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EQUILIBRIUM PRICE DISTRIBUTION WITH DIRECTED TECHNICAL CHANGE

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Equilibrium Price Distribution with Directed Technical Change

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This paper studies a non-degenerate price distribution for the homogeneous good within a model of endogenous directed technical change. A probability density function is analytically derived and shown to be related to the technology and innovation parameters of the model.

Keywords: price distribution, directed technical change, scale effects, labour endowment

JEL Classification: D41, D43, O41

1 Introduction

Following a long tradition in economic theory, several models have been developed to identify the determinants of equilibrium price dispersion in homogeneous-good markets. By now, various combinations of assumptions are known to result in an equilibrium with a non-degenerate distribution of prices.

Work in this area includes models that assume ex ante heterogeneity in firms' production costs and/or consumers' search costs (e.g., Carlson and McAfee, 1983), or information on prices is imperfect with otherwise identical agents (Preston and McAfee, 1995). More recently, Kultti and Virrankoski (2003, 2004) explore a model with ex ante symmetric agents and publicly and costlessly known prices, which features a price distribution in equilibrium by considering sellers' capacity constraint and the possibility of more than one seller in a location.

This paper relates closely to the models that feature ex ante heterogeneous agents, while unveiling a theoretical mechanism that leads to a non-degenerate price distribution within a model of endogenous directed technical change. This framework makes possible

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the study of the relation between price distribution and innovation-related factors, a topic still untreated by the literature.

For concreteness, we show that the production and innovative structure adopted in Acemoglu and Zilibotti (2001) allows for the analytical derivation of the probability density function (pdf) of prices along the balanced-growth path (BGP). This result relies on ex ante heterogeneity among producers, but no direct assumption is made with respect to the pdf of firms' production costs. Instead, the posited production function implies a uniform distribution of firms' competitive advantage in adopting high- versus low-skilled labour-complementary technology. Moreover, consumers are homogeneous, and do not support search costs, since they only care about the aggregate "consumer price index", i.e., the price of a continuously divisible basket of homogeneous goods (the composite final good).[1]

By considering an R&D technology with a varying degree of scale effects benefiting innovative activity, we show that the BGP price mean and dispersion depend on the scale effects and on the relative labour endowment measured in efficiency units. In accord with casual empiricism, prices are distributed with positive probability over a closed interval and, under broad conditions, the mode of prices is smaller than their mean.

2 Model

The model used herein is the one by Acemoglu and Zilibotti (2001), augmented with a varying degree of scale effects in R&D technology.

The economy is populated by fixed infinitely-lived households who inelastically supply one of two types of labour: low-skilled, L, and high-skilled labour, H. Households choose a consumption plan to maximize $U = \int_0^\infty \left(\frac{C(t)^{1-\theta} - 1}{1-\theta} \right) e^{-\rho t} dt$, subject to a standard flow budget constraint and a No-Ponzi game condition; $C(t)$ is aggregate consumption at time t, $\rho > 0$ is the subjective discount rate, and $\theta > 0$ is the coefficient of relative risk aversion. The plan satisfies the Euler equation $\frac{\dot{C}(t)}{C(t)} = \frac{1}{\theta} \left(r(t) - \rho \right)$.

The composite final good, Y, is produced by a continuum of competitive firms, indexed by $n \in [0, 1]$, and can be used in consumption, production of intermediate goods, X, and R&D, R. At t, $Y(t) = \int_o^1 P(n,t) Y(n,t) dn = exp \left[\int_o^1 lnY(n,t) dn \right]$, since the price of Y is normalised to one, $P_Y = exp \left[\int_0^1 lnP(n) dn \right] = 1$; P_Y can be interpreted as an aggregate "consumer price index".[2]

To produce n, two substitute technologies are available: the Low (High) technology uses a combination of L (H) and a continuum of L- $(H$-$)$specific intermediate goods indexed by $\omega \in [0, N_L(t)]$ $(\omega \in [0, N_H(t)])$. The production function of n is

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[1] These simplifying assumptions help to show clearly the role of the innovation-related factors in explaining the price distribution.

[2] The expressions for Y and P_Y are the generic symmetric Cobb-Douglas functions $Y = Y(1)^{\frac{1}{n}} \cdot Y(2)^{\frac{1}{n}} ... Y(n)^{\frac{1}{n}}$ and $P(1)^{\frac{1}{n}} \cdot P(2)^{\frac{1}{n}} ... P(n)^{\frac{1}{n}}$ for $n \to \infty$. Thus, Y and P_Y and constructed following a geometric-aggregation procedure.

$$Y(n,t)=\left[\int_0^{N_L(t)} x(n,\omega,t)^{1-\alpha}d\omega\right]\left[(1-n)\cdot L(n)\right]^{\alpha}+$$
$$+\left[\int_0^{N_H(t)} x(n,\omega,t)^{1-\alpha}d\omega\right]\left[n\cdot h\cdot H(n)\right]^{\alpha} \tag{1}$$

where $x(n,\omega,t)$ is the quantity of ω used to produce n at t; $N_L(t)$ and $N_H(t)$ represent, respectively, the number of Low and High intermediate goods; $1-\alpha$, $0<\alpha<1$, is the intermediate-goods input share; $L\,(n)$ and $H\,(n)$ are, respectively, L and H used by n. $h>1$ captures an absolute productivity advantage of H over L, while $1-n$ and n imply that L (H) is relatively more productive in producing lower (higher)-index final goods.

At t there is an equilibrium threshold final good $\bar{n}=\left[1+\left(\frac{hHN_H}{LN_L}\right)^{\frac{1}{2}}\right]^{-1}$, endogenously determined, where the switch from one technology to the other becomes advantageous. $\bar{n}$ implies that L- (H-)technology is used in final goods $0\le n<\bar{n}$ ($\bar{n}\le n\le 1$), and it can be related to the ratio of price indeces of final goods produced with L- and H-technologies:

$$\frac{P_H}{P_L}=\left(\frac{\bar{n}}{1-\bar{n}}\right)^{\alpha}, \text{ where } \begin{cases} P_L(t)^{\frac{1}{\alpha}}=P(n,t)^{\frac{1}{\alpha}}\cdot(1-n)=e^{-\alpha}\bar{n}^{-\alpha} \\ P_H(t)^{\frac{1}{\alpha}}=P(n,t)^{\frac{1}{\alpha}}\cdot n=e^{-\alpha}(1-\bar{n})^{-\alpha} \end{cases} \tag{2}$$

In (2), we first define the price indeces, P_L and P_H, by recognising that, in equilibrium, the marginal value product, $\frac{\partial}{\partial m(n)}\left(P(n)Y(n)\right)$ $(m=L,H)$, must be constant over n, implying that $P(n,t)^{\frac{1}{\alpha}}\cdot(1-n)$ and $P(n,t)^{\frac{1}{\alpha}}\cdot n$ must be constant over $n\in[0,\bar{n}]$ and $n\in[\bar{n},1]$, respectively. Then, considering that at $\bar{n}$ the L- and the H- technology firms must break even, we relate P_L and P_H with $\bar{n}$.

The intermediate-good sector consists of monopolistically competitive firms index by $\omega\in[0,N_L(t)]\cup[0,N_H(t)]$ facing isoelastic demand curves. One unit of ω is produced with one unit of Y and the profit-maximisation price yields the mark-up $p(\omega,t)\equiv p=\frac{1}{1-\alpha}$, constant over t and across industries. Since each firm n maximises profits taking as given prices and wages, and bearing in mind (2) and the mark-up p, the demand function faced by the L- and H-technology intermediate good firms are, respectively, $X_L(\omega)=\int_0^{\bar{n}}x(n,\omega)dn=(1-\alpha)^{\frac{2}{\alpha}}LP_L^{\frac{1}{\alpha}}$ and $X_H(\omega)=\int_{\bar{n}}^1 x(n,\omega)dn=(1-\alpha)^{\frac{2}{\alpha}}hHP_H^{\frac{1}{\alpha}}$. Then, it can be shown that the optimal profits accrued by monopolists are

$$\pi_L(\omega)=\overline{\pi}\cdot L\cdot P_L^{\frac{1}{\alpha}} \text{ and } \pi_H(\omega)=\overline{\pi}\cdot h\cdot H\cdot P_H^{\frac{1}{\alpha}} \tag{3}$$

where $\overline{\pi}=\left(\frac{\alpha}{1-\alpha}\right)\cdot(1-\alpha)^{\frac{2}{\alpha}}$.

Technical change takes the form of increases over t in N_L and N_H, being the producer of ω subject to a sunk cost η in units of Y to design ω, protected by a patent. The law of motion of N_m is

$$\dot{N}_L(t)=\frac{1}{\eta L^{\epsilon}}\cdot R_L(t) \text{ and } \dot{N}_H(t)=\frac{1}{\eta\,(hH)^{\epsilon}}\cdot R_H(t) \tag{4}$$

where R_m denotes the flow of resources to improve N_m, such that $R_L + R_H = R$. Different from Acemoglu and Zilibotti (2001), we consider $\epsilon \geq 0$, which measures the degree of scale-effects removal. The latter captures the idea that the difficulty of introducing new qualities and replacing old ones is proportional to the market size measured by employed labour in efficiency units, e.g., due to coordination, organisational and transportation costs (Dinopoulos and Thompson, 1999); however, depending on the effectiveness of that costs, they may partial ($0 < \epsilon < 1$), totally ($\epsilon = 1$) or over ($\epsilon > 1$) counterbalance the benefits of scale to innovation, connected to the size of profits that accrue to the R&D successful firm.

3 Balanced-growth path

Along the interior BGP, $\pi_L(\omega)$ and $\pi_H(\omega)$ in (3) are constant; indeed, P_L and P_H depend on $\bar{n}$ - see (2) -, which, once in BGP, is constant, since N_L and N_H grow at the same rate. Thus, the present value of profits is $V_m = \pi_m \int_t^{\infty} e^{\left[-\int_t^s r(\nu)d\nu\right]} ds$, where $r(\nu)$ is the real interest rate at time ν.

Moreover, with free entry into R&D and positive R, V_m must equal the cost of invention - see (4). This implies that r is constant and given by $r = \frac{\pi_L}{\eta L^{\epsilon}} = \frac{\pi_H}{\eta (hH)^{\epsilon}}$, which then implies

$$\frac{\tilde{P_H}}{\tilde{P_L}} = \left(\frac{L}{hH}\right)^{\alpha(1-\epsilon)}, \text{ where } \begin{cases} \tilde{P_L} = e^{-\alpha}\tilde{\bar{n}}^{-\alpha} \\ \tilde{P_H} = e^{-\alpha}\left(1-\tilde{\bar{n}}\right)^{-\alpha} \end{cases}, \tilde{\bar{n}} = \left[1 + \left(\frac{hH}{L}\right)^{1-\epsilon}\right]^{-1} \tag{5}$$

With $\epsilon = 0$, (5) becomes Acemoglu and Zilibotti (2001)'s equation (15).

Proposition 1

(i) If $\epsilon = 1 \vee \frac{hH}{L} = 1$, then $\tilde{P_L} = \tilde{P_H} = \tilde{P} = \left(\frac{2}{e}\right)^{\alpha} \Leftrightarrow \tilde{\bar{n}} = \frac{1}{2}$;

(ii) if $0 < \epsilon < 1\,(\epsilon > 1) \wedge \frac{hH}{L} < 1 (\frac{hH}{L} > 1)$, then $\tilde{P_L} < \tilde{P_H} = \left(\frac{\tilde{\bar{n}}}{1-\tilde{\bar{n}}}\right)^{\alpha} \tilde{P_L} \Leftrightarrow \tilde{\bar{n}} > \frac{1}{2}$;

(iii) if $0 < \epsilon < 1\,(\epsilon > 1) \wedge \frac{hH}{L} > 1 (\frac{hH}{L} < 1)$, then $\tilde{P_L} > \tilde{P_H} = \left(\frac{\tilde{\bar{n}}}{1-\tilde{\bar{n}}}\right)^{\alpha} \tilde{P_L} \Leftrightarrow \tilde{\bar{n}} < \frac{1}{2}$.

4 Equilibrium price distribution

We show that the model above defines a BGP non-degenerate price distribution for the homogeneous good.[3] Firstly, have in mind that (Rohatgi, 1976)

Theorem 1 Let n be a random variable with pdf $f(n)$ and $y = \varphi(n)$ a random variable with pdf $g(y)$. If φ is a piecewise monotonic function, then $g(y) = \sum_{i=1}^{k} f(\varphi_i^{-1}(y)) \left|\frac{d\varphi_i^{-1}(y)}{dy}\right|$, where k is the number of sub-domains in which φ is monotonic and φ_i^{-1} denote the inverse function of φ in the sub-domain i, $i = 1, ..., k$.

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[3] Henceforth, the $\tilde{}$ is omitted.

Secondly, from Section 2, $n \sim U(0,1) \Rightarrow f(n) = \begin{cases} 1,\ 0 \leq n \leq 1 \\ 0,\ otherwise \end{cases}$ and, given equation (2), $y = P(n) = \begin{cases} (1-n)^{-\alpha} P_L,\ 0 \leq n \leq \bar{n} \\ n^{-\alpha} P_H,\ \bar{n} < n \leq 1 \end{cases}$, where P_L and P_H are positive constants along the BGP (see (5)).

Finally, from Proposition 1 and Theorem 1, we get

Proposition 2 The random variable $y = P(n)$ has the BGP pdf:

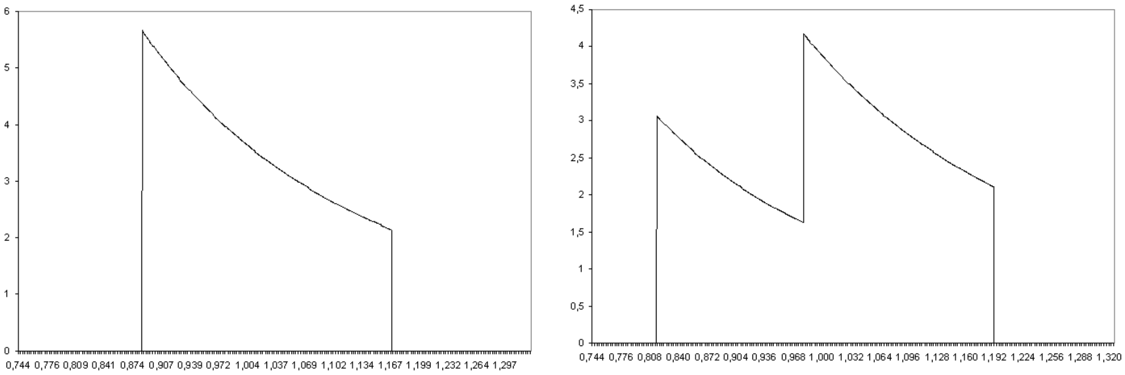
(i) If $P_L = P_H = P$, $g(y) = \begin{cases} \frac{2}{\alpha P}\left(\frac{y}{P}\right)^{-\frac{1}{\alpha}-1},\ P \leq y \leq 2^{\alpha} P \\ 0,\ otherwise \end{cases}$

(ii) if $P_L < P_H$, $g(y) = \begin{cases} \frac{1}{\alpha P_L}\left(\frac{y}{P_L}\right)^{-\frac{1}{\alpha}-1},\ P_L \leq y < P_H \\ \frac{1}{\alpha P_L}\left(\frac{y}{P_L}\right)^{-\frac{1}{\alpha}-1} + \frac{1}{\alpha P_H}\left(\frac{y}{P_H}\right)^{-\frac{1}{\alpha}-1},\ P_H \leq y \leq \bar{n}^{-\alpha} P_H \\ 0,\ otherwise \end{cases}$

(iii) if $P_L > P_H$, $g(y) = \begin{cases} \frac{1}{\alpha P_H}\left(\frac{y}{P_H}\right)^{\frac{-1}{\alpha}-1},\ P_H \leq y < P_L \\ \frac{1}{\alpha P_L}\left(\frac{y}{P_L}\right)^{\frac{-1}{\alpha}-1} + \frac{1}{\alpha P_H}\left(\frac{y}{P_H}\right)^{\frac{-1}{\alpha}-1},\ P_L \leq y \leq \bar{n}^{-\alpha} P_H \\ 0,\ otherwise \end{cases}$

The pdf of $P(n)$ is truncated from above and below, i.e., prices are distributed with positive probability over a closed interval, in accord with casual empiricism. Figure 1 depicts the pdf for $\epsilon = 1 \vee \frac{hH}{L} = 1$ ($P_L = P_H = P$) and $\epsilon \neq 1 \wedge \frac{hH}{L} \neq 1$ ($P_L \neq P_H$).

Figure 1: Probability density function for $\epsilon = 1$ (left) and $\epsilon \neq 1$ (right)



From Proposition 2, we have

Proposition 3 The mean and variance of $y = P(n)$ are $E(P(n)) = \frac{P_H}{\alpha-1}\left[\bar{n}^{-\alpha} - \left(\frac{\bar{n}}{1-\bar{n}}\right)^{-\alpha} - 1\right]$ and $Var(P(n)) = P_H^2\left\{\frac{1}{2\alpha-1}\left[\bar{n}^{-2\alpha} - \left(\frac{\bar{n}}{1-\bar{n}}\right)^{-2\alpha} - 1\right] - \frac{1}{(\alpha-1)^2}\left[\bar{n}^{-\alpha} - \left(\frac{\bar{n}}{1-\bar{n}}\right)^{-\alpha} - 1\right]^2\right\}$.

Proposition 4 The mode of $y = P(n)$, $\mu_o(P(n))$, is:

(i) $\mu_o(P(n)) = P$, if $P_L = P_H = P \Leftrightarrow \bar{n} = \frac{1}{2}$;

(ii) $\mu_o(P(n)) = P_L$, if

- **a.** $\bar{n} \in (\frac{1}{2} - \frac{1}{2+8\alpha}, \frac{1}{2})$, when $P_L > P_H$;
- **b.** $\bar{n} \in (\frac{1}{2} + \frac{1}{2+8\alpha}, 1]$, when $P_L < P_H$.

(iii) $\mu_o(P(n)) = P_H$, if

- **a.** $\bar{n} \in [0, \frac{1}{2} - \frac{1}{2+8\alpha})$, when $P_L > P_H$;
- **b.** $\bar{n} \in (\frac{1}{2}, \frac{1}{2} + \frac{1}{2+8\alpha})$, when $P_L < P_H$.

5 Comparative-statics

We discuss the impact of changes in $\frac{hH}{L}$ and ϵ on the BGP price mean and dispersion. Given Proposition 3 and (5), we have

Proposition 5 For given α and $\frac{hH}{L} \neq 1$, $E(P(n))$ and $Var(P(n))$ are decreasing functions of $\epsilon \in [0, 1)$ and increasing functions of $\epsilon \in (1, \infty)$.

Proposition 6 For given α and $\epsilon \neq 1$, $E(P(n))$ and $Var(P(n))$ are decreasing functions of $\frac{hH}{L} \in [0, 1)$ and increasing functions of $\frac{hH}{L} \in (1, \infty)$.

We conclude that countries with (i) larger scale effects (either positive or negative), given α and $\frac{hH}{L} \neq 1$ or (ii) larger imbalances between high- and low-skilled labour endowments in efficiency units, given α and $\epsilon \neq 1$, are expected to have larger price mean and variance. This result also corresponds to a larger variation coefficient $\sqrt{\frac{Var(P(n))}{E(P(n))^2}} = \sqrt{\frac{(\alpha-1)^2}{2\alpha-1}\frac{\left[\bar{n}^{-2\alpha}-\left(\frac{\bar{n}}{1-\bar{n}}\right)^{-2\alpha}-1\right]}{\left[\bar{n}^{-\alpha}-\left(\frac{\bar{n}}{1-\bar{n}}\right)^{-\alpha}-1\right]^2} - 1}$.

We also investigate under which conditions the mode of $P(n)$ is smaller than its mean, as we intuitively expect to be the empirical case. From Proposition 3 and 4, we find

Proposition 7 $E(P(n)) > \mu_o(P(n))$ requires:

(i) when $\mu_o(P(n)) = P_L = P_H = P$, $\alpha > 2^\alpha - 1$;

(ii) when $\mu_o(P(n)) = P_H$,

a. $\bar{n} \in \left[0, \frac{1}{2} - \frac{1}{2+8\alpha}\right)$, for $P_L > P_H$;

b. $\bar{n} \in \left(\frac{1}{2}, \frac{1}{2} + max\left\{\frac{1}{2+8\alpha}, \frac{1+\alpha-2^{\alpha}}{2\alpha(1-\alpha)}\right\}\right)$, for $P_L < P_H$.

(iii) when $\mu_o(P(n)) = P_L$,

a. $\bar{n} \in \left(\frac{1}{2} - max\left\{\frac{1}{2+8\alpha}, \frac{1+\alpha-2^{\alpha}}{2\alpha(1-\alpha)}\right\}, \frac{1}{2}\right)$, for $P_L > P_H$;

b. $\bar{n} \in \left(\frac{1}{2} + \frac{1}{2+8\alpha}, 1\right]$, for $P_L < P_H$.

Whatever $0 < \alpha < 1$, the inequality in (i) is universally verified, while (ii)a and (iii)b are always verified under Proposition 4. The restrictiveness of the conditions in (ii)b and (iii)a depends on the specific value of α.

We focus on the latter two cases, as they preclude extreme values for $\bar{n}$, and hence for $\frac{hH}{L}$. Let $\alpha = 0.4$, a standard value in the endogenous-growth literature. Then, (iii)a $\bar{n} \in (0.31, \frac{1}{2})$ and (ii)b $\bar{n} \in (\frac{1}{2}, 0.69)$. Consequently, if $\frac{hH}{L} = 0.2$ (or $\frac{hH}{L} = 5$), then (5) implies $\frac{1}{2} \leq \epsilon \leq 1.5$; if $\frac{hH}{L} = 0.65$ (or $\frac{hH}{L} = 1.5$), (5) implies $0 \leq \epsilon \leq 2$. Thus, with a relatively large imbalance in $\frac{hH}{L}$, small scale effects (in modulus) are required in order to $E(P(n)) > \mu_o(P(n))$. However, if $\frac{hH}{L}$ is sufficiently close to one, no constraint is imposed on scale effects from above ($\epsilon \geq 0$), although they still cannot be too negative (ϵ cannot exceed unity by too much). Only in case (i) with $\frac{hH}{L} = 1$ (see Proposition 1) are there no constraints on scale effects.

6 Conclusion

This paper analytically derives a non-degenerate price distribution for a homogeneous good within a model of endogenous directed technical change.

By obtaining an explicit result for the BGP price distribution, we are able to make testable predictions with respect to the price mean and dispersion of countries with different levels of relative labour endowment and scale effects. In particular, an empirically compatible result with respect to the mode of prices may require small scale effects, in modulus. This conforms with the well-known endogenous-growth literature debate over the counterfactual character of large (positive) scale effects (e.g., Jones, 1995).

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