

Market equilibrium with search and computational costs

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Abstract: Although it is an empirical regularity that in the trade of homogeneous goods there is persistent price dispersion and buyers search for low-priced items, theoretically one finds that in market equilibrium, when buyers have information limitations, are homogenous and optimisers (the neo-classical framework), these regularities do not occur. In the present work we introduce economic agents as having computational limitations in these neo-classical optimisation model, which is new in the literature. As a result of this alteration to the model, in market equilibrium we observe that there is an optimal level of computational cost and that there are both price dispersion and buyers search for low-priced items.

JEL codes: D43, D83

Keywords: Computational limitations, Optimisation, Search, Market equilibrium

1. Introduction

Since Simon's (1955) and Stigler's (1961) studies, economic literature has made an effort to rationalise the empirical evidence that there is persistent price dispersion in the trade of homogeneous goods and that buyers search for low-priced items. This empirical evidence has been hypothetically related to the fact that economic agents do have imperfect knowledge of prices (Lippman and McCall, 1976) and limitations on computational power (Simon, 1965).

However, within an optimisation theoretical framework, known in the literature as the neo-classical paradigm, where buyers are homogeneous and intend to acquire a product whose price is not perfectly known, a market equilibrium results where there is neither price

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dispersion nor search. This result is valid when buyers perform either a sequential sample strategy (Diamond, 1971) or a fixed sample size strategy (Vieira, 2004).

This undesirable theoretical result and the fact that optimal strategies are computationally difficult to obtain raise questions as to the relevance of using optimisation models in the rationalisation of human behaviour. In particular, Hey (1981) states that the use of optimisation models is inadequate because economic agents are unable to compute the optimal rules.

But if we want economic science to overcome the metaphysical stage of merely searching for a short-range cause-effect prevision, and considering that it is a positive science that seeks to establish the invariable regularities of economic agents' behaviour, the optimisation principle should not be abandoned. These invariable regularities are important "*because a model has to be able to isolate those aspects of behaviour that remain invariant to policy shifts from those that do not if it is to be of any use in assessing the consequences of the shift*" (Lucas, 1987: 11-12).

As to this motivation being known from agent-based computational economics literature (Tesfatsion, 2002) and evolutionary economics literature (Holland, 1995), that an 'aggregated optimum' may result from the iteration of agents with information and computational limitations.

In this work we introduce the existence of computational limitation on the part of buyers into the theoretical neo-classical optimisation framework. The methodology applied in modelling these limitations is based on the assumption that each buyer must purchase computational power so as to calculate an optimal strategy (that would be computed if there were no computational limitations). Since higher accuracy implies the use of additional computational power, buyers will not compute exactly that optimal strategy but one with an error component whose magnitude is increasing with the marginal cost of computation. This implies the sellers' will not know perfectly which is the strategy of a particular buyer, being assumed as a random variable with known mean and variance.

We conclude that the introduction of computational limitations on buyers is a sufficient condition in the appearance of price dispersion and search in market equilibrium. This result, obtained without abandoning the theoretical neo-classical optimisation framework, is important because it creates a bridge between this mainstream economic paradigm and more

qualitative heterodox views of the economic system, of which the works of Hey or Tesfatsion are elucidative examples.

2. Assumption of the theory

The neo-classical theoretical framework is based on the assumption that A1) economic agents, buyers and sellers, pursue the maximization of an objective function that is subject to restrictions; the existence of imperfect knowledge is modelled by assuming that A2) at the price p a seller fixes is a random variable with a known distribution function $F(p)$; and to model the buyers' information acquisition procedure, it is assumed that, A3) so as to know the price a specific seller fixes, a buyer must pay the search cost c . These assumptions are standard in the search literature (e.g., Diamond, 1971), and as a result, if there is market price dispersion, buyers compute a reservation price that is lower than the highest fixed price in the market. As buyers search prices until they locate a seller that has a fixed price lower than or equal to the reservation price, sellers with the highest fixed price have to lower their price, such that all sellers are forced to fix the same price. Thus price dispersion no longer exists, and it is unprofitable for buyers to search for discount prices; if buyers do not search, all sellers act as if they were monopolist. This is known as the Diamond (1971) paradox.

We introduce the existence of computational limitations on the part of buyers by assuming that A4) so as to compute the reservation price, buyers use the computational power n that costs cc per unit used; and A5) the reservation price is computed with a stochastic error component e which variance is decreasing with the computational power used.

Since there is an optimal strategy, A6) the buyers' expected expenditure increases with the error committed, where a linear functional form is assumed.

In comparison to buyers, sellers have more resources and are in the market for a longer period of time, which allows us to assume that A7) sellers are able to compute the buyers' optimal reservation price (the value that would be computed if there were no computing limitations) and the error magnitude (variance) that they incur.

Since sellers compute the buyers' optimal reservation price and the error magnitude that they incur, they assume that A8) on aggregate, the buyers' strategy is a random variable with a known mean (the optimal reservation price) and variance (the error magnitude). A9) We assume a uniform distribution around the optimal reservation price P^* , i.e. $e \sim U[-k, +k]$, that

$k = k_0 / \sqrt{n}$ and that $k \leq P^*$. The k functional form specifies that the increase in computational power is equivalent to an increase in the dimension of the sample used in the computation of the average that is a property of the Monte-Carlo algorithm. Although from this equivalence consequents that the use of the normal or lognormal distribution would be more realistic, it would introduce algebraic difficulties without a qualitative effect on the results.

As is standard, all these assumptions are common knowledge.

The assumption that buyers have limited computational power (bounded rationality) does not put in question that the optimal strategy is the computation of a reservation price because during the search process buyers do not adjust expectations (Rothschild, 1974).

3. Main results

Property 1. The buyers' strategy is a reservation price that is located in the neighbourhood of the reservation price that would be optimal if there were no computational limitations. The average neighbourhood area is increasing with the cost of computation.

Proof: It is known from the literature (McCall, 1965) that the optimal buyers' strategy, when there are no computation costs, implies computing the reservation price P^* that minimises the expected expenditure:

$$V = P^* = \int_0^{P^*} x \cdot f(x) \cdot dx + \int_{P^*}^{\infty} P^* \cdot f(x) \cdot dx + c \quad (1)$$

Assuming there are computational costs, the expected expenditure becomes:

$$V(n) = \int_{-k}^k \left(\int_0^{P^*+e} x \cdot f(x) \cdot dx + \int_{P^*+e}^{\infty} (P^*+e) \cdot f(x) \cdot dx + c \right) \cdot u(e) \cdot de + n \cdot cc \quad (2)$$

That may be simplified as

$$V(n) = P^* + g(n) + n \cdot cc, \text{ being } g(n) > 0, g(n)' < 0 \text{ and } g(\infty) = 0. \quad (3)$$

Lets assume an approximation to $g(n)$ linear in k :

$$V(n) = P^* + A \cdot \frac{1}{\sqrt{n}} + n \cdot cc \quad (4)$$

Buyers minimise expression (4) by using an optimal computational intensity. The optimal intensity of computation will be (first order condition):

$$\frac{dE[V(n)]}{dn} = -\frac{1}{2}A \cdot n^{-\frac{3}{2}} + cc = 0 \Leftrightarrow \frac{1}{2} \cdot A \cdot n^{-\frac{3}{2}} = cc \Leftrightarrow n^* = \left(2 \cdot \frac{1}{A} \cdot cc\right)^{\frac{2}{3}} \quad (5)$$

This is a minimum because (second order condition) $\frac{d^2E[V(n)]}{dn^2} = -\frac{3}{4} \cdot A \cdot n^{-\frac{5}{2}} < 0$.

Then, it becomes optimal that $k = (2 \cdot A^2 \cdot cc)^{1/3} > 0$, increasing with cc .

It is conceptually acceptable to model the buyers' difficulties in computing an optimisation problem with another optimisation problem if it is taken to mean a second step approximation: the errors of computation are not biased and, on average, the computation intensity will be decreasing and the error variance will be increasing with the computation costs increasing. In this way, it is satisfactory to conclude that from ex-ante identical buyers, ex-post different ones will result, where this ex-post heterogeneity is increasing with the increasing in computational limitations.

The existence of heterogeneity in the buyers' reservation price is considered in the literature associated with ex-ante buyers' heterogeneity, (e.g., Axell, 1977). In this work the heterogeneity results endogenously from the existence of computational limitations. Properties 2 and 3 are direct implications of the existence of ex-post heterogeneities in the buyers' reservation prices. These two properties are known in the literature (Axell, 1977).

Property 2. No seller will fix prices outside the domain $[P^* - k; P^* + k]$ where the buyers' reservation prices are located.

Proof. First, a buyer with reservation price P^+ will search the goods until he finds a price lower than or equal to that reservation price. This being so, the probability that the buyer acquires the goods with a price lower than or equal to p is:

$$W(p | P^+) = \text{Prob}(\text{acq. price} \leq p | P^+) = \begin{cases} F(p) / F(P^+), & p \leq P^+ \\ 1 & , p > P^+ \end{cases} \quad (6)$$

Expanding expression (4) to all possible reservation prices, we obtain, in expected terms, the market distribution function of the price at which buyers acquire the good (remembering that $u(P^+)$ quantifies the proportion of buyers whose reservation price is P^+):

$$\begin{aligned}
W(p) &= \int_0^{\infty} W(p | P^+) \cdot u(P^+) \cdot dP^+ = \int_0^p u(P^+) \cdot dP^+ + \int_p^{\infty} \frac{F(p)}{F(P^+)} \cdot u(P^+) \cdot dP^+ \\
&= U(p) + F(p) \cdot \int_p^{\infty} \frac{1}{F(P^+)} \cdot u(P^+) \cdot dP^+
\end{aligned} \tag{7}$$

Assuming, without loss, that the number of buyers and sellers are normalised to one, the expected profit function of a seller is the derivative of expression (7) divided by the quantity of sellers that fix price $p, f(p)$, and multiplied by p :

$$E[\mathbf{p}(p)] = p \cdot E[q(p)] = p \cdot \frac{w(p)}{f(p)} = p \cdot \int_p^{\infty} \frac{u(P^+)}{F(P^+)} \cdot dP^+ \tag{8}$$

Simplifying by substituting $u(P^+)$ in expression (8), we obtain:

$$E[\mathbf{p}(p)] = p \cdot \frac{1}{2 \cdot e^*} \cdot \begin{cases} \int_{P^* - e^*}^{\infty} \frac{1}{F(P^+)} \cdot dP^+, & p < P^* - k \\ \int_p^{\infty} \frac{1}{F(P^+)} \cdot dP^+, & P^* - k \leq p \leq P^* + k \\ 0, & p > P^* + k \end{cases} \tag{9}$$

Thus we find that the expected profit function (9) is negative if the price is negative, is increasing with the price until $P^* - k$, is positive for all prices in the interval $[P^* - k; P^* + k]$ and zero elsewhere. This being so, it is not optimal that a firm fixes a price outside the interval where buyers' reservation prices are probably located: $[P^* - k; P^* + k]$.

Property 3. The market equilibrium price distribution function has the form:

$$F(p) = p^2 \cdot \frac{1}{(P^* + k)^2} \text{ with } p \in [P^* - k; P^* + k] \text{ and } f(p) \text{ zero elsewhere} \tag{10}$$

This means that there is a mass point at price $p = P^* - k$ that is related with the assumption A9. If the assumed prices distribution function were smooth and included prices near zero, there would be no mass point, e.g. a log normal distribution.

Proof. In order to have a market Nash equilibrium state, the expected profit function must be horizontal for all fixed prices (where property 2 is in the domain $[P^* - k; P^* + k]$). Thus, from expression (9) and property 2, we find that:

$$p \cdot \frac{1}{2 \cdot k} \cdot \int_p^{\infty} \frac{1}{F(P^+)} \cdot dP^+ = Const \quad (11)$$

Deriving both members of this expression, we obtain:

$$F(p) = p^2 \cdot \frac{1}{2 \cdot k \cdot Const} \Rightarrow F(p) = p^2 \cdot \frac{1}{(P^* + k)^2} \quad (12)$$

Property 4. The reservation price decreases with the increase in computation costs. This indicates an increase in competition between sellers.

Proof. As it is assumed that sellers do not have computational limitations, they compute the “would be” optimal reservation price by substituting expression (10) in (1).

$$P^* = \frac{c + \frac{(P^* - k)^2}{(P^* + k)^2} (P^* - k) + \int_{P^* - e}^{P^*} 2p^2 \frac{1}{(P^* + k)^2} dp}{\frac{(P^*)^2}{(P^* + k)^2}} \quad (13)$$

Simplifying this expression we obtain the following implicit function:

$$0 = P^{*2} \cdot k - P^* \cdot k^2 + \frac{1}{3} k^3 - \frac{c}{(P^* + k)^2} \quad (14)$$

The properties of the reservation price result from this implicit function. From (8) and (3), it is

straightforward to see that $\frac{dP^*}{dcc} < 0$ and $\frac{dP^*}{dc} > 0$ (see fig. 1 where $A = 1$).

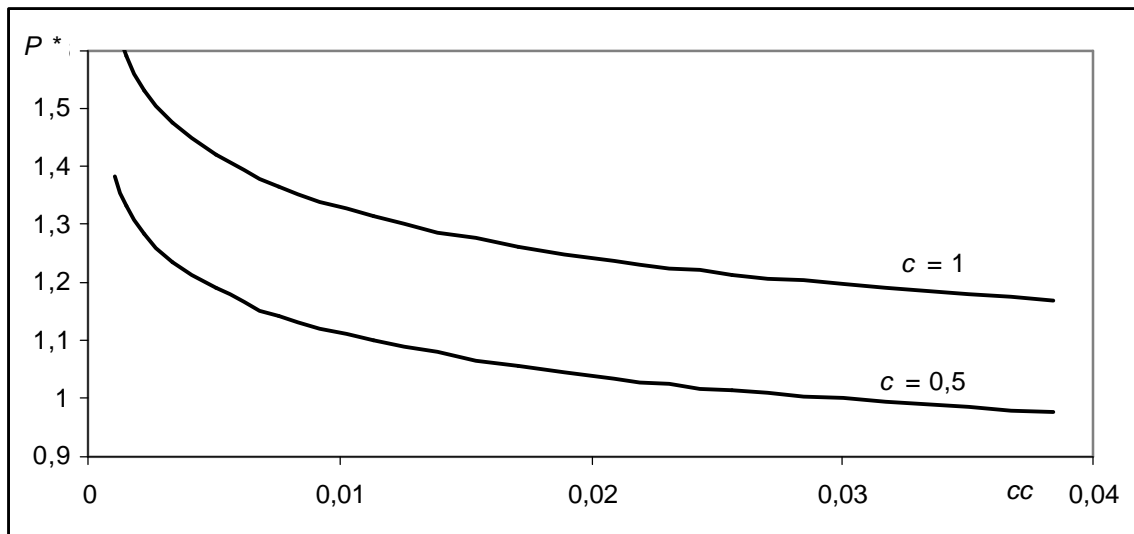


Fig. 1 – Evolution of the reservation price with search and computational costs

The economic meaning of the existence of a positive link between the buyers' computational limitations and the sellers' level of competition is puzzling. Comparing to bees, the fact that each individual does not realise that it dies when it sting an intruder implies that the intruders must improve their tactics of attack.

Corollary. When computation costs tend to zero, with positive search costs, the solution presented by the model with computational limitations comes close to Diamond's (1971) result (the reservation price tends to the monopoly price and price dispersion tends to zero).

Proof. From expression (5) we get that when computation costs tend to zero, the computation intensity increases and the error tends to zero. Then, from properties 2 and 3, there is no price dispersion. From expressions (8) and (5), we find that the equilibrium price is the monopoly

price as in $\lim_{cc \rightarrow 0} \left[P^* \cdot k - P^* \cdot k^2 + \frac{1}{3} k^3 - \frac{c}{(P^* + k)^2} = 0 \right] \Rightarrow P^* = \infty .$

This limit situation is important to assure that the model we have built is a generalisation of models existing in the literature, namely Diamond's (1971) model.

Property 5. On aggregated consumers' side, there is an optimal computational cost level.

Proof. From property 4, the reservation price P^* is decreasing with the computational cost. From expression (4) the expected expenditure related to the existence of computational limitations $A/\sqrt{n} + n \cdot cc$ is increasing with computational cost. Being so, the sum of the two components is U shaped, having a minimum point (see fig. 2 where $A = 1$).

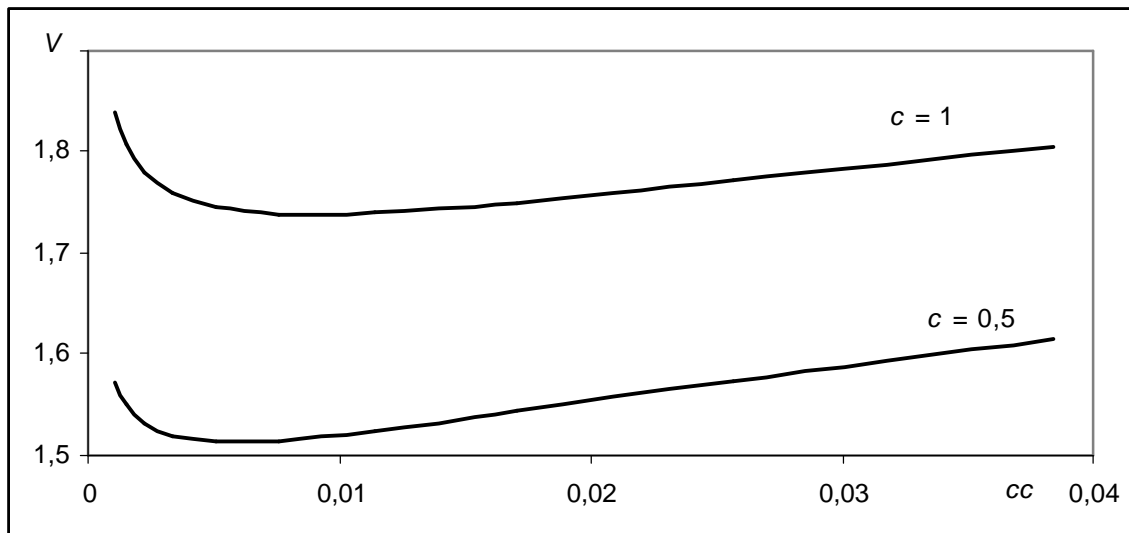


Fig. 2 – Evolution of the expected expenditure with computational cost

This property is perplexing. Although, the existence of computation limitations aggravates the individual buyer's *ceteris paribus* situation, on aggregate the inexistence of computational cost is neither good. Completing the comparison to bees, if each individual were perfectly unaware of the negative effect that to sting has on its life, an over optimal percentage of bees would dye attacking potential intruders, putting the colony existence at risk.

4. Conclusion

With the purpose of rationalising the existence of persistent price dispersion in the trade of homogeneous goods, in this work we introduce computational limitations in the neo-classical theoretical framework that assume that economic agents are optimisers. In a theoretical situation where buyers have imperfect knowledge about prices, we introduce computational limitations on the buyers' side by assuming that they need to acquire computational power to calculate their strategies. We conclude that when buyers have information and computational limitations, a market equilibrium results where there is price dispersion, buyers search for low-priced items and sellers compete between them.

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Appendix A

Algebraic steps from expression (7) to (8)

As $P^* - k \geq 0$, there is a mass point at price $p = P^* - k$

$$P^* = \frac{\frac{c}{(P^*+k)^2} + (P^*-k)^3 + \int_{P^*-k}^{P^*} 2 \cdot p^2 \cdot dp}{P^{*2}} \Leftrightarrow$$

$$P^{*3} = \frac{c}{(P^{*}+k)^2} + (P^{*}-k)^3 + \int_{P^{*}-k}^{P^{*}} 2 \cdot p^2 \cdot dp \Leftrightarrow$$

$$P^{*3} = \frac{c}{(P^{*}+k)^2} + (P^{*}-k)^3 + \frac{2}{3} \cdot (P^{*})^3 - \frac{2}{3} \cdot (P^{*}-k)^3 \Leftrightarrow$$

$$0 = \frac{c}{(P^{*}+k)^2} - \frac{1}{3} P^{*3} + \frac{1}{3} \cdot (P^{*3} - 3 \cdot P^{*2} \cdot k + 3 \cdot P^{*} \cdot k^2 - k^3) \Leftrightarrow$$

$$P^{*2} \cdot k - P^{*} \cdot k^2 + \frac{1}{3} \cdot k^3 - \frac{c}{(P^{*}+k)^2} = 0$$

Algebraic steps from expression (13) to (14)

$$V(n) = \int_{-k}^k \left(\int_0^{P^{*}+e} x \cdot f(x) \cdot dx + \int_{P^{*}+e}^{\infty} (P^{*}+e) \cdot f(x) \cdot dx + c \right) \cdot u(e) \cdot de + n \cdot cc$$

$$V(n) = \int_{-k}^0 \left(\int_0^{P^{*}+e} x \cdot f(x) \cdot dx + \int_{P^{*}+e}^{\infty} (P^{*}+e) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de + \\ + \int_0^k \left(\int_0^{P^{*}+e} x \cdot f(x) \cdot dx + \int_{P^{*}+e}^{\infty} (P^{*}+e) \cdot f(x) \cdot dx + c \right) \cdot u(e) \cdot de + c + n \cdot cc$$

$$V(n) = \int_{-k}^0 \left(\int_0^{P^{*}} x \cdot f(x) \cdot dx - \int_{P^{*}+e}^{P^{*}} x \cdot f(x) \cdot dx + \int_{P^{*}}^{\infty} (P^{*}+e) \cdot f(x) \cdot dx + \int_{P^{*}+e}^{P^{*}} (P^{*}+e) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de \\ + \int_0^k \left(\int_0^{P^{*}} x \cdot f(x) \cdot dx + \int_{P^{*}}^{P^{*}+e} x \cdot f(x) \cdot dx + \int_{P^{*}}^{\infty} (P^{*}+e) \cdot f(x) \cdot dx - \int_{P^{*}}^{P^{*}+e} (P^{*}+e) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de + c + n \cdot cc$$

$$V(n) = \int_{-k}^k \left(\int_0^{P^{*}} x \cdot f(x) \cdot dx + \int_{P^{*}}^{\infty} P^{*} \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de + c \\ + \int_{-k}^0 \left(- \int_{P^{*}+e}^{P^{*}} x \cdot f(x) \cdot dx + \int_{P^{*}}^{\infty} e \cdot f(x) \cdot dx + \int_{P^{*}+e}^{P^{*}} (P^{*}+e) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de \\ + \int_0^k \left(\int_{P^{*}}^{P^{*}+e} x \cdot f(x) \cdot dx + \int_{P^{*}}^{\infty} e \cdot f(x) \cdot dx - \int_{P^{*}}^{P^{*}+e} (P^{*}+e) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de + n \cdot cc$$

$$V(n) = P^{*} + \int_{-k}^0 \left(\int_{P^{*}+e}^{P^{*}} (P^{*}+e-x) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de + \int_0^k \left(\int_{P^{*}}^{P^{*}+e} (x-P^{*}-e) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de + n \cdot cc$$

$$V(n) = P^{*} + g(n) + n \cdot cc$$

$$g(n) = \int_{-k}^0 \left(\int_{P^{*}+e}^{P^{*}} (P^{*}+e-x) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de + \int_0^k \left(\int_{P^{*}}^{P^{*}+e} (x-P^{*}-e) \cdot f(x) \cdot dx \right) \cdot u(e) \cdot de$$

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