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# Effects of Learning-by-doing, technology-adoption costs and wage inequality

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# Effects of learning-by-doing and technology-adoption costs on wage inequality

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## Abstract

In the dominant literature, the technological-knowledge bias that drives wage inequality is determined by the market-size channel. We develop an endogenous growth model with two technologies in which: a specific quality of labour, low or high-skilled, is combined with a specific set of quality-adjusted intermediate goods; the market-size channel is practically removed; adoption costs and learning-by-doing are linked with labour endowments. By solving transitional dynamics numerically, we show that changes in the supply of labour affect learning-by-doing and technology-adoption costs, which, in turn, influence the technological-knowledge bias and thus wage inequality. The proposed mechanisms can accommodate facts not explained by the previous literature.

*Keywords*: Learning-by-doing; Adoption costs; Technological-knowledge bias; Wage inequality; Numerical simulations.

*JEL classification Codes*: C61, J31, O31, O33.

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# 1 Introduction

The generic rise in the relative wage of more-skilled workers (i.e., in the skill premium) in many developed and developing countries during the 1980s and the 1990s seem a little puzzling. Indeed, we would expect a decline in the skill premium, in face of the relative increase in more-skilled workers. By paying special attention to the skill-biased technological change literature, which is the main explanation aimed at reconciling these apparent contradictory trends, we build a new framework to address some new mechanisms that can accommodate the occurrences observed in different country.

Using different proxies for skills, several studies document the rise in the relative wage of more-skilled workers during the 1980s and the 1990s. For example, in the case of developed countries, Katz and Murphy (1992) report the increase of the relative wage of college graduates when compared to high-school graduates in the United States; Juhn et al. (1993) describe the rise in hourly and weekly wage differentials between the $90^{th}$ wage percentile (more-skilled workers) and $10^{th}$ wage percentile (less-skilled workers) also in the United States; and Nickell and Bell (1996) illustrate the enlargement of the earnings differential between high and low-educated males in Germany, the United Kingdom and the United States – see also Machin and Van Reenen (1998) and Acemoglu (2003a), among many others.

The increase in the skill premium is also documented for some newly industrialised (developing) countries. For example, Zhu and Trefler (2005) show this happened in Hong Kong, India, Thailand and Uruguay, among many other countries; Avalos and Savvides (2006) confirm the increase in wage inequality in Latin America and East Asia; and Brainerd (1998) verifies that wage differential between the $90^{th}$ and $10^{th}$ wage percentiles widened in Russia.

In addition to these changes in wages, many developed countries have also experienced an increase in the relative supply of more-skilled workers. For example, Kranz (2006) shows that the share of workers with more than high school increased in Italy, Germany, the United Kingdom and the United States between the 1980s and the 1990s; and Acemoglu (2003a) attests that the same happened in other developed countries (e.g., The Netherlands, Sweden, Norway, Belgium and Finland). In developing countries, the generic rise in the proportion of high-skilled workers is also confimed by, for example, Zhu and Trefler (2005).

The skill-biased technological change literature (e.g., Bound and Johnson, 1992; Katz and Murphy, 1992; Juhn et al., 1993) attempts to work out the contradiction between the rise in the skill premium and the relative increase in the supply of skills. The argument is that technological-knowledge change induces an increase in the relative demand of more-skilled workers that exceeds the increase in the relative supply, thus increasing the skill premium.

Acemoglu (1998, 2002) and Acemoglu and Zilibotti (2001) further enhance this literature by considering that technological-knowledge change responds to shifts in labour endowments. When the supply of a type of labour increases, the market for technologies that complement it broadens, and this creates additional incentives for R&D aimed at those technologies. As a result, technological-knowledge change steers towards those technologies, which, in turn, increases the demand for the complementary type of labour. Hence, these recent contributions interpret the rise in the skill premium as a direct consequence of the increase in the relative supply of more-skilled workers.

However, some empirical evidence seems to contradict the explanation proposed by the skill-biased technological change hypothesis. In fact, despite the generic paths for wages and skills, Acemoglu (2003a), for example, documents a decline in the skill premium in The Netherlands between the early 1980s and the mid 1990s, in a scenario with relative increase of skills, and an increase in the skill premium in Canada between the late 1980s and the late 1990s, in a scenario with stable relative supply of skills.

Moreover, data from developing countries reveals additional problematic evidence. Crinò (2005), for example, shows that Hungary and the Czech Republic experienced an increase in the skill premium between 1993 and 2004, while at the same time the relative employment of more skilled workers declined. Robertson (2004), among others, detects that wage differential between the $90^{th}$ and $10^{th}$ wage percentiles decreased in Mexico between 1994 and 2002, even with the relative increase of high-educated workers. And Zhu and Trefler (2005), for example, reveal that the same situation occurred in Bolivia, South Korea and the Philippines.

Nevertheless, by stressing the market-size effect on technological-knowledge change, the skill-biased technological change literature contradicts the dominant literature on scale effects since Jones (1995a, b). In line with this literature, we propose a framework that aims at accounting for the related different paths of the skill premium. Our endogenous R&D growth model is closely related to the contributions of Acemoglu (1998, 2002), Acemoglu and Zilibotti (2001) and Afonso (2006, 2007). However, by considering learning-by-doing (Arrow, 1962) and technology-adoption costs (Parente and Prescott, 1994), which affect the direction of technological-knowledge change and thus the relative demand of high-skilled labour and the skill premium, we intend to accommodate the distinct paths of both the skill premium and the relative supply of workers.

The remainder of this paper is organised as follows. In section 2, we present a model of the economy. In section 3, we derive the static equilibria and transitional dynamics. In section 4, we use this framework to study the behaviour of the skill premium in different scenarios. Finally, in section 5, we close the paper with concluding comments.

## 2 Model of the economy

In this section, we expand the endogenous R&D-growth model proposed by Afonso (2006, 2007),[1] by connecting labour endowments with learning-by-doing and technology-adoption costs. The economy is populated by infinitely-lived

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[1] Basically, Afonso (2006, 2007) connects the skill-biased technological change literature (e.g., Acemoglu, 1998, 2002, 2003b) with the Schumpeterian growth approach (e.g., Aghion and Howitt, 1992; Grossman and Helpman, 1991; Barro and Sala-i-Martin, 2004, Ch. 7).

households and population growth is zero. Households supply labour, consume final goods and own firms. Final goods are produced under perfect competition and firms can use low (or high)-skilled labour together with low (or high)-specific quality-adjusted intermediate goods. Quality-adjusted intermediate goods are produced under monopolistic competition by combining units of aggregate output and innovative designs (e.g., Aghion and Howitt, 1992). Designs are obtained through R&D, which, in turn, drive economic growth, technological-knowledge bias and thus the path of wage inequality.

## 2.1 Households

Households are endowed with ability level $a \in [0,1]$ and supply one of two types of labour. They supply low (high)-skilled labour, $L_a$ $(H_a)$, if $a \leq \overline{a}$ $(a > \overline{a})$. The amount of low (high)-skilled labour supplied to the economy is $L = \int_0^{\overline{a}} L_a \, da$ $\left(H = \int_{\overline{a}}^1 H_a \, da\right)$, and is paid at a wage rate $w_L$ $(w_H)$; thus, $L + H = 1$.

All households have identical preferences characterized by a constant relative risk aversion lifetime utility function: $\int_0^\infty \frac{C_a(t)^{1-\theta}-1}{1-\theta} \cdot e^{-\rho t} \, dt$, where $C_a(t)$ is the consumption of household $a$ at time $t \in \mathbb{R}_0^+$, $\rho$ is the subjective discount rate, and $\theta$ is the coefficient of relative risk aversion.

Households accumulate assets, $K$, in the form of ownership of firms that produce quality-adjusted intermediate goods. Those assets earn returns at the interest rate $r(t)$. A household's assets stock is affected by its net savings, given by the difference between its income (interest and wages) and its consumption. The flow budget constraint of household $a$ is $\dot{K}_a(t) = r(t) K_a(t) + w_z(t) Z_a(t) - C_a(t)$, where $\dot{K}_a(t)$ is the change in the assets stock of $a$, $Z = L$ if $a \leq \overline{a}$ and $Z = H$ if $a > \overline{a}$.

Household $a$ maximizes lifetime utility subject to the budget constraint and the"no Ponzi games" condition ($\lim_{t\to\infty} K_a(t) e^{-\rho t} = 0$). The solution for the consumption path, which is independent of the household, is the standard Euler equation

$$\frac{\dot{C}_a(t)}{C_a(t)} = \frac{\dot{C}(t)}{C(t)} = \frac{r(t) - \rho}{\theta}, \tag{1}$$

where $\dot{C}(t)$ is the change in aggregate consumption.

## 2.2 Final-goods sector

In this sector, competitive firms are indexed by $n$ over the range $[0,1]$. Two substitute production technologies are available. A low (high)-technology – the $L$ $(H)$-technology – uses a combination of low (high)-skilled labour and a continuum of low (high)-specific quality-adjusted intermediate goods indexed by $j \in [0,J]$ $(j \in [J,1])$. The production function of firm $n$ is given by:

$$Y_n(t) = A\left[\left(\int_0^J B_{jn}(t)^{1-\alpha}\,dj\right) D_{Ln}(t)^{\alpha} + \left(\int_J^1 B_{jn}(t)^{1-\alpha}\,dj\right) D_{Hn}(t)^{\alpha}\right]. \tag{2}$$

Variable $A$ is exogenous and measures the overall efficiency.

By considering $B_{jn}(t) = X_{jn}(t)\,q^{k_j(t)}$, the integral terms are the contributions of quality-adjusted intermediate goods to production. In line with the Schumpeterian growth models (e.g., Aghion and Howitt, 1992), $X_{jn}(t)$ is the quantity of $j$ used by firm $n$, and $q^{k_j(t)}$ measures its quality level. Qualities are ordered along a quality ladder, and $k_j(t)$ is the top quality rung of $j$ available at $t$.[2] Parameter $q$, greater than one, measures the quality improvement that occurs in $j$ when a new quality is introduced, i.e., when $k_j(t)$ increases by one.

Parameter $\alpha$, between 0 and 1, is the labour share in production. Thus, $D_{Ln}(t) = L_n(1-n)\sigma_L$ and $D_{Hn}(t) = H_n n \sigma_H$ sum up the contribution of labour to production: $L_n$ and $H_n$ are the amounts of low and high-skilled labour used by firm $n$; $(1-n)$ and $n$ imply that low (high)-skilled labour is relatively more productive in producing lower (higher)-index final goods; $\sigma_L$ and $\sigma_H$ measure the technological readiness of low and high-skilled labour, respectively.

On the one hand, technological readiness of labour means how efficiently workers use the respective complementary intermediate goods; this is connected with the idea of learning-by-doing popularized by Arrow (1962). On the other hand, it denotes how easily workers adapt new and improved qualities of intermediate goods; and this is associated with the negative impact of barriers to technology adoption in economic growth proposed by Parente and Prescott (1994). We model $\sigma_L$ and $\sigma_H$ as:

$$\sigma_L = L^l e^{\phi_1 L} \text{ and } \sigma_H = cH^h e^{\phi_2 H}\text{, where:} \tag{3}$$

(i) $c \geq 1$ reflects an absolute advantage of high-skilled labour over low-skilled labour in terms of technological readiness.

(ii) $L^l$ and $H^h$ (with $l, h \geq 0$) are generically related to learning-by-doing effects. In particular, we consider that each worker acquires certain technological expertise by interacting with each $j$ during the production process. This expertise, in turn, is shared with the other workers of the same type and becomes useful for working with the complementary type of intermediate goods, since we regard that each type of intermediate goods comprises a common technological ground. Thus, $L$ $(H)$ governs the current level of low (high)-specific technological expertise and $l$ $(h)$ captures the spillover arising from the exchange of expertise between low (high)-skilled workers.[3] The effects instigated by these terms are in line with the cross-industry knowledge spillovers of earlier models of endogenous growth with learning-by-doing (e.g., Stokey, 1988; Young, 1993).

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[2] We consider an equilibrium in which final-goods producers only use the highest quality intermediate goods (subsection 2.3 provides further details).

[3] For example, if the low-specific technological expertise grows, due to an increase of $L \in [0,1]$, the benefit obtained by low-skilled workers increases at an increasing rate when $l < 1$ and increases at a decreasing rate when $l > 1$ (we consider this latter situation).

They are also related with Lucas (1988) in which the average level of human capital is influenced by each individual's human capital stock and contributes to the productivity of all production factors (the external effect of human capital).

(iii) $e^{\phi_1 L}$ and $e^{\phi_2 H}$ capture the effect of technology adoption, since $\phi_1, \phi_2 < 0$. We consider the introduction of new quality-adjusted intermediate goods costly, since workers have to make an effort in adapting the new technological-knowledge.[4] In particular, we consider specific technology-adoption costs and connect these costs with the respective labour level. For example, more low-skilled workers implies higher specific $L$-technology adoption costs, since more workers need to adapt new qualities of low-specific intermediate goods.

By using these two terms, we are in line with Parente and Prescott (1994) that stress the negative impact of barriers to technological-knowledge adoption. We are also in line with Bessen (2002), among others, who points out that the adoption of new technological knowledge requires significant adjustment costs. For some values of $L$, $H$, $\phi_1$ and $\phi_2$ the adoption costs are greater in $H$-technology than in $L$-technology, which differs from approaches such as those of Caselli (1999) and Lloyd-Ellis (1999). These studies assume that more-skilled workers have an advantage over less-skilled workers in adopting new technological knowledge, but they ignore the fact that different types of workers use distinct types of technological knowledge. As this is not negligible for us, we leave room for situations in which low-skilled workers could be better prepared to adapt new qualities of the respective complementary intermediate goods.

## 2.3 Intermediate-goods sector

Firms in this sector use one unit of aggregate output to obtain one unit of $j$ and thus its marginal cost of production is one. Indeed, assuming that $\exp \int_0^1 \ln P_n \, dn = 1$, where $P_n$ is the price of $n$, the aggregate output (numeraire) at each $t$ is given by $Y = \int_0^1 P_n Y_n \, dn = \exp \int_0^1 \ln Y_n \, dn \equiv C + X + R$; i.e., $Y$ can be used in consumption, $C$, in production of quality-adjusted intermediate goods, $X$, and in R&D, $R$.

Moreover, each quality of $j$ is exclusively produced by the owner of its patent and, therefore, the monopolist that holds the patent for the highest quality at $t$ obtains a profit flow $\pi_j(t) = (P_j(t) - 1)\; X_j(t)$, where $P_j$ denotes the price of $j$ and $X_j$ represents the aggregate demand for the highest-quality. $X_j = \int_0^1 X_{jn} \, dn$ is obtained from the demand for its highest quality by final-goods producers, which, due to perfect competition in final goods, is at each $t$:

$$X_{jn} = P_j^{-\frac{1}{\alpha}} (P_n A)^{\frac{1}{\alpha}} D_{Zn} (1-\alpha)^{\frac{1}{\alpha}} q^{k_j \left(\frac{1-\alpha}{\alpha}\right)}, \tag{4}$$

where $Z = L$ if $0 \leq j \leq J$ (i.e., if $a \leq \overline{a}$, due to complementarity between inputs in (2)) and $Z = H$ if $J < j \leq 1$ (i.e., if $a > \overline{a}$).[5] The goal of the monopolist is to

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[4] That is, technological readiness relies also on the manner of how workers cope with technological-knowledge progress and, as a result, the standard positive effect of improvements in quality-adjusted intermediate goods diminishes.

[5] Due to the complementarity between inputs in (2), firms (in final-goods sector) use more

choose the sequence of prices $[P_j(t), P_j(t+1), \ldots]$ that maximizes the present discounted value of all profit flows.

We assume that intermediate goods bought by the producers of final goods fully depreciate at the end of each $t$ (as in, e.g., Acemoglu and Zilibotti, 2001). Under such assumption, the monopolist faces no dynamic constraints and every $t$ chooses $P_j$ so as to maximize $\pi_j$, obtaining:

$$P_j = P = \frac{1}{1-\alpha}, \text{ for all } j \in [0,1], \tag{5}$$

which is: (i) a mark-up over the marginal cost of production, since $0 < \alpha < 1$; (ii) constant across $t$, $j$ and $k$. Whether or not a monopolist can price its output according to (5) depends on the substitutability between qualities of $j$ and on the value of $q$. Following Barro and Sala-i-Martin (2004, Ch. 7), we assume that $q > \frac{1}{1-\alpha}$ and that monopolists set $P_j$ according to (5).[6]

## 2.4 Quality-improving R&D

Firms in the intermediate-goods sector carry out R&D activities in order to improve their qualities. Let $\delta_j(k,t)$ denote the probability of the $k^{th}$ quality of $j$ being introduced at $t$, thereby improving the quality level of that good from $q^k$ to $q^{k+1}$, which is given by:[7]

$$\delta_j(k,t) = R_j(k,t)\, \Gamma q^{k_j(t)}\, Z^{-1}\, \chi^{-1} q^{-(1/\alpha)k_j(t)}, \text{ for all } j \in [0,1], \text{ where:} \tag{6}$$

(i) $R_j(k,t)$ is the total amount of R&D spending (in terms of $Y$) aimed at improving $j$.

(ii) $\Gamma q^{k_j(t)}$ is a learning effect, which relates past successful R&D in $j$ with the current probability of success. Through this effect we take into account that technological knowledge is non-rival and that the legal system only gives protection to production rights.[8] Thus, firms learn from past innovations in $j$ (measured by $q^{k_j(t)}$) and use that knowledge in their R&D efforts, since the learning coefficient $\Gamma$ is greater than zero.

(iii) $Z^{-1}$ is the adverse effect of the market size, which is measured by $L$ and $H$, due to the complementarity between inputs in (2). Indeed, a successful introduction of a new quality of $j$ requires not only its invention, but also other tasks positively related with the market size. For example, as Becker and Murphy (1992) point out, coordination among agents might be harder to achieve in a large market. Furthermore, information dissemination and processing can

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intermediate goods when: they employ more workers, i.e., when $L_n$ or $H_n$ are higher; the prices of their own goods, $P_n$, increase; intermediate-goods prices, $P_j$, decrease – see (4).

[6] An additional assumption underlying this result is that the monopolist of the top quality has a one-rung quality advantage over its closest competitor – see subsection 3.2 below.

[7] This is an adaptation of the probability function for R&D success proposed by Afonso (2006, 2007). We assume that this function is the same for low and high-specific intermediate goods, whereas, for example, Afonso (2006) considers R&D aimed at high-specific intermediate goods more effective.

[8] That is, no protection is given to the technological knowledge.

become more complex as the market grows, and innovators may experience additional difficulties in marketing their products. Through this effect, we practically remove the scale effects induced by the market size and thus we are in line with the dominant literature on scale effects (e.g., Jones, 1995a, b).

(iv) $\chi^{-1}q^{-(1/\alpha)k_j(t)}$ is an adverse effect, since $\chi$ is a positive constant. More specifically this effect reflects an increasing difficulty in improving the quality of intermediate goods as their quality level rises (e.g., Barro and Sala-i-Martin, 2004, Ch. 7). A common theoretical justification provided for this assumption is that the first qualities to be introduced are the easiest to invent, therefore making innovation more difficult by emptying the pool of trivial ideas.

# 3 Equilibria

We now proceed with the equilibrium analysis of the model. Firstly, we derive the equilibrium for a given technological-knowledge level. Then, bringing into consideration R&D activities, we derive the aggregate spending in R&D and the law of motion of technological knowledge. Finally, we use these results to characterize transitional dynamics and steady-state growth.

## 3.1 Equilibrium given a technological-knowledge level

Production function (2) combines complementarity between inputs with substitutability between the two technologies and features that inputs of $L$ ($H$)-technology is relatively more productive in producing low (high)-index final goods. The optimal choice of technology is reflected in the equilibrium threshold final good $\overline{n}$, which results from profit maximization (by perfectly competitive final-goods producers and by intermediate-goods monopolists) and full-employment equilibrium in factor markets, given the supply of labour and the current state of technological knowledge,

$$\overline{n}(t) = \left\{ 1 + \left[ \frac{H \ \sigma_H \ Q_H}{L \ \sigma_L \ Q_L} \right]^{\frac{1}{2}} \right\}^{-1} . \tag{7}$$

In (7) $Q_L = \int_0^J q^{k_j\left(\frac{1-\alpha}{\alpha}\right)} dj$ and $Q_H = \int_J^1 q^{k_j\left(\frac{1-\alpha}{\alpha}\right)} dj$ evaluate the aggregate quality of the intermediate goods (i.e., the technological-knowledge level) that complement, respectively, low and high-skilled labour, and $S \equiv \frac{Q_H}{Q_L}$ measures the technological-knowledge bias. From (7), the relative supply of labour, the size of the learning-by-doing, the amount of technology-adoption costs and the technological-knowledge bias all determine the number of final goods produced with each technology.

The threshold $\overline{n}$ can be implicitly expressed in terms of price indexes. This is achieved by taking into account that in the production of $\overline{n}$ both a firm that uses $L$-technology and a firm that uses $H$-technology should break even. This turns out to yield, at each $t$, the following ratio of index prices of goods produced with $H$ and $L$ technologies:

$$\frac{P_H(t)}{P_L(t)} = \left[\frac{\overline{n}(t)}{1-\overline{n}(t)}\right]^{\alpha}. \tag{8}$$

Moreover, bearing in mind that the aggregate output is obtained by integration over final goods and equations (7) and (8), the price-indexes of $L$ and $H$ final goods are, respectively, at each $t$

$$P_L = (1-n)^{\alpha} P_n = e^{-\alpha}\overline{n}^{-\alpha}, \text{ if } 0 \leq n \leq \overline{n}, \tag{9a}$$

$$P_H = n^{\alpha} P_n = e^{-\alpha}(1-\overline{n})^{-\alpha}, \text{ if } \overline{n} < n \leq 1. \tag{9b}$$

We can now compute equilibrium values for the macroeconomic aggregates $X \equiv \int_0^J \int_0^{\overline{n}} X_{jn}\, dn\, dj + \int_J^1 \int_{\overline{n}}^1 X_{jn}\, dn\, dj = \int_0^J X_j\, dj + \int_J^1 X_j\, dj$ and $Y \equiv \int_0^{\overline{n}} P_n Y_n\, dn + \int_{\overline{n}}^1 P_n Y_n\, dn$. By considering equations (2), (4), (7), (9a) and (9b) we obtain:

$$X = e^{-1}\left[\frac{A(1-\alpha)}{1/(1-\alpha)}\right]^{\frac{1}{\alpha}} \left[(L\sigma_L Q_L)^{\frac{1}{2}} + (H\sigma_H Q_H)^{\frac{1}{2}}\right]^2, \tag{10}$$

and

$$Y = X\left[\frac{(1-\alpha)}{1/(1-\alpha)}\right]^{-1}. \tag{11}$$

In equilibrium, production factors are paid at their marginal productivities. Differentiation of (11) with respect to $H$ and $L$ yields, respectively, the wage rates for high and low-skilled labour at each $t$:

$$\begin{aligned} w_H = {} & \tfrac{\lambda}{2}\left[ce^{\phi_2 H} H^{1+h} Q_H\right]^{-\frac{1}{2}} \times \\ & \times \left[c\phi_2 e^{\phi_2 H} H^{1+h} Q_H + ce^{\phi_2 H}(1+h) H^h Q_H\right] \end{aligned}, \tag{12a}$$

$$\begin{aligned} w_L = {} & \tfrac{\lambda}{2}\left[e^{\phi_1 L} L^{1+l} Q_L\right]^{-\frac{1}{2}} \times \\ & \times \left[\phi_1 e^{\phi_1 L} L^{1+l} Q_L + e^{\phi_1 L}(1+l) L^l Q_L\right] \end{aligned}, \text{ where} \tag{12b}$$

$\lambda \equiv 2e^{-1}\left[\frac{A(1-\alpha)}{1/(1-\alpha)}\right]^{\frac{1}{\alpha}} \left\{\left[e^{\phi_1 L} L^{1+l} Q_L\right]^{\frac{1}{2}} + \left[ce^{\phi_2 H} H^{1+h} Q_H\right]^{\frac{1}{2}}\right\}$.

Finally, we can define the wage ratio (equilibrium skilled premium), measuring intra-country wage inequality at each $t$:

$$\frac{w_H}{w_L} = \left[\frac{e^{\phi_1 L} L^{1+l}}{ce^{\phi_2 H} H^{1+h}} \frac{1}{S}\right]^{\frac{1}{2}} \left[\frac{ce^{\phi_2 H} H^h}{e^{\phi_1 L} L^l} S\right] \left[\frac{\phi_2 H + 1 + h}{\phi_1 L + 1 + l}\right], \tag{13}$$

and, thus, there is a positive relationship between the wage premium of high-skilled labour and the technological-knowledge bias, $S$.

On the one hand, an increase in $H$, for example, depresses $w_H$ (and thus $\frac{w_H}{w_L}$), due to full employment and decreasing marginal productivity of labour,[9]

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[9] Since $L + H = 1$, increases in $H$ decrease $L$, thereby decreasing $H$ productivity and $w_H$.

but, on the other hand, improves its technological readiness, which, in turn, increases its productivity and thus $w_H$ (and $\frac{w_H}{w_L}$). Furthermore, in this case $\overline{n}$ falls, see (7); i.e., more final goods are produced with the $H$-technology and sold at a relatively low price, see (8). By the operation of the price (of final goods) channel (from the stocks of labour to the flows of resources used in R&D and to wage inequality), profit opportunities in the production of intermediate goods used by the relatively high-priced $L$-technology final goods induce a gradual slowdown in the technological-knowledge bias, which is reflected in the skill premium, see (13).[10]

## 3.2 R&D equilibrium

It can be shown that, independently of $j$ and the respective $q^k$, it is more profitable to introduce a new quality of $j$ by an outside firm than by the current monopolist.[11] Indeed, profits of the outside firm jump from zero (prior to the innovation) to $\pi_j$ (when the new quality is introduced). As the firm gains one-rung quality advantage over its closest competitor and $P_j$ is given by (5), the change in profits, $\Delta\pi_j$, is:

$$\Delta\pi_j = \pi_j - 0 = \left[\frac{1}{1-\alpha} - 1\right]\left[\frac{P_z A\left(1-\alpha\right)}{1/\left(1-\alpha\right)}\right]^{\frac{1}{\alpha}} Z\sigma_Z q^{k_j\left(\frac{1-\alpha}{\alpha}\right)}. \tag{14}$$

Let $\tau$ $(\tau + d)$ be the time when a firm introduces the quality $q^k$ $(q^{k+1})$ for $j$. The firm that introduces $q^k$ becomes the monopolist between $\tau$ and $\tau + d$ in $j$ and earns a sum of profits given by $V_j\left(k,t\right) = \int_{\tau}^{\tau+d} \pi_j\left(k,t\right) e^{-r(t)}\, dt$. Since innovations arrive randomly, $d$ is undetermined and the reward for introducing $q^{k_j}$, i.e., the true value of $V_j\left(k,t\right)$ is unknown. However, if the interest rate is constant between $\tau$ and $\tau + d$, which will be the case in equilibrium, then

$$E\left[V_j\left(k,t\right)\right] = \frac{\pi_j\left(k,t\right)}{r\left(t\right) + \delta_j\left(k,t\right)}. \tag{15}$$

That is, the expected value of introducing $q^{k_j}$ shown in (15) depends positively on the dimension of the profits at each $t$, and negatively on the interest rate and on the probability of successful innovation, which captures the Schumpeterian idea of "creative destruction".

By considering free entry in R&D activities, free access to the R&D technology and a proportional relationship between successful innovation and the share of R&D effort, the R&D spending aimed at improving $j$ should equal the expected payoff generated by the innovation, i.e., $R_j\left(k-1,t\right) = E\left[V_j\left(k,t\right)\right]$ $\delta_j\left(k-1,t\right)$. Then, using (6), (14) and (15), we obtain for each $t$ the equilibrium probabilities of successful R&D, $\delta_L$ and $\delta_H$, which are independent of $j$ and $k$:

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[10] This price channel appears in various papers by Acemoglu (*e.g.*, 2002), although always dominated by the market-size effect, which, in our case, is practically removed – see below the equilibrium R&D in subsection 3.2.

[11] This "replacement effect" is a common feature of Schumpeterian quality ladder models (e.g., Aghion and Howitt, 1992; Barro and Sala-i-Martin, 2004, Ch. 7).

$$\delta_Z = \left\{ \left( \frac{\alpha}{1-\alpha} \right) \left[ P_Z A \left(1-\alpha\right)^2 \right]^{\frac{1}{\alpha}} \sigma_Z q^{\frac{1-\alpha}{\alpha}} \frac{\Gamma}{\chi} \right\} - r, \tag{16}$$

and the equilibrium aggregate R&D spending, $R = \int_0^J R_j\left(k\right) dj + \int_J^1 R_j\left(k\right) dj$,

$$\begin{array}{c} R = Q_L L \left\{ \left( \frac{\alpha}{1-\alpha} \right) \left[ P_L A \left(1-\alpha\right)^2 \right]^{\frac{1}{\alpha}} \sigma_L - r\frac{\chi}{\Gamma} \right\} + \\ + Q_H H \left\{ \left( \frac{\alpha}{1-\alpha} \right) \left[ P_H A \left(1-\alpha\right)^2 \right]^{\frac{1}{\alpha}} \sigma_H - r\frac{\chi}{\Gamma} \right\} \end{array} . \tag{17}$$

Following Barro and Sala-i-Martin (2004, Ch. 7), the introduction $q^{k_j}$ implies a change in the respective aggregate quality index, resulting in:

$$\frac{\dot{Q_Z}}{Q_Z} = \delta_Z \ \left( q^{\frac{1-\alpha}{\alpha}} - 1 \right). \tag{18}$$

## 3.3 Transition dynamics and steady-state growth

Since all macroeconomic aggregates ($Y$, $X$, $R$, $C$ and also, for example, $\frac{w_H}{w_L}$) can be expressed as multiples of $Q_L$ and $Q_H$,[12] the path of all relevant variables outside the steady state depends on the single differential equation that governs the path of technological-knowledge bias, i.e., $S\hat{(t)} \equiv \frac{\dot{S(t)}}{S(t)} = \frac{\dot{Q_H(t)}}{Q_H(t)} - \frac{\dot{Q_L(t)}}{Q_L(t)}$. Thus, using (3), (9a), (9b), (16) and (18), we obtain the required expression:

$$\begin{array}{l} \hat{S} = e^{-1} \left[ q^{\left(\frac{1-\alpha}{\alpha}\right)} - 1 \right] \left\{ \left( \frac{\alpha}{1-\alpha} \right) \left[ A \left(1-\alpha\right)^2 \right]^{\frac{1}{\alpha}} q^{\left(\frac{1-\alpha}{\alpha}\right)} \frac{\Gamma}{\chi} \right\} \\ \left[ cH^h e^{\phi_2 H} \left( 1 + \frac{cH^{h+1} e^{\phi_2 H}}{L^{l+1} e^{\phi_1 L}} S \right)^{-1/2} - L^l e^{\phi_1 L} \left( 1 + \frac{cH^{h+1} e^{\phi_2 H}}{L^{l+1} e^{\phi_1 L}} S \right)^{1/2} \right]. \end{array} \tag{19}$$

At the end of transitional dynamics, the economy reaches the steady state and all relevant variables grow at the same constant rate. The steady-state growth rate, $g^*$, is:

$$g^* \equiv \frac{\dot{Q_L^*}}{Q_L^*} = \frac{\dot{Q_H^*}}{Q_H^*} = \frac{r^* - \rho}{\theta}. \tag{20}$$

By considering (18) and (20), we can obtain $r^*$. In addition, from $\frac{\dot{Q_L^*}}{Q_L^*} = \frac{\dot{Q_H^*}}{Q_H^*}$ we find that final goods price indexes, $P_H^*$ and $P_L^*$, the threshold-final good, $\overline{n}^*$, and the skilled premium, $\frac{w_H^*}{w_L^*}$, remain stable; i.e., $\frac{\dot{P_H^*}}{P_H^*} = \frac{\dot{P_L^*}}{P_L^*} = \frac{\dot{\overline{n}^*}}{\overline{n}^*} = \frac{\dot{w_H^*}}{w_H^*} - \frac{\dot{w_L^*}}{w_L^*} = 0$, and also that wages rise steadily in line with the technological-knowledge progress; i.e., $\frac{\dot{w_H^*}}{w_H^*} = \frac{\dot{w_L^*}}{w_L^*} = \frac{\dot{Q_L^*}}{Q_L^*} = \frac{\dot{Q_H^*}}{Q_H^*}$.

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[12] As can be seen in (10), (11) and (17), aggregates $Y$, $X$, $R$ and $C$ (since $Y = X + R + C$) can be expressed as multiples of $Q_L$ and $Q_H$.

# 4 Analysis of the main results

Now, we fit our model to real data from a wide range of countries and periods. Following the calibration approach pioneered by Kydland and Prescott (1982),[13] the goal is to understand to which extent the behaviour of the skill premium can be explained by changes in the relative supply of high-skilled labour and, consequently, in learning-by-doing and in technology-adoption costs.

We first distinguish between core and non-core parameters. Core parameters are those which affect technological readiness; i.e., that are related to the main focus of our study. The remaining are non-core parameters and the respective values are in line with Afonso (2006, 2007); i.e., $A = 1.5$, $q = 3.33$, $\alpha = 0.7$, $\Gamma = 1.6$, $\chi = 4$, $\rho = 0.02$ and $\theta = 1.5$. Subsequently, we delimit the range for core-parameter values to $\phi_1 = \phi_2 \in [-2, 0]$, $l = h \in [1, 2]$ and $c \in [1, 1.5]$. Then, the precise set of values for $\phi_1, \phi_2, l, h$ and $c$ is country specific; that is, it is defined in order to replicate the real country data.

## 4.1 Accommodation of distinct real paths

Using data from Machin and Van Reenen (1998), we start by calibrating the model to replicate the behaviour of the skill premium in the United States between 1973 and 1989. During this period the employment share of non-production workers increased from 0.246 to 0.303, leading to a shift in the ratio $\frac{H}{L}$ from 0.326 to 0.435.[14] In addition, the ratio between wages of non-production and production workers rose from 1.553 to 1.623.

Figure 1 presents the simulated paths of $\frac{Q_H}{Q_L}$ and $\frac{w_H}{w_L}$ by setting $c = 1.35$, $l = h = 1.8$ and $\phi_1 = \phi_2 = -1.2$. At the initial value of $\frac{H}{L}$ (i.e., in 1973), the simulated (steady-state) skill premium is 1.556. When the exogenous relative supply of high-skilled workers shifts from 0.326 to 0.435, the skill premium immediately drops to 1.531. This short-run drop results from the interaction of two distinct effects. On the one hand, changes in $H$ and $L$ alter the technological readiness of both types of labour – by considering (3), $\sigma_H$ shifts from 0.081 to 0.109 and $\sigma_L$ moves from 0.243 to 0.226; that is, through this mechanism the skill premium increases since the productivity of high (low)-skilled labour increases (decreases). On the other hand, high-skilled labour has become relatively more abundant, which, with decreasing marginal productivity and full labour employment, decreases the skill premium. In the present case, the latter effect dominates the former.

Transitional dynamics towards a new steady state shows that the shift in the relative supply of high-skilled labour (together with the respective effect in technological readiness) reinforces the technological-knowledge bias in favour of high-skilled intermediate goods. Such bias increases the supply of high-skilled intermediate goods, thereby increasing the number of final goods produced with

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[13] For a detailed discussion of this technique see, for example, Kydland and Prescott (1996) and Dejong and Dave (2007, Ch. 7).

[14] Workers allocated to non-production activities are used as a proxy for high-skilled workers. The increase in $H$ from 0.246 to 0.303 implies a decrease in $L$ from 0.754 to 0.697.

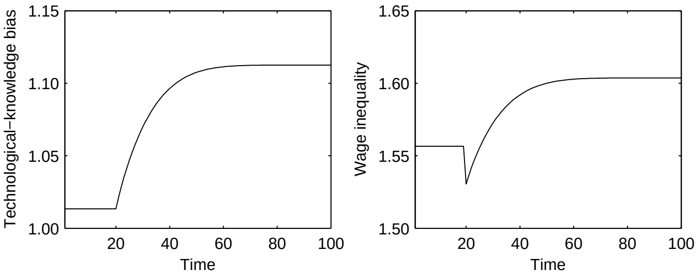

Figure 1: Fixed-parameter simulation for the United States, 1973-1989.

$H$-technology, see (7), and lowering their relative price, see (8). Thus, relative prices of final goods produced with $H$-technology drop continuously towards the new constant steady-state levels, which implies that the technological-knowledge bias is increasing, but at a decreasing rate until it reaches its new (higher) steady state value.

Due to the complementarity between inputs in (2), the skill premium is closely related with the technological-knowledge bias, as (13) shows. Thus, the short-run effect on the skill premium ends up being reverted in transition towards the new steady state. Once the new steady state is reached, the skill premium stabilises at 1.604, a higher value than that observed initially.

Simulated results seem to provide a reasonable approximation to the real behaviour of the skill premium. On the one hand, the initial and ending values are very close to the ones reported by Machin and Van Reenen (1998). On the other hand, Machin and Van Reenen (1998)'s data also shows that an initial fall in the skill premium indeed exists: from 1.556 in 1973, the ratio between the wages of production and non-production workers dropped to 1.531 in 1977.

Similar parameter values are useful in replicating the behaviour of the skill premium in the United Kingdom and Sweden. According to Machin and Van Reenen (1998), between 1973 and 1989 the relative supply of non-production workers increased in the United Kingdom from 0.351 to 0.481, while the wage premium of these workers increased from 1.316 to 1.470. In Sweden $\frac{H}{L}$ shifted from 0.372 to 0.435 and $\frac{w_H}{w_L}$ from 1.487 to 1.509.

Figure 2 shows simulation results using $c = 1.45$, $l = h = 1.4$ and $\phi_1 = \phi_2 = -0.2$ for the United Kingdom; and $c = 1.4$, $l = h = 1.25$ and $\phi_1 = \phi_2 = -0.2$ for Sweden. In response to the reported shift in the $\frac{H}{L}$ ratio, simulations illustrate an increase in the skill premium for the United Kingdom from 1.318 to 1.441 and for Sweden from 1.479 to 1.510. Results are consistent with Swedish real data, but they are poorer for the United Kingdom. Nevertheless, our parameter calibration can explain roughly 80% of the increase in the United Kingdom skill premium between 1973 and 1989. In both cases the skill premium increases even in the short-run because the initial changes in technological readiness of labour dominates changes in the relative abundance of high-skilled workers. The data in Machin and Van Reenen (1998) supports this kind of short-run adjustment in Sweden, but evidence for the United Kingdom is somewhat mixed.

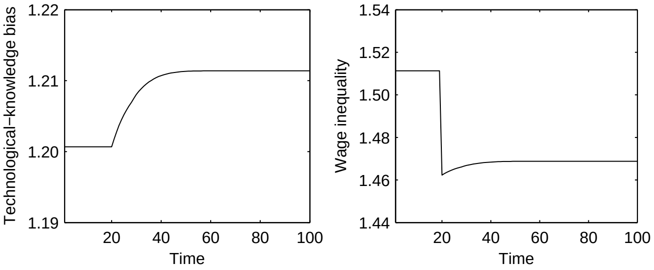

Figure 2: Fixed-parameter simulation for Denmark, 1973-1989.

In the above three cases there is a positive relationship between the relative supply of high-skilled labour and the skill premium. However, our model also accommodates other scenarios (not captured by the skill-biased technological change literature). For example, according to Machin and Van Reenen (1998), between 1973 and 1989 the $\frac{H}{L}$ in Denmark shifted from 0.335 to 0.466 and the skill premium decreased from 1.511 to 1.437. Simulated results using $c = 1.2$, $l = h = 1.25$ and $\phi_1 = \phi_2 = -0.55$ also replicate very accurately the Denmark path of the skill premium (see Figure 3). The initial simulated skill premium is equal to the observed value and we can account for roughly 56% of the short-run observed drop. Furthermore, the drop in the skill premium and the small recovery fits well into the data of Machin and Van Reenen (1998).[15]

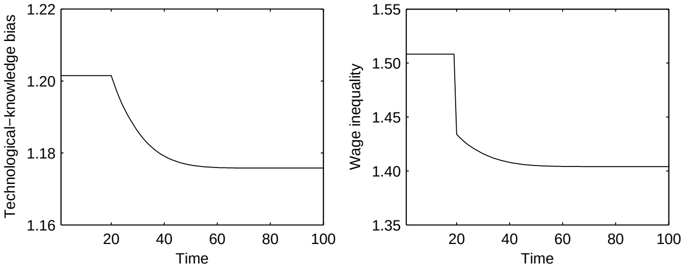

Figure 3: Variable-parameter simulation for Denmark, 1973-1989.

Therefore, with some variability in core-parameter values,[16] we are able to obtain a closer approximation to the real data. Next, in order to highlight the effects of both learning-by-doing and technology-adoption costs, we first introduce a slight change in $l = h$ and then a slight change in $\phi_1 = \phi_2$. Considering

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[15] This is a case in which the improvement of the technological-knowledge bias during transition towards a new steady state augments $\frac{w_H}{w_L}$, but this is not enough to offset the initial drop.

[16] Note that the main divergence in core-parameter values is between the United States and the above mentioned european countries.

$c = 1.2$, $\phi_1 = \phi_2 = -0.4$ and the change in learning-by-doing parameters from $l = h = 1.15$ to $l = h = 1.2$, simulation for Denmark between 1973 and 1989 also explains the decrease in the Denmark skill premium (see Figure 4). The real path is more in line with the one in Figure 3. Nevertheless, a small change in learning-by-doing parameters can help to account for and are compatible with changes in the skill-premium induced by shifts in $\frac{H}{L}$.

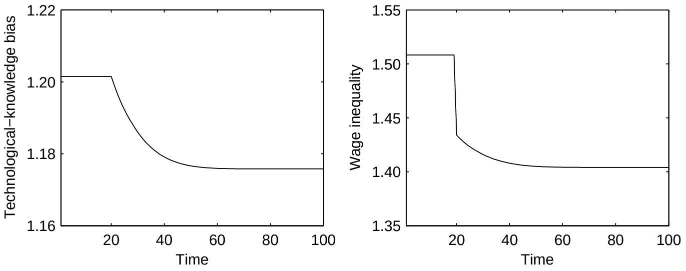

Figure 4: Variable-parameter simulation for Denmark, 1973-1989.

Taking into account $c = 1.2$, $l = h = 1.15$ and the decrease in the barriers to technology adoption ($\phi_1 = \phi_2$ shift from $-0.35$ to $-0.3$), we can replicate Acemoglu's (2003a) data for Belgium, which is characterised by a slight increase in $\frac{H}{L}$ (from 0.105 to 0.119) and by a decrease in the skill premium (from 1.419 to 1.365) between 1985 and 1997 (see Figure 5). That is, simultaneous shifts in labour endowments and in technology-adoption parameters can help to account for a decrease in the Belgian skill premium.

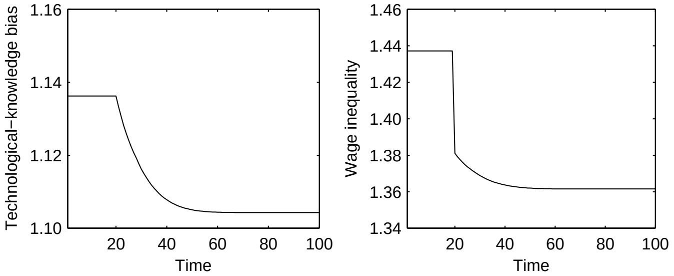

Figure 5: Variable-parameter simulation for the Belgium, 1985-1997.

Table 1 provides some additional calibration configurations, which replicate the real data for some developed countries: The Netherlands, Canada and the United States. These results prove that small variations in the learning-by-doing and technology-adoption parameters are enough to replicate a wide range of different situations with a relatively homogeneous set of parameters.

We can also replicate the trajectory of developing countries: a good example would be the Chilean case during 1960-1996. According to Beyer et al. (1999),

| Country | Initial $\frac{H}{L}$ | Final $\frac{H}{L}$ | Initial $\frac{w_H}{w_L}$ | Final $\frac{w_H}{w_L}$ | $\phi_1 = \phi_2$ | $l = h$ | new $\phi_1 = \phi_2$ | new $l = h$ |
|---|---|---|---|---|---|---|---|---|
| The Netherlands[a]<br>1983-1994 | 0.087 | 0.337 | 1.359<br>(1.354) | 1.305<br>(1.296) | $-0.7$ | 1.35 | $-0.5$ | 1.35 |
| Canada[a]<br>1987-1997 | 0.241 | 0.256 | 1.303<br>(1.299) | 1.379<br>(1.364) | $-0.3$ | 1.2 | $-0.35$ | 1.2 |
| The United States[b]<br>1973-1989 | 0.326 | 0.435 | 1.533<br>(1.578) | 1.623<br>(1.604) | $-0.75$ | 1.35 | $-0.75$ | 1.3 |

[a] Original country data is from Acemoglu (2003a). [b] Original country data is from Machin and van Reenen (1998).

Simulated skill premia are given in parentesis.

Table 1: Alternative simulations of transitional dynamics.

in 1960 around 7.5% of all heads of household in Chile had university education. By 1996 that number had risen to 21.1%. Taking these values as a proxy for the relative abundance of high-skilled labour in Chilean economy, the ratio $\frac{H}{L}$ shifted from 0.081 in 1960 to 0.267 in 1996. During the same period the ratio between wages of workers with university education (high-skilled labour) and without university education (low-skilled labour) increased from 3.740 to 3.941.[17]

Figure 6 illustrates the transitional dynamics by considering $c = 1.2$, $\phi_1 = \phi_2 = -1.55$ and the change in learning-by-doing parameters from $l = h = 1.45$ to $l = h = 1.3$.[18] The initial and ending simulated skill premia are, respectively, 3.639 and 3.975. Although the initial skill premium deviates moderately from its real value (about 3% lower), the strong increase of $\sigma_H$ and the light increase of $\sigma_L$ (due to the changes in $\frac{H}{L}$ and $l = h$) allow the simulation to satisfactorily accommodate the Chilean transitional dynamics (to a higher level of skill premium).

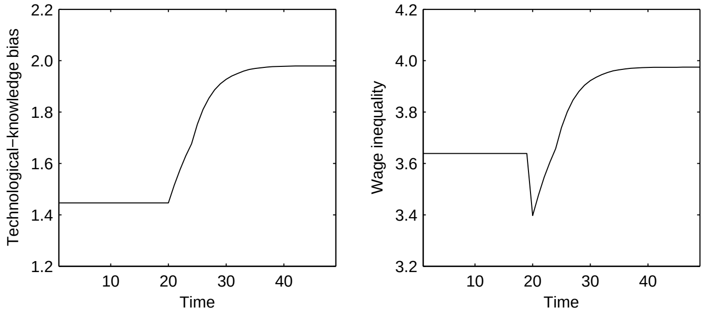

Figure 6: Variable-parameter simulation for the Belgium, 1985-1997.

These cases reinforce the idea that learning-by-doing and technology-adoption costs are important in understanding the evolution of wage inequality.

### 4.2 Effects of changes in core parameter values and/or in labour endowments

In this subsection, we analyse how changes in core parameters and/or in relative supply of high-skilled labour affect labour technological readiness, which in turn influence the technological-knowledge bias and the skill premium. Throughout these computations we consider $c = 1$, and once again that $l = h$ and $\phi_1 = \phi_2$.

First, we analyse the effects of changes in core parameter values considering fixed labour endowments. When learning-by-doing is more intense (i.e., $l = h$ are lower) and technology-adoption costs are higher (i.e., $\phi_1 = \phi_2$ are more

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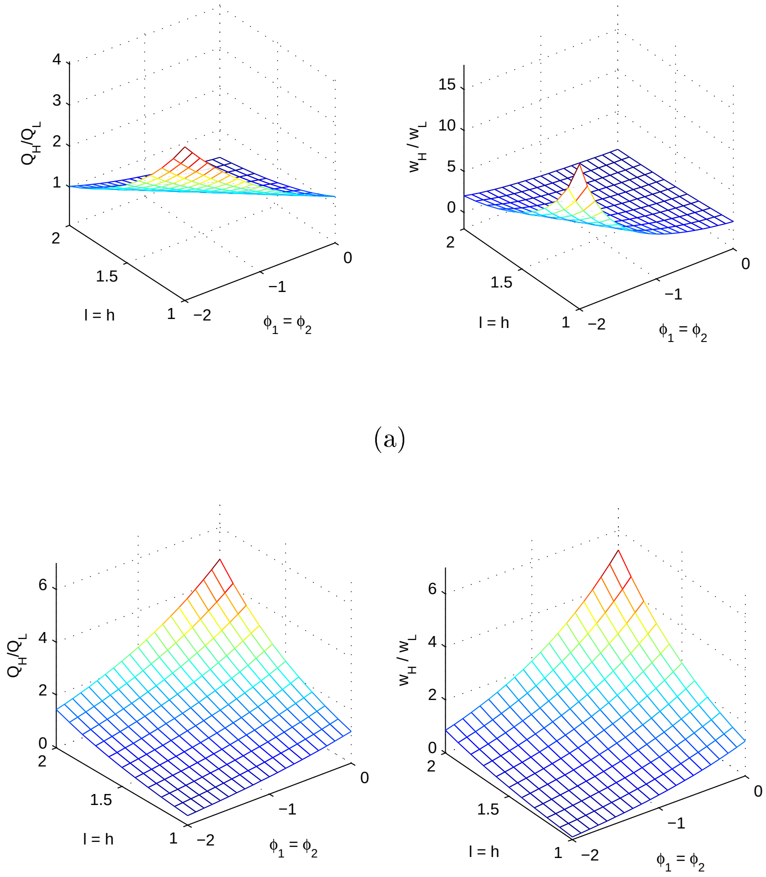
[17] The average per-capita labour income of heads of household (quoted in 1996 *pesos*) with a university degree increased from 176675 *pesos* in 1960 to 666813 *pesos* in 1996, whereas for heads of households without a university degree the average pay increased from 47234 *pesos* to 169220 *pesos*.

[18] Since learning-by-doing parameters decline, learning-by-doing effects become stronger.

negative), the steady-state levels of both technological-knowledge bias and skill premium are higher (lower) in case of relative abundance of low (high)-skilled labour – see, respectively, Figures 7a and 7b.[19]



(a)

(b)

Figure 7: The effects of learning-by-doing and technolocy-adoption costs.

For example, when low-skilled labour is relatively abundant, lower values for $l = h$ imply higher values for $L^l$ and $H^h$ and higher $\frac{H^h}{L^l}$.[20] That is, the increase in learning-by-doing and consequently in technological readiness is biased

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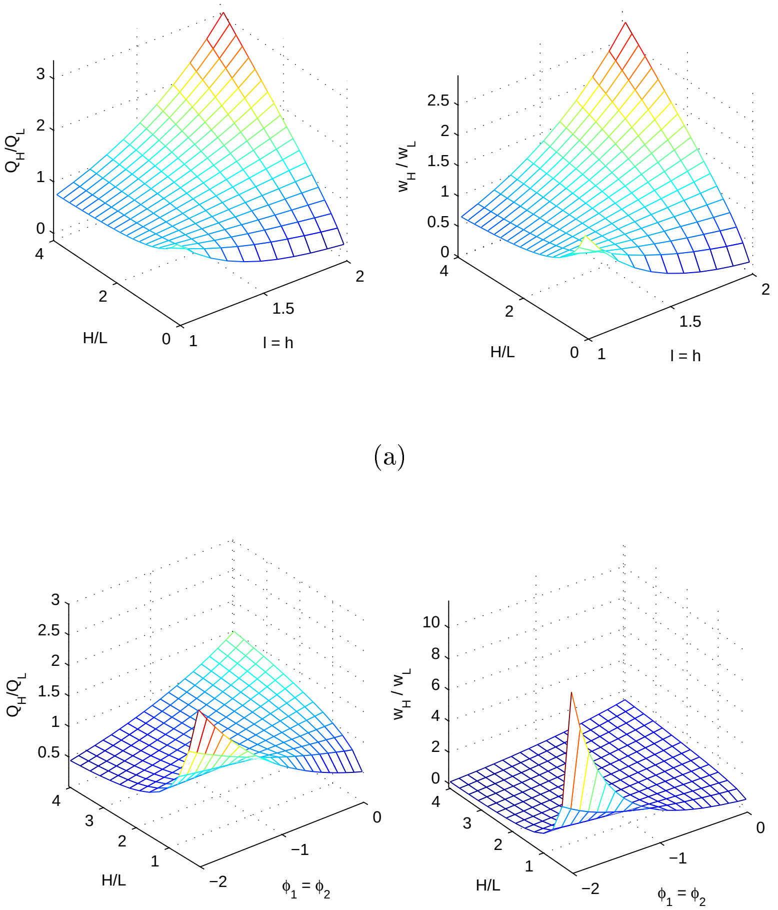
[19] Since $H + L = 1$ and $H, L \in [0, 1]$, we consider for relative abundance of low (high)-skilled labour $L = 0.8$ ($L = 0.2$) and $H = 0.2$ ($H = 0.8$), i.e., $\frac{H}{L} = 0.25$ $\left(\frac{H}{L} = 4\right)$.

[20] The same decrease in $l$ and $h$ from 1.3 to 1.1, for example, implies that: (i) $L^l$ shifts from 0.748 to 0.782; (ii) $H^h$ shifts from 0.123 to 0.170; (iii) $\frac{H^h}{L^l}$ increases from 0.165 to 0.218 as well as the ratio between the technological readiness of high and low-skilled labour.

towards high-skilled labour. As a result, the skill premium increases since the productivity ratio changes in favour of high-skilled labour and since it also becomes relatively more atractive to do R&D in high-specific intermediate goods – see equations (14) and (15) –, which increases $\frac{Q_H}{Q_L}$ (and thus $\frac{w_H}{w_L}$).



(a)

(b)

Figure 8: The interaction of the relative supply of skills with learning-by-doing and technolocy-adoption costs.

Considering once again relatively abundance of low-skilled labour, lower values for $\phi_1$ and $\phi_2$ also induce an increase in the skill premium. In this case, $\exp(\phi_1 L)$ and $\exp(\phi_2 H)$ decrease, but $\frac{\exp(\phi_2 H)}{\exp(\phi_1 L)}$ increases. On the one hand, since production factors are paid at their marginal productivity, the downward pressure on wages is stronger for low-skilled labour, increasing the skill premium. On the other hand, the stronger decrease in the technological readiness of low-skilled labour makes R&D in high-specific intermediate goods relatively more atractive – see equations (14) and (15) –, which leads to a higher $\frac{Q_H}{Q_L}$ (and thus $\frac{w_H}{w_L}$) – see equation (13).

In line with the previous discussion, we also observe that $\frac{Q_H}{Q_L}$ (and thus $\frac{w_H}{w_L}$) is higher in the presence of:

(i) higher $l = h$ and $\frac{H}{L}$ – see Figure 8a. In fact, when learning-by-doing parameters are high, the size of labour endowments is responsible for determining much of the (positive) learning-by-doing effects. Hence, the more abundant type of labour achieves greater learning-by-doing and this, in turn, benefits its relative technological readiness, productivity and wage.

(ii) lower $\phi_1 = \phi_2$ and $\frac{H}{L}$ – see Figure 8b. In this case, the adverse effect of technology-adoption costs is relatively smaller for high-skilled labour, which also enhances its relative technological readiness, productivity and wage.

# 5 Concluding remarks

In this paper we have proposed an endogenous growth model where individuals decide between consumption and savings on income allocation and where two productive technologies of perfectly competitive final goods are used. One combines low-skilled labour with a specific sets of (complementary) quality-adjusted intermediate goods and the other uses high-skilled labour complemented with a continuum of high-specific quality-adjusted intermediate goods. Labour endowments are linked with learning-by-doing and technology-adoption costs to measure the technological readiness of each type of labour. Intermediate goods, which are improved in the R&D sector, are produced in monopolistic competition. Technological readiness is connected with the direction of technological-knowledge progress and, thus, with wage inequality.

Our simulated results can be interpreted in comparison with previous literature about skill-biased technological change. In that literature, the bias that causes wage inequality is mainly induced through the market-size channel. In our case, the path of wage inequality is similarly influenced by the direction of technological-knowledge progress, but this direction, however, is strongly induced by the price channel under technological readiness of labour.

In contrast with the skill-biased technological change literature, the operation of the price channel under technological readiness of labour can accommodate the recent trends of relative high-skilled labour and wage inequality observed in developed and developing countries. That is, in view of an exogenous increase of the relative abundance of high-skilled labour, the skill premium always increases in the skill-biased technological change literature; and in our model, it either increases or decreases.

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