their high prices made them mostly unaffordable in the past. Customization and low prices were at that time considered as conflicting goals. The simultaneous existence of advanced technologies for customization and competition in customization are now letting firms to offer custom design and individualized services on a large scale and at low prices, allowing more personalization at the lower mass production prices: integrating efficiency with customization results in mass customization. The two features of customization and mass production are combined together.

[9] One might quote Anderson and Narus (1995): 'Virtually all managers are keenly aware that the key to winning in market after market today is excelling in tailoring one's offerings to the specific needs of each customer while still maintaining low costs and prices.'

3.2.4 Concluding remarks

In this paper we have discussed the optimal pricing strategies of firms offering customized products in an imperfect competitive spatial environment and the optimal structure of these markets. It must be stressed that the paper does not discuss neither the conditions under which firms can profitably increase their ability to customize, nor the issue of the optimal degree of customization. Rather, the model embodies the idea that each consumer always achieves the desidered good; though bearing a cost, firms can produce all desired versions of a basic commodity, so that that we can refer to the basic structure of the model as one of 'perfect customization'. Therefore, the emphasis of the paper has been given to the analysis of the conditions ensuring that perfect customization can be supported at low prices.

We can identify two main directions of our analysis: we have explored the effects of competition in the customization technology and examined the equilibrium market structure under the two alternative hyptheses of exogenous and endogenous set-up costs. Indeed, two types of cost have been modeled: the cost of producing a basic variety of a good and the cost of customizing it in order to obtain different versions, with the plausible assumption that production costs are fixed, while customization costs are variable, depending on the extent of customization and the quantity produced.[10] The exogenous set-up cost version of the model is one in which the two costs are independent; in the second the size of fixed costs is inversely related to the unit customization cost.

The first result of our analysis is that, under the assumption of a costless technology choice, competition in customization induces firms handling multiple versions to adopt the most efficient personalization technology. In particular, it has been demonstrated that when firms may choose non cooperatively the customization parameter, the existence of a perfect spillover - due to the correspondence between the price set at equilibrium and the technological parameter chosen by the closest rivals - leads to an equilibrium outcome of the Prisoner's Dilemma type: prices and profits are reduced to the minimum levels consistent with technology and the nature of discriminatory price competition. The optimal number of varieties and market concentration is determined by two technological factors: the size of the exogenous set-up costs (as usual) and the cost parameter of the most efficient customization technology. In the long run equilibrium, the maximum effi-

[10] In the information economy, production costs are often considered to be independent of scale. As stated in Shapiro and Varian (1999) and in Choi et al. (1997), information or digital products involve high fixed cost but low, often zero, marginal costs.

ciency in customization turns out to be associated to a mostly concentrated market structure, which is equivalent to the existence of a few basic varieties offered, each of them in many versions.

These extreme results are quantitatively smoothed, but qualitatively confirmed, in an endogenous set-up cost framework. If set-up costs increase when customization costs are lowered, market concentration turns out to depend on the marginal loss, in terms of set-up costs, of an increase of efficiency in customization. When the set-up costs increase slowly following a reduction in customization costs, more efficiency in customization will be chosen at equilibrium and this will lead to lower prices. In contrast with the existing literature based on Hotelling models, a more concentrated market is associated to lower prices for customized products. In other words customization at low prices becomes feasible as the investment in implementing personalization systems is relatively low. In contrast, as long as the accessible technology allows to reduce the customization costs by enhancing significantly the set-up costs, prices for customized goods will be higher and a more fragmented market will arise at equilibrium. Even in this richer framework, the tendency towards customization at low prices stems from two basic elements: the technological possibility of customizing at low cost and the implementation of these efficient technologies due to a sort of technological competition between firms, which is translated into a price competition.

Finally the paper can offer insights on the role of customization technology competition in explaining the mass-customization phenomenon. To the best of our knowledge, this issue, widely discussed in the management literature, has been mostly neglected in the theoretical economic analysis. In this sense the paper can represent a step towards the development of a research agenda focused to an economic analysis of customization strategies.