Tradable and nontradable directed technical change

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We wish to reconcile the major trends in wages and the terms of trade using a directed technical change approach in which: (i) tradable and nontradable goods can be substitutes or complements; and (ii) scale effects can be present or can be partially or totally removed. With a lower skilled labor ratio and a higher relative wage in the tradable sector, the price (real exchange rate or terms of trade) mechanism is crucial in determining sectoral productivity differences and thus wage inequality. Along the balanced growth path (BGP), the real exchange rate can be negatively related with the relative advantage to entry through horizontal innovation and with the relative labor level, depending on scale effects. The wage premium increases due to an increase in the relative labor level in the nontradable sector under substitutability with scale effects or under complementarity without scale effects. A calibrated version of the model indicates that the model replicates closely the data on wages for Germany. Moreover, as substitutability increases, the nontradable technological-knowledge bias, which drives wages, rises, while the nontradable relative price and nontradable value of knowledge decrease.

Keywords: Directed technological change; substitutability; scale effects; relative prices; wage premium; economic growth.

JEL Classification: O30, O41, J31.

1 Introduction

The past decades have witnessed some major trends regarding unskilled versus skilled wage inequality in developed and newly industrialized developing countries: rise in wage inequality in favor of skilled labor (the usual intra-country wage inequality or skill-premium measure), rise in the proportion of skilled labor, and strong technological-knowledge progress (e.g., Acemoglu 1998, 2002, 2008). These trends are concomitant with the evidence supporting the result of the Balassa (1964)-Samuelson (1964) model, which states that price level differences between

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countries – real exchange rates (or terms of trade) – can be ascribed to productivity differentials between nontradable/domestic (facing no foreign competition) and tradable sectors (facing foreign competition) – e.g., De Gregorio and Wolf (1994), MacDonald and Ricci (2007): relatively higher productivity growth in tradable sectors tends to increase the relative price of nontradable goods – a real exchange rate appreciation occurs. We wish to reconcile these major trends in wages and in the terms of trade using a tradable and nontradable directed technical change approach.

Our model considers the division of the economy into nontradable and tradable sectors. That is, in a context with different degrees of substitutability between the labor level employed in the nontradable sector and in the tradable sector as well as with distinct intensity of scale effects, we seek to understand the impact of the allocation of labor levels between both sectors on: (i) relative prices; i.e., on the real exchange rate; (ii) the wage gap between sectors; and (iii) the economic growth rate. To our knowledge there have been no similar comprehensive studies that contribute to the theoretical debate on both relative prices and wage differential between tradable and nontradable sectors, or on economic growth in a context as flexible as the one proposed.

With this goal we develop a directed technical change endogenous growth model with two sectors, tradable and nontradable, in which the unique final good is produced by combining tradable and nontradable final goods. Researchers build on the R&D productivity by discovering new intermediate goods to be used in each sector and on the flow of devoted resources; as a result, profit maximizing researchers direct their effort to increase the quantity of intermediate goods to be used in one sector. Thus, our model highlights the central roles played by the market-size channel and the price channel on the direction of technical change (Acemoglu 1998, 2002): the former channel encourages innovation toward the sector with larger market, and the latter channel directs innovation toward the sector with higher price. The relative importance of both channels is determined by five factors: (i) the relative labor levels of both sectors;[1] (ii) the relative importance of both sectors in the production of the unique final good; (iii) the elasticity of substitution between sectors; (iv) the relative advantage to entry through horizontal innovation in one sector, based on the relative R&D productivity; and (v) market complexity effect in R&D activities; i.e., the degree of scale effects by considering that the difficulty of introducing new products and replacing old ones depends on the market size. That is, we aim at understanding the ways in which each factor, (i)-(v), affects the directed technical change in contexts with flexible scale effects.

It has long been acknowledged that prices of final (consumer) goods differ across countries and, since the tradable sector competes internationally, tradable-goods prices tend to be equalized across countries. In the long run, as is usually assumed by the economic growth models, countries have balanced external accounts, tradable goods in different countries are perfect substitutes for one another, and cross-country differentials in prices are exclusively generated by differences in nontradable goods, as observed by, for example, Berka and Devereux (2010, 2013) in European Union countries. In the aggregate, inter-country relative goods-prices are defined as real exchange rates and understanding their determination remains an important and difficult question in Economics.

The above-mentioned Balassa-Samuelson model, which also considers tradable goods in different countries as perfect substitutes, is the main theoretical framework for interpreting movements in real exchange rates. Its popularity comes from the widespread observation that the relative price of nontradable goods tends to be higher in developed countries (e.g., Heston and Summers, 1991) and derives from sectoral productivity differentials (e.g., MacDonald and Ricci, 2007). Despite the simplicity, the model does not do well in explaining real exchange rates since the

[1] We regard the independence between the labor employed in the nontradable sector and in the tradable sector as mainly instrumental to the isolation of "pure" directed technical change effects.

mechanism for the effect of productivity growth on real exchange rates is quite weak (e.g., Rogoff, 1996; Lothian and Taylor, 2008; Chong et al., 2012). We conjecture that the productivity mechanism is particularly induced by the bias of the technological-knowledge progress. Nonetheless, in line with the *LeChatelier* principle, after the adjustment of the technological-knowledge bias, the response of the relative price of nontradable goods becomes dependent on: (i) the relative advantage to entry through horizontal innovation into the nontradable sector, (ii) the relative supply of labor into the nontradable sector, (iii) the elasticity of substitution between sectors, and (iv) the degree of scale effects.

The directed technical 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 triggers an increase in the relative demand of skilled workers that exceeds the increase in the relative supply, thereby increasing the skill premium. Acemoglu (1998, 2002, 2008) and Acemoglu and Zilibotti (2001) further enhance this literature by considering that technological-knowledge change responds to shifts in labor levels. When the supply of a type of labor – skilled or unskilled – increases, the market for technologies that complement it broadens, which creates additional incentives for R&D aimed at those technologies. Hence, technological-knowledge change steers toward those technologies, which in turn increases the demand for the complementary labor type. Thus, these recent contributions interpret the rise in the skill premium as a direct consequence of the increase in the relative supply of skilled labor.

Some empirical evidence seems to contradict the explanation proposed by the technological-knowledge bias hypothesis, however. In fact, despite the generic paths for wages and skills, Acemoglu (2003), 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. Nevertheless, by stressing the market-size effect on technological-knowledge change, the directed technical change literature has contradicted the dominant literature on scale effects since Jones (1995a, b). In line with this literature, our endogenous R&D growth model is then very flexible in relation to the scale effects.

We go further and to some extent, we accommodate the point of view of Krugman (2008) and Helpman et al. (2009), among others, who consider wage differentials between exporters and other firms contribute to rising inequality. Also deserving mention is the paper of Erosa et al. (2010), who devise a two-sector (also tradable and nontradable) model with heterogeneous agents to explain wage inequality in the United States (USA). The focus of their paper is to explore the decisions of individual families in the investment in human capital. In opposition to them, we focus on the technological-knowledge bias to explain wage inequality. Additionally, we also concentrate on the explanation of the real exchange rate, and accommodate different possibilities concerning the elasticity of substitution and the scale effects such that our model applies more generally to countries other than the USA.

Most commonly, the tradable sector consists largely of sectors of the manufacturing industry, while the nontradable sector consists of locally-rendered services, including government, health care, hospitality, food service, education, retail, and construction.[2]

Our paper is thus related to many strands of the literature, which are followed and to which it contributes. These strands include the aforementioned literatures on relative prices or real

[2]As Zeugner (2013, p. 5, fn: 5) points out "The AMECO database conventionally classifies the NACE setors A_E, G_I (agriculture and fishing, mining and utilities, manufacturing, trade, hotels, communications) as tradable, while setors F, J_P (construction, finance and business services, market services, other service activities) are considered as nontradable." Table 1 systematizes this classification.

Tradable Sector	Nontradable Sector
Agriculture and fishery	Construction
Mining and Quarrying	Real Estate
Manufacturing	Finance
Trade	Public Services
Hotels	
Transports	

Table 1: Tradable and nontradable sectors. Source: AMECO Database (Zeugner, 2013).

exchange rate and on directed technical change, (but) between tradable and nontradable sectors, and its relation to the wage inequality, along with the literature on substitutability/complementarity between sectors and on scale effects.

Some general results are emphasized concerning the relative price of the nontradable sector, the relative wage of the nontradable sector (wage premium), and the economic growth rate.

The relative price of the nontradable sector – "the real exchange rate" – accommodates the Balassa-Samuelson hypothesis, which states that price level differences between countries can be attributed to different productivity differentials between sectors, represented by the technological-knowledge bias. Along the balanced growth path (BGP), after the adjustment of the technological-knowledge bias, the real exchange rate is negatively related with: (i) the relative advantage to entry through horizontal innovation in the sector, which in a way now reflects the Balassa-Samuelson hypothesis; and (ii) the relative labor level in the sector, but just when scale effects are present or are only partially removed.

An increase in the relative labor level in the nontradable sector increases the wage premium when, under substitutability, the scale effects are present or when, under complementarity, the scale effects are removed. In those cases, the market-size channel commands the chain of effects and the labor-level effect on the technological-knowledge bias, which drives the wage-premium dynamics, dominates the immediate direct effect induced by the relative supply. The wage premium can also be independent of the relative labor level, which occurs when, under the dominance of the market size (price) channel, the substitutability (complementarity) has particular values. In all other cases, the price channel dominates the chain of effects, such that in view of, for example, an increase in the relative supply of labor in the nontradable sector, the relative price of the sector decreases, which discourages R&D activities in this sector, biasing the technological-knowledge in favor of the other, and generating a decrease of the wage premium. Moreover, the wage premium is positively related with the relative importance of the nontradable sector in the production of the final good and, under substitutability, with the relative productivity of developing intermediate goods for the nontradable sector.

The remainder of the paper is organized as follows. Section 2 presents some empirical motivation for the use of the directed technical change approach to study the relationship between wages and sectoral composition between tradable and nontradable goods. Section 3 deals with the set-up of the model and solves for the equilibrium. Section 4 evaluates the sensitivity of the main macroeconomic ratios of the model to variations in the scale effects and in the elasticity of substitution between tradable and nontradable sectors. Section 5 concludes.

Country	Tradable Sector	Nontradable Sector
The United States	0.29	0.88
Canada	0.32	1.24
Germany	0.37	1.36
France	0.51	0.93
Italy	0.23	1.00
Spain	0.25	0.88
Portugal	0.19	0.66
Belgium	0.42	1.13
The Netherlands	0.35	1.48
Japan	0.30	1.15
The UK	0.34	0.89

Table 2: Skilled-unskilled labor ratio. Source: ILOsta (www.ilo.org) Database, simple annual average based on years with available data for each country. See footnote 2 for definitions.

2 Empirical Motivation

Strauss and Ferris (1996) showed (using data from 1970 and 1990) that (i) productivity is higher in the tradable than in the nontradable sector, (ii) real wage growth is higher in the tradable sector than in the nontradable sector; and (iii) productivity growth is highly related to wages growth. Adding to this, in order to motivate the use of a directed technical change framework, we collected data for labor and human capital endowments for tradable and nontradable sectors and the overall conclusion is that the nontradable goods sector is more skill-intensive than the tradable goods sector. Examining years with data available between 1997 and 2008 from the Laborsta database, we are able to evaluate the skilled and unskilled workers in tradable and nontradable sectors.[3] Then, by considering 11 developed countries (Germany, Belgium, Canada, Spain, the USA, France, Italy, Japan, Netherlands, Portugal, and the UK);[4] i.e., countries with greater data availability, we observe that the tradable sector has more unskilled-labor intensive workers, while the nontradable sector is more skilled-labor intensive. Table 2 details this information on the skilled/unskilled labor ratio in both sectors.

With a lower skilled labor ratio in the tradable sector in most countries, the application of the directed technical change framework would point to the price mechanism as the main one in determining productivity differences between sectors if the wage ratio is higher in the tradable sector, which would be according to the removal of the scale effects advocated by empirical studies such as Jones (1995b) and Laincz and Peretto (2006). This suggests that the real exchange rate (or the terms of trade) should be crucial in explaining the higher relative skilled labor force. However, if the wage ratio is lower in the tradable sector, the market-effect

[3] We consider the set for tradable and nontradable sector, following the AMECO approach (Zeugner, 2013) – see Table 1. The Laborsta database is available online at (accessed for the first time in December 2013) http://laborsta.ilo.org/data_topic_E.html and evaluates workers from level 1 (the most skilled level) to level 9 (the most unskilled level): level 1 "legislators, senior officials and managers", level 2 "professionals", level 3 "technicians and associate professionals", level 4 "clerks", level 5 "service workers and shop and market sales workers", level 6 "skilled agricultural and fishery workers", level 7 "craft and related trade workers", level 8 "plant and machine operators and assemblers" and level 9 "elementary occupations". We have considered levels 1, 2, and 3 as skilled levels, and levels 4, 5, 6, 7, 8, and 9 as unskilled levels.

[4] We have also collected data for other countries and the conclusion remains: the nontradable sector is more skilled than the tradable sector.

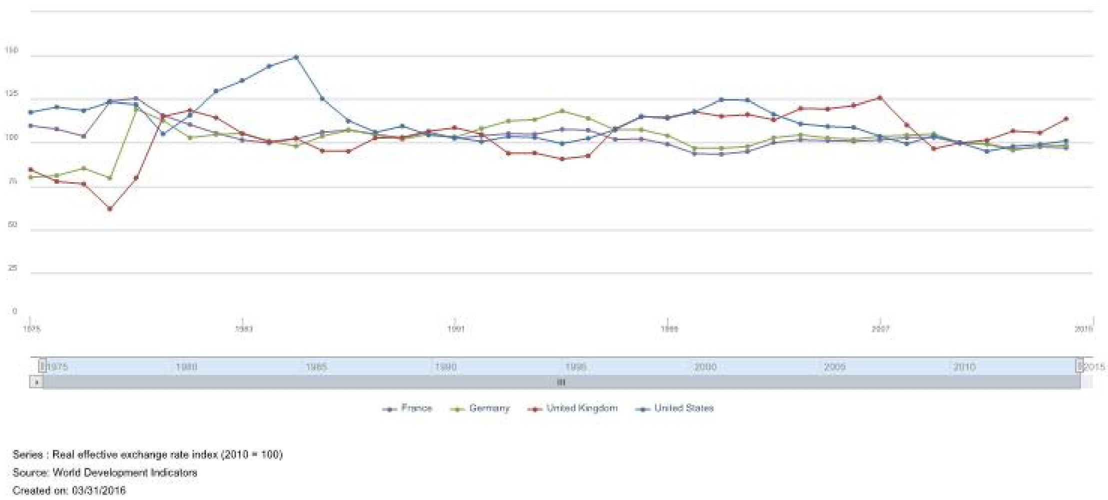

Figure 1: Evolution of the real exchange rate in different countries between 1975 and 2015.

should be also important. Therefore, the model encompasses several outcomes on the relative importance of the price and the market-size channels and thus can also be applied to different countries with different sectoral and wage structures. As the evolution of the real exchange rate varies between different historical periods in a given country and also varies between different countries (see Figure 1), the effect of real exchange rates on wage inequality may be dependent on other features of the model, which will be considered further in the next Section.

3 Theoretical model

This section describes the economic set-up, emphasising the interactions among economic agents, and the dynamic general equilibrium in which (i) households and firms are rational and solve their problems, (ii) free-entry R&D conditions are met, and (iii) markets clear. We start by considering the optimizing behavior of the infinitely-lived households that inelastically supply labor, maximize utility of consumption, and invest in the firm's equity. Then, we describe the productive side, stressing the maximization problem facing final-good firms, intermediate-good firms, and R&D firms.

The inputs of the aggregate (composite, homogenous, or consumption) final good (or numeraire) are two intermediate final goods, each composed of a large number of competitive firms: one is produced in the tradable sector (T-sector) and the other produced in the non-tradable or domestic sector (D-sector), and each uses specific labor and a continuum of specific non-durable intermediate goods. Each intermediate-goods sector consists of a continuum of industries, $j \in [0, N_j(t)]$, $j = T, D$, and there is monopolistic competition if we consider the whole sector: the monopolist in industry j uses a design, sold by the R&D sector (domestically protected by a perpetual patent), and aggregate final good to produce a non-durable intermediate good at a price chosen to maximize profits. That is, imperfectly competitive firms buy designs (technological knowledge) in the R&D sector to produce intermediate goods, which can complement the inputs used by perfectly competitive final-goods firms in either the T-sector or the D-sector. Therefore, the relative productivity of the technological knowledge depends on the sector in which it is employed. In the perfectly competitive R&D sector there is free entry and each potential entrant devotes aggregate final good to produce/invent successful horizontal designs, which are then supplied to a new (monopolist) firm in a new intermediate-goods industry; i.e., the R&D sector allows increasing the number of intermediate-goods industries $N(t)$ and thus the technological knowledge.

3.1 Technology and preferences

The economy is populated by a fixed number of infinitely-lived households that consume and collect income from investments in financial assets (equity) and from labor. Households inelastically supply labor to two final-goods sectors: the tradable (T-sector), L_T, and nontradable (D-sector), L_D. Thus, total labor supply, $L_T + L_D$, is exogenous and constant. We assume that consumers have perfect foresight concerning the technological-knowledge change over time, $\frac{\dot{N}_j(t)}{N_j(t)}$, $j = T, D$, and choose the path of final-good aggregate consumption $[C(t)]_{t \geq 0}$ to maximize discounted lifetime utility $U = \int_0^{\infty} \left(\frac{C(t)^{1-\theta} - 1}{1-\theta} \right) e^{-\rho t} dt$, where $\rho > 0$ is the subjective discount rate, ensuring that $U(.)$ is bounded away from infinity if C were constant over time, and $\theta > 0$ is the inverse of the intertemporal elasticity of substitution, subject to the budget flow constraint $\dot{a}(t) = r(t) \cdot a(t) + w_T(t) \cdot L_T + w_D(t) \cdot L_D - C(t)$, where a denotes households' real financial assets holdings and w_j is the wage for labor employed in the final j-sector. The initial level of wealth $a(0)$ is given and the non-Ponzi games condition $lim_{t \to \infty} e^{-\int_0^t r(s) ds} a(t) \geq 0$ is imposed. The optimal consumption path Euler equation,

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

and the transversality condition, $\lim_{t \to \infty} e^{-\rho t} \cdot C(t)^{-\theta} \cdot a(t) = 0$, are standard. The aggregate financial wealth held by households comprises equity of intermediate goods producers $a(t) = a_T(t) + a_D(t)$, where $a_j(t) = N_j(t) V_j(t)$, $j = T, D$, where, remember, N_j is the number of available types of intermediate goods and thus the technological-knowledge frontier in each j-sector, and V_j is the present value of monopoly profits seized by each intermediate good producer – see the analysis below. Taking time derivatives and comparing with the budget flow constraint above, the aggregate budget flow constraint is equivalent to the final product market equilibrium condition

$$Y(t) = C(t) + X(t) + Z(t) \tag{2}$$

where $Y(t)$ is the aggregate final good (or numeraire), $X(t)$ is the total investment in production of intermediate goods, and $Z(t)$ are the aggregate R&D expenditures. Hence, implicitly, we consider that eventual international exchanges of tradable goods are always balanced or, more generally, that there are "internal balance" (demand for nontradables equals the respective supply) and "external balance" (trade account is zero), which must be true in the long run. Moreover, we assume that international capital flows do not occur – i.e., the domestic interest rate is determined domestically – and that international mobility of labor is also not possible. Final-good producers are competitive and Y is produced with a CES aggregate production function of tradable and nontradable final goods:

$$Y(t) = \left[\chi_T Y_T(t)^{\frac{\varepsilon - 1}{\varepsilon}} + \chi_D Y_D(t)^{\frac{\varepsilon - 1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon - 1}}, \quad \varepsilon \in (0, +\infty), \tag{3}$$

where: Y_T and Y_D are the total outputs of the T-sector and the D-sector, respectively (i.e., the intermediate final goods); χ_T and χ_D, with $\chi_T + \chi_D = 1$, are the distribution parameters, measuring the relative importance of the inputs; $\varepsilon \geq 0$ is the elasticity of substitution between the two inputs in the production of the aggregate final good, wherein $\varepsilon > 1$ ($\varepsilon < 1$) means that the inputs from the sectors T and D are gross substitutes (complements) in the production of Y.[5] Without loss of generality, we normalize the price of the aggregate final good at unit, $P_Y \equiv 1$.[6] Thus, $P_Y \equiv 1 = \left[\chi_T^{\varepsilon} P_T^{1-\varepsilon} + \chi_D^{\varepsilon} P_D^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}}$, where, since P_T and P_D are the prices of the outputs of, respectively, the T-sector and the D-sector, the right hand side of the expression is the unit cost of production. This normalization and the assumption of competitive final-good firms imply the following maximization problem: $Max\,\Pi = Y - P_T Y_T - P_D Y_D$. From the first-order conditions, we obtain the following expression for the relative price of the D-sector in terms of the T-sector, which can be labelled as "a real exchange rate":[7]

$$\frac{P_D}{P_T} = \frac{\chi_D}{\chi_T}\left(\frac{Y_D}{Y_T}\right)^{-\frac{1}{\varepsilon}}, \tag{4}$$

which is the usual relative inverse demand curve that, as expected, has a negative slope. Hence, the relative price of the D-sector is a decreasing function of the relative output of the sector, $\frac{Y_D}{Y_T}$. Moreover, the relative importance of the D-sector's output, $\frac{\chi_D}{\chi_T}$, which serves as an input in final-good production, makes the relative price higher.

Concerning the output of each intermediate final-goods sector, we consider that the output of the j-sector, $j = T, D$, is produced with specific labor, L_j, and a continuum set of domestically available complementary non-durable differentiated intermediate goods x_j in the interval $(0, N_j]$. That is, each set of intermediate goods complements either type of labor, not both. In particular, we presume that L_D is relatively more school intensive since the nontradable sector includes real estate, finance and public services (see Table 1), while L_T is relatively more on-the-job-training intensive since the tradable sector includes agriculture and fishery, mining and quarrying, manufacturing, trade, hotels and transports (see Table 1). Intuitively, we assume that schooling helps in working with intermediate goods in the nontradable sector more than on-the-job-training does, and vice-versa.[8] In order to solve the model analytically, we use the Dixit-Stiglitz constant elasticity structure for production in the intermediate final-goods sector:

[5]When $\varepsilon = 0$ there is no substitution between Y_T and Y_D, and the production function is Leontieff. When $\varepsilon = 1$ the production function is Cobb-Douglas. When $\varepsilon = +\infty$, Y_T and Y_D are perfect substitutes, and the production function is linear. As we shall see later, this parameter plays a central role in our analysis. There is a vibrant discussion in the literature on the estimated value, looking at the elasticity of substitution between domestic and foreigh goods. Some examples, using the US data, include Blonigen and Wilson (1999) – average value of 0.81 –, Feenstra et al. (2014) – with elasticities ranging from approximately 0.88 to 4 –, Acemoglu and Ventura (2002) – average value of 2.60 –, Gallaway et al. (2003) – average value for macro elasticities of 1.55 –, Broda and Weinstein (2006) and Epifani and Gancia (2009) – have estimated ε, respectively, in the intervals 2.7-3.6 and 2.2-2.6. Moreover, for the European Monetary Union, Rabanal and Tuesta (2013) present values that range between 0.13 and 1.

[6]To simplify notations we suppress the time argument t and will do so throughout as long as this causes no confusion.

[7]It is a measure of the real exchange rate between intermediate final goods sectors since it evaluates how one unit of the T-sector exchanges for a unit of the D-sector. Since the eventual international trade is assumed to be balanced and, under international trade, P_T should be common in all countries, whereas P_D generally differs across countries, the ratio $\frac{P_D}{P_T}$ is indeed "the real exchange rate".

[8]That is, since in reality workers perform very different tasks in D-sector and T-sector, we will treat these two types of labor as distinct, and assume, also in accordance with reality, that shooling (on-te-job-training) skills are employed relatively more intensively in the D-sector (T-sector). In a certain sense we can say that we are in line with Grossman and Shapiro (1982), Grossman and Helpman (1991, chp. 5 and 6), Mincer (1993), Van Zon and Antonietti (2004) and Hassler and Rodriguez-Mora (2000).

$$Y_j = A \cdot L_j^{\alpha} \cdot \int_0^{N_j} x_j(n)^{1-\alpha} dn,\ j = T, D, \tag{5}$$

where: A is a positive exogenous variable representing the level of productivity, dependent on the country's institutions; $1-\alpha$ and $\alpha \in [0,1]$ are the intermediate-goods and the labor shares, respectively; N_T and N_D represent the number of already available intermediate goods, which measure the technological knowledge and can be interpreted as the extent of specialization (e.g., Gancia and Bonfiglioli, 2008); i.e., the former (latter) increases the productivity of L_T (L_D) and hence the output of the T-sector (D-sector). The maximization problem facing the firms in the j-sector is $Max\, P_j Y_j - w_j L_j - \int_0^{N_j} P_{x_j}(n) x_j(n) dn,\ j = T, D$, where P_{x_j} is the price of the j-sector (labor complementary) intermediate good and w_j is the wage paid for L_j.[9] From the first-order conditions results:

$$w_j = P_j \cdot \alpha \cdot A \cdot {L_j}^{\alpha-1} \cdot \int_0^{N_j} x_j(n)^{1-\alpha} dn = \alpha \frac{P_j Y_j}{L_j},\ j = T, D, \tag{6}$$

$$P_{x_j}(n) = P_j \cdot {L_j}^{\alpha} \cdot x_j(n)^{-\alpha} \Rightarrow x_j(n) = \left(\frac{P_j}{P_{x_j}(n)} \right)^{\frac{1}{\alpha}} L_j,\ j = T, D. \tag{7}$$

From (6) the wage paid for the labor employed in a particular sector is equal to the value of the respective marginal contribution to the production in the sector.[10] In turn, in (7), we have the demand for the n-type intermediate good used in each sector, T and D, which depends on three factors: (i) the price of the respective output, P_T or P_D, since the greater the price of the output the higher the demand for n; (ii) the price of the intermediate good, $P_{x_T}(n)$ or $P_{x_D}(n)$, since the demand for n is a decreasing function of its own price; and (iii) the respective employed labor level, L_T or L_D, since the larger the labor level, the greater is the demand for n, given that larger supply of labor raises the productivity of n, thereby increasing its demand.

We need to look now at the profit maximization problem facing intermediate-good firms. Once the intermediate-good firm has a new design, sold by the R&D sector, it can retain a perpetual monopoly over the use of this design. The production of one intermediate good requires η units of the aggregate final output. Thus, the flow of the monopolist's operational profit, which sells its good to the j-sector, at a point in time, is $\pi_j = \left[P_{x_j}(n) - \eta \right] \cdot x_j(n),\ j = T, D$, and the present value of the returns from the operation is $V_j = \int_t^{\infty} \pi_j(v) \cdot e^{-\int_t^v r(\omega) d\omega} dv,\ j = T, D$, where r is the interest rate. Hence, the monopolist facing the demand curve (7) solves the following problem:

$$max \int_t^{\infty} \left[P_{x_j}(v) - \eta \right] \cdot x_j(v) \cdot e^{-\int_t^v r(\omega) d\omega} dv,\ j = T, D, \tag{8}$$

and reaches:

$$P_{x_T}(n) = P_{x_D}(n) = P_x = \frac{\eta}{1-\alpha} = 1, \tag{9}$$

by considering, as Acemoglu (2002), that $\eta = 1 - \alpha$, which simplifies the notation without any loss of generality. Hence, the profit maximizing price of intermediate goods is equal to one unit of the aggregate final good, implying that one unit of intermediate good employed by either sector is exchanged one for one with the aggregate final good. Indeed, the isoelastic nature of the demand for n implies that each monopolist sets a constant markup over the marginal cost:

[9] Since the (labor complementary) intermediate goods depreciate fully after use, the optimizations for the j-sector, $j = T, D$, are static.

[10] The result about wage setting follows from basic microeconomic principles on the assumption that the labor market is competitive.

$1 > \eta$ since $\alpha \in [0,1]$. Thus, regardless of the employed sector, each monopolist charges the same price, produces the same amount, and has the same profit at every period, and therefore the present value of the monopoly operational profit is the same for each firm.

Before the introduction of the R&D sector to consider endogenous technological knowledge, we analyze the productive equilibrium under constant technological knowledge. We begin by substituting the equilibrium price of intermediate goods in (9) into the intermediate-goods demand functions in (7), yielding:

$$x_j(n) = P_j^{\frac{1}{\alpha}} \cdot L_j,\ j = T, D. \tag{10}$$

As expected, the equilibrium intermediate-goods demand functions in (10) imply that the equilibrium demanded quantities do not depend on the identity of the intermediate good. What matters is the sector's output price and labor level in which the intermediate good is used. As a result, profits are also independent of intermediate-goods variety. Substituting (10) into the flow of the monopolist's operational profit gives:

$$\pi_j = \alpha \cdot P_j^{\frac{1}{\alpha}} \cdot L_j,\ j = T, D. \tag{11}$$

Bearing also in mind (10), the equation (5) can be written as:

$$Y_j = P_j^{\frac{1-\alpha}{\alpha}} \cdot A \cdot L_j \cdot N_j,\ j = T, D, \tag{12}$$

which indicates that the equilibrium quantity produced in each intermediate final-goods sector depends positively on the sector's (i) output price, P_T or P_D, (ii) labor level, L_T or L_D, (iii) technological-knowledge level, N_T or N_D, as well as on (iv) the exogenous productivity, A. We interpret the aggregate tradable output, Y_T, as a continuum mass of tradable varieties indexed by $u \in [0,1]$; i.e., $\underbrace{Y_T = P_T^{\frac{1-\alpha}{\alpha}} \cdot A \cdot L_T \cdot N_T}_{From\ equation (12)} \equiv \left[\int_0^1 Y_{Tu}^{\frac{\varrho-1}{\varrho}} du\right]^{\frac{\varrho}{\varrho-1}}$. As $\left[\int_0^1 Y_{Tu}^{\frac{\varrho-1}{\varrho}} du\right]^{\frac{\varrho}{\varrho-1}}$ is a CES function, the optimal price is $P_{Tu} = P_T$. Moreover, assuming, as in Gancia and Bonfiglioli (2008) and Gancia et al. (2013), that countries have different tradable factor endowments and that tradable varieties Y_{Tu} require specific factor endowments, each country will then produce the varieties according to the respective abundance of endowments. Thus, and for simplicity reason, Y_T denote the set of u tradable varieties produced, which require and employ specific labor L_T,[11] and, under free trade, the price $P_{Tu} = P_T$ is worlwide. Now, from (12) and (4), the relative price of the D-sector (a real exchange rate) can be rewritten as:

$$\frac{P_D}{P_T} = \left[\left(\frac{\chi_D}{\chi_T}\right)^{\varepsilon\alpha} \left(\frac{L_D \cdot N_D}{L_T \cdot N_T}\right)^{-\alpha}\right]^{\frac{1}{1+\Omega}}, \tag{13}$$

where $1+\Omega$, with $\Omega \equiv (\varepsilon - 1)\,\alpha$, is the elasticity of substitution between the two (tradable and nontradable) intermediate final goods in the aggregate final good production; in fact, $1+\Omega > 1$ only occurs when $\varepsilon > 1$. From (13), the relative price of the D-sector intermediate input depends: (i) positively on the relative importance of the D-sector intermediate input in the production of the aggregate final good, $\frac{\chi_D}{\chi_T}$; (ii) negatively on the relative supply of L_D, $\frac{L_D}{L_T}$, and on the technological-knowledge bias between sectors, $\frac{N_D}{N_T}$.

Fact. *Thus, equation (13) accommodates the Balassa-Samuelson hypothesis, which states that price level differences between countries can be ascribed to different productivity differentials between nontradable and tradable sectors (e.g., MacDonald and Ricci, 2007), induced by the bias*

[11] Remember that to keep things as simple as possible, we assume that L_T is on-the-job-training intensive, while L_D is school intensive.

of the technological-knowledge progress, $\frac{N_D}{N_T}$. Since under our context of balanced international trade, P_T is worldwide and only P_D can differ across countries,[12] *the real exchange rate, $\frac{P_D}{P_T}$, tends to be higher in countries whose tradable sector has higher productivity than the domestic sector; indeed, ceteris paribus, $\frac{P_D}{P_T}$ depends positively on N_T.*

To reach the relative wage of the nontradable sector (wage premium); i.e., the intra-country wage inequality measure, $\frac{w_D}{w_T}$, with constant technological knowledge, equations (12) and (13) should be substituted into (6):

$$\frac{w_D}{w_T} = \left[\left(\frac{\chi_D}{\chi_T} \right)^{\varepsilon} \left(\frac{L_D}{L_T} \right)^{-1} \left(\frac{N_D}{N_T} \right)^{\Omega} \right]^{\frac{1}{1+\Omega}}, \tag{14}$$

and thus the wage premium depends: (i) positively on $\frac{\chi_D}{\chi_T}$ and on $\frac{N_D}{N_T}$ if $\varepsilon > 1$; and (ii) negatively on $\frac{L_D}{L_T}$ and on $\frac{N_D}{N_T}$ if $\varepsilon < 1$.

By combining (11) and (13), the equilibrium expression for the relative profitability between the two intermediate final goods is:

$$\frac{\pi_D}{\pi_T} = \left[\left(\frac{\chi_D}{\chi_T} \right)^{\varepsilon} \left(\frac{L_D}{L_T} \right)^{\Omega} \left(\frac{N_D}{N_T} \right)^{-1} \right]^{\frac{1}{1+\Omega}}, \tag{15}$$

and thus it depends: (i) positively on $\frac{\chi_D}{\chi_T}$ and on $\frac{L_D}{L_T}$ if $\varepsilon > 1$; and (ii) negatively on $\frac{N_D}{N_T}$ and on $\frac{L_D}{L_T}$ if $\varepsilon < 1$.

3.2 Directed technological change

We now analyze how the results of the model are affected by considering that the rate and the direction of the technological knowledge are both endogenous. In the perfectly competitive R&D sector there is free entry and each potential entrant devotes aggregate final good to produce a successful design, which is protected by a system of patents and allows the introduction of a new intermediate good; i.e., a new firm in a new industry n. This new variety complements either L_T or L_D, but not both; i.e., we adopt a horizontal lab-equipment R&D specification (e.g., Acemoglu, 2002). Hence, innovations that complement the resource and the manufacturing sectors evolve over time according to the following equation of motion:

$$\dot{N}_j(t) = \sigma_j \cdot Z_j(t) \cdot L_j^{-\delta}, \; j = T, D, \tag{16}$$

where, as already stated, σ_j is the productivity of the R&D activity in j-sector and we assume that $\sigma_T > \sigma_D$ due to strong positive international technology linkages on R&D performance in the T-sector;[13] thus, $\frac{\sigma_D}{\sigma_T} < 1$ can be interpreted as a measure of relative advantage to entry through horizontal innovation into the D-sector. Moreover, Z_j is the flow of aggregate final-good resources devoted to R&D directed at discovering a new intermediate good to be used in the j-sector. Thus, total R&D expenditure, Z, satisfies $Z = Z_T + Z_D$, and $Z_j(t) = \frac{\dot{N}_j(t)}{\sigma_j \cdot L_j^{-\delta}}$. Finally, given that scale effects are often considered implausible (e.g., Jones, 1995a, b), $L_j^{-\delta}$, $\delta \geq 0$, implies that an increase in market scale, measured by L_T or L_D, dilutes the effect of R&D outlays on the

[12] In accordance with this view, Berka and Devereux (2010, 2013) should be recalled. These authors show that for European Union countries, differentials in prices are generated exclusively by differences in nontradable goods.

[13] The international technology linkages are channeled through, for example, communication patterns and have been frequently adopted in the growth literature that looks into cross-country data (e.g., Borensztein et al., 1998; Dinopoulos and Thompson, 2000; Caselli and Coleman, 2006; Vandenbussche et al., 2006; Fadinger and Mayr 2014).

innovation rate, due to coordination, organizational, and transportation costs related to market size (e.g., Afonso, 2012), which, as we can see below, can partially ($0 < \delta < 1$), totally ($\delta = 1$), or over counterbalance ($\delta > 1$) the scale benefits on profits, and thus allows us to remove scale effects in the economic growth rate. This contrasts with the usual knife-edge assumption that either $\delta = 0$ or $\delta = 1$ (e.g., Barro and Sala-i-Martin, 2004, ch. 6).

We assume that there is free entry into R&D, such that in equilibrium the cost of discovering a new variety, Z_j, is also its price, V_j, which corresponds to the present value of monopoly profits seized by the monopolist; i.e., $V_j(t) = \int_t^{\infty} \pi_j(v) \cdot e^{-\int_t^v r(\omega)d\omega} dv,\ j = T, D$. Differentiating both sides of the latter expression with respect to t yields:

$$V_j(t) = \frac{\pi_j(t)}{r(t)} + \frac{\dot{V}_j(t)}{r(t)},\ j = T, D, \tag{17}$$

Along the balanced growth path (BGP), $V_j(t)$ is constant for all t, $\dot{V}_j(t) = 0$, and the interest rate is constant; that is, on the BGP the interest rate is identical to the ratio of the profit flow to the lump-sum cost of discovery: $r(t) = \frac{\pi_j(t)}{V_j(t)}$. Hence, from (11),

$$V_j(t) = \frac{\alpha \cdot P_j^{1/\alpha} \cdot L_j}{r(t)},\ j = T, D, \tag{18}$$

i.e., the present value of monopoly profits depends: (i.a) positively on the product price of the sector in which the intermediate good is used, P_j, since it increases the value of the marginal product of all factors, including that of intermediate goods, thus encouraging firms to rent more intermediate goods and raising the instantaneous profits of the monopolist (price channel); (i.b) positively on production firms' employment, L_j, since it implies more labor to use intermediate goods, increasing demand, and thereby raises the profits (market-size channel); (ii) negatively on the rental price of capital, r, since it raises the discount rate for the future profit flow, and so reduces the present value. Hence, it should be stressed that, for example, the greater V_T is relative to V_D, the greater are the incentives to develop T-complementary intermediate goods, N_T, rather than D-complementary intermediate goods, N_D, and there are two forces determining the technological-knowledge bias, which are the price and the market-size channels since the incentives to invent technologies are greater when, respectively, goods are expensive and the market for the technology is larger:

$$\frac{V_D}{V_T} = \frac{\pi_D}{\pi_T} = \underbrace{\left(\frac{P_D}{P_T}\right)^{\frac{1}{\alpha}}}_{Price\ channel} \cdot \underbrace{\left(\frac{L_D}{L_T}\right)}_{Market-size\ channel}. \tag{19}$$

Thus, considering (13) the equilibrium expression for the relative profitability of developing technologies that complement the D-sector is:

$$\frac{V_D}{V_T} = \frac{\pi_D}{\pi_T} = \left[\left(\frac{\chi_D}{\chi_T}\right)^{\varepsilon} \left(\frac{L_D}{L_T}\right)^{\Omega} \left(\frac{N_D}{N_T}\right)^{-1}\right]^{\frac{1}{1+\Omega}}, \tag{20}$$

and it depends: (i) positively on $\frac{\chi_D}{\chi_T}$ and on $\frac{L_D}{L_T}$ if $\varepsilon > 1$; (ii) negatively on $\frac{N_D}{N_T}$ and on $\frac{L_D}{L_T}$ if $\varepsilon < 1$. Along the BGP, the relative profitability $\frac{V_D(t)}{V_T(t)} = \frac{\pi_D(t)}{\pi_T(t)}$ in (19) is equal to relative R&D cost, which from (16) is $\frac{Z_D(t)}{Z_T(t)} = \frac{\sigma_T \cdot L_T^{-\delta}}{\sigma_D \cdot L_D^{-\delta}}$; i.e., balanced growth (steady state) technology market clearing condition implies that $\pi_T(t) \cdot \sigma_T \cdot L_T^{-\delta} = \pi_D(t) \cdot \sigma_D \cdot L_D^{-\delta}$ or, which is equivalent, $V_T(t) \cdot \sigma_T \cdot L_T^{-\delta} = V_D(t) \cdot \sigma_D \cdot L_D^{-\delta}$, yielding the endogenous equilibrium technological-knowledge bias between the D-sector and the T-sector:

$$\frac{N_D}{N_T} = \left(\frac{\chi_D}{\chi_T}\right)^{\varepsilon} \left(\frac{\sigma_D}{\sigma_T}\right)^{1+\Omega} \left(\frac{L_D}{L_T}\right)^{\Omega(1-\delta)-\delta}, \tag{21}$$

which, by driving the wage inequality dynamics, is the key result of the directed technical change literature.[14]

Proposition 1. *The technological-knowledge bias, $\frac{N_D}{N_T}$, depends:*

(i) positively on both the relative importance of the D-sector in the production of the aggregate final good, $\frac{\chi_D}{\chi_T}$, and the relative productivity of developing D-sector complementary intermediate goods, $\frac{\sigma_D}{\sigma_T}$;

(ii) positively, null, or negatively on the relative supply of labor in the D-sector, $\frac{L_D}{L_T}$, according to the sign of the exponent $\Omega(1-\delta)-\delta$.

Proof. From (21), regardless of the size of the elasticity of substitution between sectors in the production of the aggregate final good, ε, $\frac{N_D}{N_T}$ is positively related with $\frac{\chi_D}{\chi_T}$ and $\frac{\sigma_D}{\sigma_T}$ because $\varepsilon \geq 0$ and $1+\Omega > 0$. Moreover, the sign and intensity of the relationship between $\frac{N_D}{N_T}$ and $\frac{L_D}{L_T}$ relies on the sign and value of the exponent $\Omega(1-\delta)-\delta = (\varepsilon-1)(1-\delta)\alpha-\delta$ and, as a result, on the value of the parameters ε and δ, as is summarized in Table 3.

That is, under substitutability, if $\varepsilon > 1$ (i.e., factors used in the two intermediate sectors are gross substitutes) and $\delta = 0$ (i.e., R&D activity is independent of the labor level), $\frac{N_D}{N_T}$ is positively related with $\frac{L_D}{L_T}$ since the exponent is positive. In this case, such as in Acemoglu (1998, 2002, 2008), the technological-knowledge change favors the labor type employed in the larger sector of the economy due to the market-size effect, and thus technologies that use the more abundant type of labor are favored. The essential idea is that the same economic forces (profitability of the R&D) that affect the technological-knowledge progress also shape the technological-knowledge bias, and the labor level is connected to the size of profits that, in each period, accrue to the leader producer – see (11); i.e., the dimension of the market affects the monopolist's profits and thus the incentives to allocate resources to R&D, thereby directing technological knowledge. The effect of the market-size channel is stronger, $\alpha(\varepsilon-1) > 1$, under intense substitutability, $\varepsilon > \frac{1+\alpha}{\alpha}$, and is directly proportional to $\frac{L_D}{L_T}$, $\Omega \equiv \alpha(\varepsilon-1) = 1$, when $\varepsilon = \frac{1+\alpha}{\alpha}$.

Still under substitutability, if $\varepsilon > 1$ and $0 < \delta < 1$, the exponent $\Omega(1-\delta)-\delta$ is positive and the market-size channel operates when $\varepsilon > \frac{\delta+\alpha(1-\delta)}{\alpha(1-\delta)}$. In turn, when $\varepsilon = \frac{\delta+\alpha(1-\delta)}{\alpha(1-\delta)}$ the exponent is null and $\frac{N_D}{N_T}$ is independent of the relative supply of labor $\frac{L_D}{L_T}$. Otherwise, when $1 < \varepsilon < \frac{\delta+\alpha(1-\delta)}{\alpha(1-\delta)}$ the exponent is negative and the chain of effects is induced by the price channel by which there are stronger incentives to improve technologies when the goods that they produce command higher prices; i.e., an increase in the relative supply of labor in the D-sector biases the technological knowledge in favor of the T-sector or, in other words, technologies that use the scarcer labor are favored.

If $\varepsilon = 1$ and $\delta = 0$, $\frac{N_D}{N_T}$ is also independent of the relative supply of labor $\frac{L_D}{L_T}$.

In all other cases the exponent $\Omega(1-\delta)-\delta$ is negative, so that the price channel dominates the chain of effects. However, the intensity of the effect depends on the case: (i) it is smaller; i.e., $-1 < \Omega(1-\delta)-\delta < 0$, when $\delta = 0$ and $\varepsilon = 0$, or $\delta = 0$ and $0 < \varepsilon < 1$, or $0 < \delta < 1$ and $\varepsilon = 0$, or $0 < \delta < 1$ and $0 < \varepsilon < 1$, or $0 < \delta < 1$ and $\varepsilon = 1$; (ii) it is inversely proportional to $\frac{L_D}{L_T}$;

[14] In the standard directed technical change literature (e.g., Acemoglu 1998, 2002, 2008), the scale has no impat on R&D technology; i.e., scale effects are not removed, $\delta = 0$, and the chain of effects is dominated by the market-size channel, by which technologies that use the more abundant labor type are favored; thus, this literature has been interpreting the rise in the skill premium as a result of the market-size effect. In our case, however, the level of scale effects removal lends much more flexibility to the technological-knowledge bias.

	$\delta = 0$	$0 < \delta < 1$	$\delta = 1$	$\delta > 1$
$\varepsilon = 0$	< 0	< 0	$= -1$	< -1
$0 < \varepsilon < 1$	< 0	< 0	$= -1$	< -1
$\varepsilon = 1$	$= 0$	< 0	$= -1$	< -1
$\varepsilon > 1$	> 0	$(-\infty, +\infty)$	$= -1$	< -1

Table 3: Elasticity of the technological-knowledge bias, $\frac{N_D}{N_T}$, with respect to the labor ratio, $\frac{L_D}{L_T}$.

i.e., $\Omega(1-\delta) - \delta = -1$, whenever $\delta = 1$; and (iii) it is stronger; i.e., $\Omega(1-\delta) - \delta > -1$, whenever $\delta > 1$.

□

As a result of the ajustment of the technological-knowledge bias in (21), the relative profitability of developing technologies that complement the D-sector, $\frac{V_D}{V_T}$, in (19) becomes

$$\frac{V_D}{V_T} = \left(\frac{\sigma_D}{\sigma_T}\right)^{-1} \left(\frac{L_D}{L_T}\right)^{\delta}, \tag{22}$$

and thus it depends negatively on the relative productivity of developing D-sector complementary intermediate goods, $\frac{\sigma_D}{\sigma_T}$, and positively on relative supply of labor, $\frac{L_D}{L_T}$.

We are also interested in knowing the relationship between the relative price (real exchange rate or terms of trade), $\frac{P_D}{P_T}$, along the BGP. From (13) and due to complementarity between inputs in (3),[15] the relative price of the D-sector is negatively related with the endogenous technological-knowledge bias, $\frac{N_D}{N_T}$ – see the Fact above. Thus, substituting (21) into (13), along the BGP, after the adjustment of the technological-knowledge bias, the real exchange rate is:

$$\frac{P_D}{P_T} = \left(\frac{\sigma_D}{\sigma_T}\right)^{-\alpha} \left(\frac{L_D}{L_T}\right)^{\frac{-\alpha-\alpha[(\varepsilon-1)(1-\delta)\alpha-\delta]}{1+\Omega}}, \tag{23}$$

which can be related with the Balassa-Samuelson model in which inter-country productivity differences between the nontradable and tradable sectors are determinant for inter-country price level differences. However, in our case, the productivity mechanism, governed by the bias of the technological-knowledge progress, is endogenous and clear.

Proposition 2. *The real exchange rate, $\frac{P_D}{P_T}$, depends*

(i) negatively on the relative advantage to entry through horizontal innovation into the D-sector, $\frac{\sigma_D}{\sigma_T}$, which, after the adjustment of the technological-knowledge bias, reflects the Balassa-Samuelson hypothesis;

(ii) positively, null, or negatively on the relative supply of labor in the D-sector, $\frac{L_D}{L_T}$, according to the sign of the exponent $\frac{-\alpha-\alpha[(\varepsilon-1)(1-\delta)\alpha-\delta]}{1+\Omega}$.

Proof. Since $0 < \alpha < 1$ results directly from (23) that the real exchange rate, $\frac{P_D}{P_T}$, is higher in countries whose tradable sector has higher relative advantage to entry through horizontal innovation; i.e., *ceteris paribus*, $\frac{P_D}{P_T}$ depends positively on σ_T. However, the sign of the effect of $\frac{L_D}{L_T}$ on $\frac{P_D}{P_T}$ is ambiguous, as is shown in Table 4 – it depends on the degree of scale effects..

That is, the effect is: (i) negative when scale effects are present, $\delta = 0$, or are only partially removed, $0 < \delta < 1$; null when scale effects are totally removed, $\delta = 1$; positive, when $\delta > 1$.

[15] In general terms, concerning the production of final goods there is complementarity between inputs – labor and intermediate goods – and substitutability between technologies – D and T.

	$\delta = 0$	$0 < \delta < 1$	$\delta = 1$	$\delta > 1$
$\varepsilon = 0$	< 0	< 0	$= 0$	> 0
$0 < \varepsilon < 1$	< 0	< 0	$= 0$	> 0
$\varepsilon = 1$	< 0	< 0	$= 0$	> 0
$\varepsilon > 1$	< 0	< 0	$= 0$	> 0

Table 4: Elasticity of the relative price, $\frac{P_D}{P_T}$, with respect to the labor ratio, $\frac{L_D}{L_T}$.

.

□

Finally, we analyze the implications of endogenous technological-knowledge bias on the relative wage, $\frac{w_D}{w_T}$, since, by reason of complementarity between factors in (3), changes in $\frac{w_D}{w_T}$ are closely related to $\frac{N_D}{N_T}$, as (14) clearly shows. Hence, we substitute (21) into (14):

$$\frac{w_D}{w_T} = \left(\frac{\chi_D}{\chi_T}\right)^{\varepsilon} \left(\frac{\sigma_D}{\sigma_T}\right)^{\Omega} \left(\frac{L_D}{L_T}\right)^{\Omega(1-\delta)-1}. \tag{24}$$

Proposition 3. $\frac{w_D}{w_T}$ *is:*

(i) positively related with the relative importance of the D-sector in the production of the final good, $\frac{\chi_D}{\chi_T}$, as well as with the relative productivity of developing D-sector complementary intermediate goods, $\frac{\sigma_D}{\sigma_T}$, but, in this latter case, only when $\varepsilon > 1$;

(ii) positively, null, or negatively related with the relative supply of labor in the D-sector, $\frac{L_D}{L_T}$, according to the sign of the exponent $\Omega(1-\delta)-1$.

Proof. Bearing in mind (24), $\frac{w_D}{w_T}$ is always positively related with $\frac{\chi_D}{\chi_T}$ since $\varepsilon \geq 0$ and, when $\varepsilon > 1$, with $\frac{\sigma_D}{\sigma_T}$ since in this case $\Omega > 0$. However, the sign of the effect of $\frac{L_D}{L_T}$ on $\frac{w_D}{w_T}$ is ambiguous, as is shown in Table 5.

That is, under substitutability, if (i) $\frac{1+\alpha}{\alpha} < \varepsilon < +\infty$ and $\delta = 0$, or (ii) $\frac{1+\alpha(1-\delta)}{\alpha(1-\delta)} < \varepsilon < +\infty$ and $0 < \delta < 1$, as well as under complementarity, if (iii) $\varepsilon = 0$ and $\delta > \frac{1+\alpha}{\alpha}$ or (iv) $0 < \varepsilon < 1$ and $1 < \delta < \frac{(\varepsilon-1)\alpha-1}{(\varepsilon-1)\alpha}$, an increase of $\frac{L_D}{L_T}$ increases $\frac{w_D}{w_T}$ since the effect of $\frac{L_D}{L_T}$ on $\frac{N_D}{N_T}$, which drives wage-inequality dynamics, dominates the direct effect induced by the relative supply.[16] In these four cases the increase in the supply of $\frac{L_D}{L_T}$ causes, due to the usual substitution effect – see (14), an immediate steep drop in $\frac{w_D}{w_T}$ since the relative labor supply decreases the respective relative wage. This immediate effect is, however, reverted in the transitional dynamics toward the new constant steady-state of $\frac{w_D}{w_T}$, due to the stimulus to the demand for $\frac{L_D}{L_T}$ resulting from the induced $\frac{N_D}{N_T}$ in favor of the D-sector. Once in steady state, with a constant $\frac{N_D}{N_T}$, $\frac{w_D}{w_T}$ also remains constant.

Under substitutability, if $\varepsilon = \frac{1+\alpha}{\alpha}$ and $\delta = 0$ or $\varepsilon = \frac{1+\alpha(1-\delta)}{\alpha(1-\delta)}$ and $0 < \delta < 1$, as well as under complementarity, if $\varepsilon = 0$ and $\delta = \frac{1+\alpha}{\alpha}$ or $0 < \varepsilon < 1$ and $\delta = \frac{1+\alpha(1-\delta)}{\alpha(1-\delta)}$, $\frac{w_D}{w_T}$ is independent of $\frac{L_D}{L_T}$.

[16] Comparing (24) to (14) results that, in line with the *LeChatelier* principle, the response of relative wages $\frac{w_D}{w_T}$ to changes in relative supply $\frac{L_D}{L_T}$ is now more elastic since the respective demand curves become more elastic after the adjustment of the "other factors", which here correspond to the number of intermediate goods N_D and N_T; thus, bearing in mind the exponents of $\frac{L_D}{L_T}$ it results that $\alpha(\varepsilon-1)(1-\delta)-1 > -\frac{1}{\alpha(\varepsilon-1)-1}$ in all four cases (i), (ii), (iii), and (iv).

	$\delta = 0$	$0 < \delta < 1$	$\delta = 1$	$\delta > 1$
$\varepsilon = 0$	< -1	< -1	$= -1$	$(-\infty, +\infty)$
$0 < \varepsilon < 1$	< -1	< -1	$= -1$	$(-\infty, +\infty)$
$\varepsilon = 1$	$= -1$	$= -1$	$= -1$	$= -1$
$\varepsilon > 1$	$(-\infty, +\infty)$	$(-\infty, +\infty)$	$= -1$	< -1

Table 5: Elasticity of the relative wage, $\frac{w_D}{w_T}$, with respect to the labor ratio, $\frac{L_D}{L_T}$.

In all other cases the exponent $\alpha(\varepsilon-1)(1-\delta)-1$ is always negative, so that the price channel dominates the chain of effects, such that in view of, for example, an increase in the relative supply of L_D, $\frac{L_D}{L_T}$, the relative price of the D-sector decreases, $\frac{P_D}{P_T}$, which discourages R&D activities in this sector, biasing the technological-knowledge in favor of the T-sector, and thus generates a decrease of $\frac{w_D}{w_T}$. However, the intensity of the effect depends on the case: (i) it is smaller; i.e., $-1 < \alpha(\varepsilon-1)(1-\delta)-1 < 0$, when $1 < \varepsilon < \frac{1+\alpha}{\alpha}$ and $\delta = 0$, or $1 < \varepsilon < \frac{1+\alpha(1-\delta)}{\alpha(1-\delta)}$ and $0 < \delta < 1$, or $\varepsilon = 0$ and $\delta < \frac{1+\alpha}{\alpha}$, or $0 < \varepsilon < 1$ and $\delta > \frac{(\varepsilon-1)\alpha-1}{(\varepsilon-1)\alpha}$; (ii) it is inversely proportional to $\frac{L_D}{L_T}$; i.e., $\alpha(\varepsilon-1)(1-\delta)-1 = -1$, when $\varepsilon = 1$ ($\delta = 1$) whetever the value of δ (ε); and (iii) it is stronger; i.e., $\alpha(\varepsilon-1)(1-\delta)-1 < -1$, when $\varepsilon = 0$ and $\delta = 0$, or $\varepsilon = 0$ and $0 < \delta < 1$, or $0 < \varepsilon < 1$ and $\delta = 0$, or $0 < \varepsilon < 1$ and $0 < \delta < 1$, or $\varepsilon > 1$ and $\delta > 1$.

.

□

To sum up, with perfect competition in final goods, economic viability of either type of sector depends on the output prices, P_T or P_D, as well as on the importance of the sectors, χ_D and χ_T, on the degree of substitutability, ϵ, on the labor prices, w_D and w_T, and on the productivity and the intermediate-goods prices, due to complementarity between inputs in production. In particular, the labor prices rely on the quantities, L_D and L_T, and the productivity and intermediate-goods prices depend on complementarity with either type of labor, L_D and L_T, on the technological knowledge embodied, N_D and N_T, and on the mark-up summarized in α. Then, the application of the directed technical change framework points out the market-size channel and the price channel mechanisms as the drivers of the technological-knowledge bias, $\frac{N_D}{N_T}$, which in turn affects the real exchange rate, $\frac{P_D}{P_T}$, and the labor premium, $\frac{w_D}{w_T}$. By removing the scale effects, the price channel mechanism takes over the chain of effects and is crucial in determining $\frac{N_D}{N_T}$, $\frac{P_D}{P_T}$, and $\frac{w_D}{w_T}$.

To close the model we need to find the long-run economic growth rate of the economy. Taking into account that agents are delaying consumption by investing in R&D, as a function of the interest rate, and bearing in mind (2), in BGP the consumption, C, the total investment in production of intermediate goods, X, the aggregate R&D expenditures, Z, the aggregate output, Y, and the technological knowledge grow at the same rate, g; i.e., C, X, Z, and Y are multiples of N_D and N_T. Thus, since the country's interest rate is unique, from (1) $r = \theta g + \rho$ and this condition ensures that the steady-state growth rate is unique. Hence, along the BGP, the growth rate of the economy depends on the market interest rate and preference parameters. Now, using (18) the free-entry condition for the technology monopolists working to invent j-complementary intermediate goods implies that $V_j = Z_j$, which is equivalent to stating that $L_j^{-\delta}\sigma_j V_j = 1$ since $L_j^{-\delta}\sigma_j Z_j$ units of composite final-good resources are required to invent a new design (to produce a new intermediate good); that is, $L_j^{-\delta}\sigma_j Z_j = 1$. In steady state, this condition implies that $L_j^{-\delta}\sigma_j V_j = \frac{L_j^{-\delta}\sigma_j \cdot \alpha \cdot P_j^{1/\alpha} \cdot L_j}{r(t)} = 1$. Now, using (4), (13), and (21), we obtain:

$$g = \frac{1}{\theta}\left\{\alpha\left[\chi_D^{\varepsilon}\left(\sigma_D L_D^{1-\delta}\right)^{\Omega} + \chi_T^{\varepsilon}\left(\sigma_T L_T^{1-\delta}\right)^{\Omega}\right]^{\frac{1}{\Omega}} - \rho\right\}, \tag{25}$$

from which higher productivity in R&D activity, σ_j, makes the steady-state growth rate of the economy higher, while the rate of time preference, ρ, and the elasticity of marginal utility of consumption, θ, have depressing effects on the steady-state growth rate. Moreover, it is clear from (25) that indeed scale effects can be present ($\delta = 0$), positively affecting the economic growth rate, can be partially removed ($0 < \delta < 1$), having a smaller impact on economic growth, can be totally removed ($\delta = 1$), no longer affecting the economic growth rate, or can over counterbalance the scale benefits on profits ($\delta > 1$) and thus negatively affecting the economic growth rate.

Finally, it should be also emphasized that outside the BGP, just one type of innovation arises: when $\frac{V_D(t)}{V_T(t)} > \frac{\sigma_T L_T^{-\delta}}{\sigma_D L_D^{-\delta}}$ $\left(\frac{V_D(t)}{V_T(t)} < \frac{\sigma_T L_T^{-\delta}}{\sigma_D L_D^{-\delta}}\right)$ R&D activity is directed to create new designs to produce D-complementary (T-complementary) intermediate goods. Moreover, as (20) shows, $\frac{V_D}{V_T}$ is decreasing in $\frac{N_D}{N_T}$, which implies that the economy always returns to the BGP in which $\frac{V_D(t)}{V_T(t)} = \frac{\sigma_T L_T^{-\delta}}{\sigma_D L_D^{-\delta}}$: when $\frac{N_D}{N_T}$ is higher (lower) than in (21), the technological-knowledge change will only be directed to T-complementary (D-complementary) intermediate goods until the economy returns back to the BGP in which both sectors grow at the same rate. Thus, without any exogenous disturbance, the economy converges and remains in the unique and stable steady state in which both sectors grow at the same rate.

4 Quantitative results

In this section we evaluate quantitatively the sensitivity of the main macroeconomic aggregate ratios of the model in steady state to differences in the values for the scale effects, governed by δ , for the elasticity of substitutions between the tradable and the nontradable sector, governed by ε , and for the relative labor level $\frac{L_D}{L_T}$.

First we calibrate the model and then we discuss the main results.

4.1 Calibration

In order to obtain quantitative results we must calibrate, besides δ and ε , parameters χ_T and χ_D (the relative shares of tradable and nontradable goods in the final good production), α (the share of labor in the intermediate goods production), σ_T and σ_D (the productivities in R&D directed to tradable and nontradable goods, respectively), L_T and L_D (the force employed in the tradable and nontradable goods sectors), θ (the elasticity of intertemporal substitution), and ρ (the utility discount factor). We use typical values for $\alpha = 0.66$, $\theta = 2$, and $\rho = 0.02$. These values are typical in calibration exercises of endogenous growth models (e.g., Jones and Williams, 2000; Strulik, 2007; Grossmann et al., 2013; Gómez and Sequeira, 2013). We calibrate the model using values for Germany, as it is one of the economies with greater availability of data needed for this model calibration. Generally, we use the AMECO definition for the division between tradable and nontradable goods (Table 1) – see, e.g., Zeugner (2013).

For χ_T and χ_D we use data from ILOsta,[17] (for the year 2011), summing the percentage of employment in Agriculture and Fishery, Mining and Quarrying, and Industry (for the tradable sector) and Education and Health and Social Services (for the nontradable sector). For L_T and L_D we use data for the number of workers from ILOsta, (an average between 1999 and 2008).

[17] Data available (accessed in February 2016) at: www.ilo.org

Due to the availability of data, we use for the tradable sector the sum of Agriculture and Fishery, Mining and Quarrying, Hotels and Restaurants and Industry and for the nontradable sector the sum of Construction, Electricity, Gas and Water Supply, Financial Intermediation, Education, and Health and Social Work. Finally, in order to calculate the ratio of productivities $\frac{\sigma_D}{\sigma_T}$ in the R&D sectors, we use R&D technologies (equations 16) such that

$$\frac{\sigma_D}{\sigma_T} = \frac{\frac{\dot{N}_D}{\dot{N}_T}}{\frac{Z_D}{Z_T}\left(\frac{L_D}{L_T}\right)^{-\delta}}. \tag{26}$$

The ratio $\frac{\dot{N}_D}{\dot{N}_T}$ is the ratio of the number of patents between the nontradable and tradable sectors, for which we use patent applications by NACE classifications from the Eurostat (averaged between 2003 and 2012), with available data for Agriculture, Forestry and Fishing; Manufacturing; Construction, Electricity and Education. The ratio $\frac{Z_D}{Z_T}$ is the ratio between R&D expenditures in both sectors. We use data for 'business enterprise R&D expenditure (BERD) by economic activity and type of costs' from the Eurostat. For the tradable sector we sum the expenditures for Agriculture and Fishing, Mining and Quarrying, Hotels and Restaurants and Manufacturing (average from 2007 to 2013). However, for the nontradable sector data are available only for Construction, Electricity, Gas and Water supply and Health and Social Work – in this case only for 2010 to 2013. This underestimates the R&D effort in nontradable sectors, as it ignores the R&D effect made by the public sector, which would enter in the nontradable sector (see Table 1). In fact, Eurostat estimates that near 1/3 of the R&D expenditure come from the Government sector in Germany.[18] Thus, we use these estimates to add the public sector to the R&D effort in the nontradable sector. As equation (26) shows, we would also need the parameter that governs the scale effect δ . We consider different values for δ in order to perform sensitivity analysis for the scale effect, although it is reasonable to assume that for a developed economy the scale effect almost vanishes, and thus δ should approach 1 for a developed country such as Germany. Tables 6 and 7 summarize the values for calibration. From the values in Table 7 we conclude that the R&D sector for nontradable goods is less productive than the R&D sector for tradable goods, for all values of the scale effect. As the scale effect gradually vanishes ($\delta \to 1$), the relative productivity of the nontradable R&D sector increases. This means that the tradable R&D sector benefits relatively more in terms of productivity than the nontradable R&D sector. This is in line with our conjecture in equation (16) in which we have assumed that $\sigma_T > \sigma_D$ due to strong positive international technology linkages on R&D performance in the T-sector.

4.2 Results

In this section we want to see the sensitivity of the main ratios of the model – $\frac{V_D}{V_T}$ (relative value of knowledge), $\frac{P_D}{P_T}$ (terms of trade), $\frac{N_D}{N_T}$ (technological-knowledge bias), and $\frac{w_D}{w_T}$ (wage premium) – to variations in the scale effects δ and in the elasticity of substitution between tradable and nontradable goods, ε , and to the relative labor level $\frac{L_D}{L_T}$.[19]

[18]Data available at (acessed February 2016) http://ec.europa.eu/eurostat/statistics-explained/index.php/R_%26_D_expenditure, Table 3.

[19]We want to note that variations in $\frac{L_D}{L_T}$ may represent mobility of labor between the two sectors in the economy.

Parameters	Values
θ	2.0000
ρ	0.0200
α	0.6600
$\frac{L_D}{L_T}$	1.2556
$\frac{Z_D}{Z_T}$	0.3123
$\frac{\chi_D}{\chi_T}$	1.4390
$\frac{\dot{N}_D}{\dot{N}_T}$	0.1996

Table 6: Calibrated parameter values.

δ	0	0.25	0.5	0.75	1
$\frac{\sigma_D}{\sigma_T}$	0.639	0.676	0.716	0.758	0.802

Table 7: The ratio of R&D productivities $\frac{\sigma_D}{\sigma_T}$ for different scale effects δ .

4.2.1 Sensitivity to different elasticities of substitution and scale-effects

Bearing in mind (22), the relative profitability of developing technologies that complement the D-sector, $\frac{V_D}{V_T}$, does not depend on the substitutability, as the positive effect ε has on the ratio of proportion of nontradable and tradable goods on the final production, $\frac{\chi_D}{\chi_T}$, is offset by the negative effect it has through $\frac{L_D}{L_T}$ (Figure 2a). Moreover, as a combination between equations (19) and (21) yields $\frac{V_D}{V_T} = \left(\frac{L_D}{L_T}\right)^{\delta}\left(\frac{\sigma_D}{\sigma_T}\right)^{-1}$, the direct effect of δ is also offset by the indirect effect it has on $\left(\frac{\sigma_D}{\sigma_T}\right)^{-1}$, due to the calibration strategy explained above (Figure 2a).

Because of the direct link between prices and the value of innovations – see equation (19), the same constant pattern occurs with the ratio of prices (the terms of trade) – see Figure 2b. Due to the calibration strategy, the variation of the scale effect δ compensates the evolution of $\frac{\sigma_D}{\sigma_T}$ as this ratio is calculated to fulfil the data ratio of innovations, $\frac{\dot{N}_D}{\dot{N}_T}$, as explained above. This implies that the ratios do not change with the scale effect – see Figures 2a, 2b, 2c, and 2d. Due to complementarity, changes in intra-country wage inequality, $\frac{w_D}{w_T}$, are closely related to the technological-knowledge bias, $\frac{N_D}{N_T}$, as (14) clearly shows (see also Figure 2c). That is, the effects that exogenous changes have on technological-knowledge bias, $\frac{N_D}{N_T}$, and on the wage premium $\frac{w_D}{w_T}$ are, thus, closely related (Figure 2c and 2d). An increase in ε (i.e., in the substitutability between the D-sector and the T-sector), favors D-technology in the production of (intermediate) final goods because the developed economy for which we calibrate the model begins with relatively more weight in the nontradable sector. Consequently, relative demand for intermediate goods used together with L_D rises, enhancing, in turn, profits of D-specific R&D and thereby biasing technological knowledge in that direction as shown by (21). The stimulus to the relative demand for L_D arising from the technological-knowledge bias increases the wage premium, $\frac{w_D}{w_T}$, relative to what would have prevailed under lower substitutability - see Figure 2d.

It is interesting to note that for reasonable values for the elasticity of substitution – e.g., according to Rabanal and Tuesta (2013), ranging from 0.13 to 1 –, the wage inequality ratio ranges from 0.95 to 1.14. According to the ILOsta, the wage inequality between the nontradable sector and the tradable sector in Germany average between 1995 and 2011 is 1.09, thus very

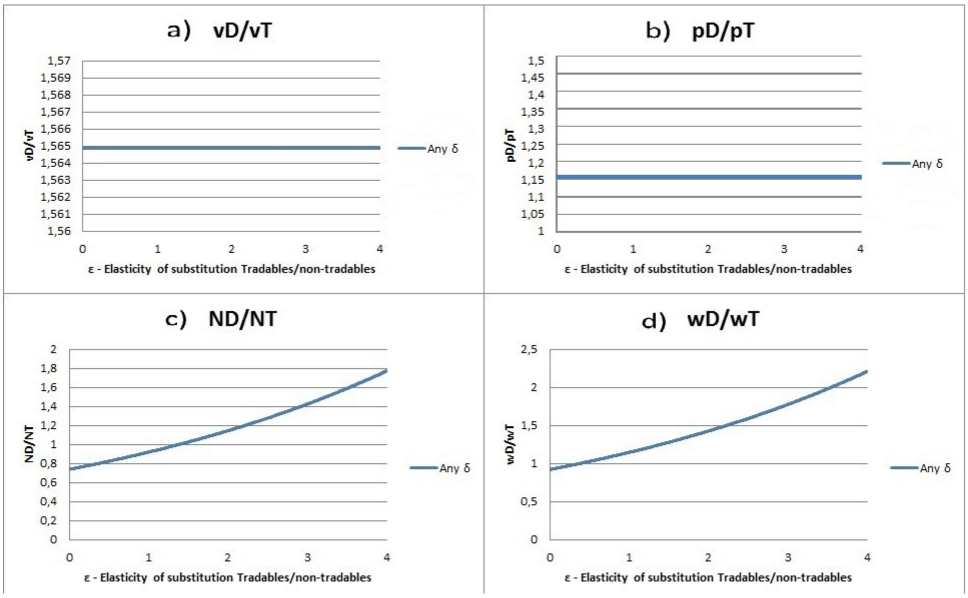

Figure 2: Main steady-state ratios for different elasticities of substitution and scale effects.

close and in between the model's predicted values.

4.2.2 Sensitivity to relative labor endowments and scale-effects

In this section we maintain the elasticity of substitution fixed on the average value of the range presented in Rabanal and Tuesta (2013), which yields a value of $\varepsilon = 0.565$.

With low removal of the scale effects, low δ, the relative profitability of the nontradable sector responds very slowly to an increase in the relative labor employment in the nontradable sector – recall equation (22). In fact, with $\delta = 0$, the profitability ratio will not depend on the labor ratio. However, as the labor employed in the nontradable sector increases with some removal of the scale effects, $\delta > 0$, there will be an increase in profitability of research in the nontradable sector, which will bias research toward this sector – see the paths of $\frac{V_D}{V_T}$ in Figure 3a. Another way to see this effect is to look at equation (19). As the labor ratio increases, the ratio for the value of innovations also increases. However, this effect tends to vanish when scale effects in R&D increase, $\delta \to 1$, because as this happens the price effect tends to offset the market-size effect. The effect of an increase of relative labor employed in the nontradable sector on the price ratio tends to be negative – see equation (13) and Figure 3b (note that with the given ε, $-1 < \Omega < 0$). The slope of terms of trade toward the labor ratio tends to decrease as the scale effects decrease, which is a natural result due to the gradual removal of scale effects as $\delta \to 1$.

Without surprise, the price effect dominates the scale effect for this level of elasticity and the relationship between the wage premium, $\frac{w_D}{w_T}$, and the labor endowments, $\frac{L_D}{L_T}$, is always negative for all the levels of removal of the scale effects, δ. It is interesting to note that the scale effect dominates – and thus yields a positively sloped demand curve for relative labor endowments – only for an elasticity higher than 2.6. For example, when $\varepsilon = 2.6$, the demand curve is positively sloped for $\delta = 0$, and when $\varepsilon = 4$, the demand curve is positively sloped for $\delta = 0$ and $\delta = 0.25$. This means that for the most reasonable calibrations for the elasticity of substitution and removal of the scale effects, the labor demand curve is negatively sloped – see Figure 3d. As above, due

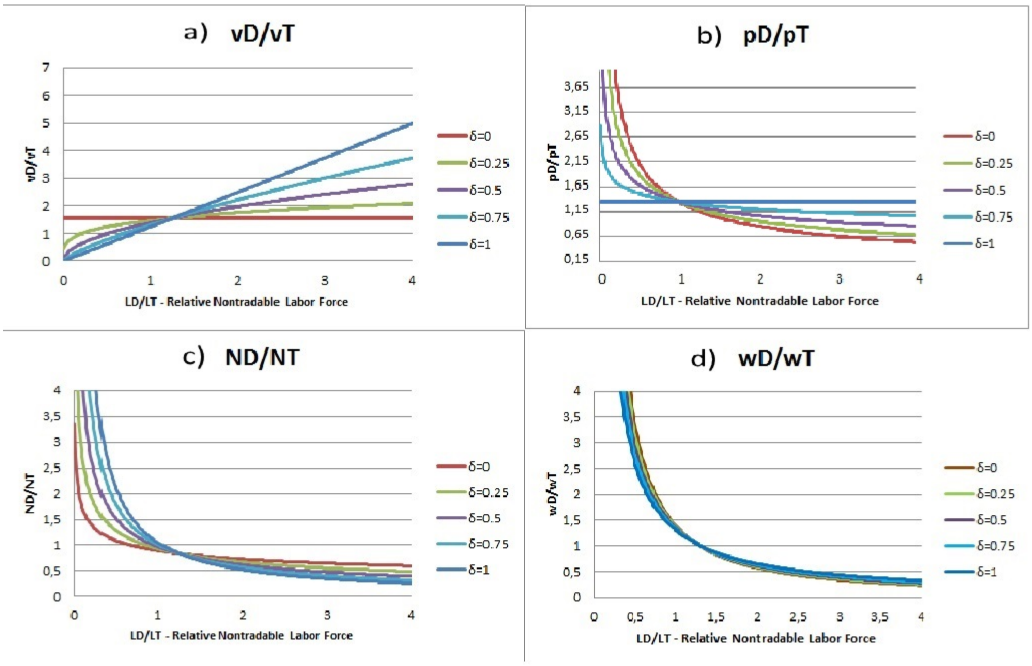

Figure 3: Main steady-state ratios for different labor ratios and scale effects.

to complementarity between inputs in the production of (intermediate) final goods, changes in intra-country wage inequality, $\frac{w_D}{w_T}$, are closely related to the technological-knowledge bias, $\frac{N_D}{N_T}$ – as (14) as well as Figures 3c, and 3d clearly show.

4.2.3 Simultaneous variation of elasticity of substitution and relative labor endowments

In this section we study the effect on steady-state ratios of the simultaneous change in the elasticity of substitution and relative labor endowment, gaining some insight on the interplay between the elasticity of substitution and the relative labor ratio. Here we restrict the analysis to the most interesting variables: the wage premium, $\frac{w_D}{w_T}$, and the terms of trade, $\frac{P_D}{P_T}$. Figure 4 shows the relationship between wage premium and the elasticity of substitution and the labor ratio. With low relative labor allocated to the nontradable sector, due to relative scarcity, the relative wage of the nontradable sector tends to be higher. This happens clearly without or with low scale effects and for all levels of the elasticity of substitution – see Figures 4c and 4d. However, with higher scale effects – see Figures 4a and 4b – and with higher levels of substitutability, for much lower relative labor allocated to the nontradable sector, an increase in the nontradable sector labor ratio will tend to increase the relative wage inequality (i.e., a positively sloped demand curve). This happens because there is a technological-knowledge bias that favors the nontradable sector, both because scale effect favors the existence of this bias and also because lower complementarity also favors the nontradable sector when nontradable labor is relatively low. This pattern highlights a hump-shaped relationship between the relative labor ratio and the wage inequality, which depends on the degree of substitutability.

Observe also that for higher levels of relative labor in the nontradable sector, further increase in this ratio and high substitutability will tend to favor the sector with the relative abundant

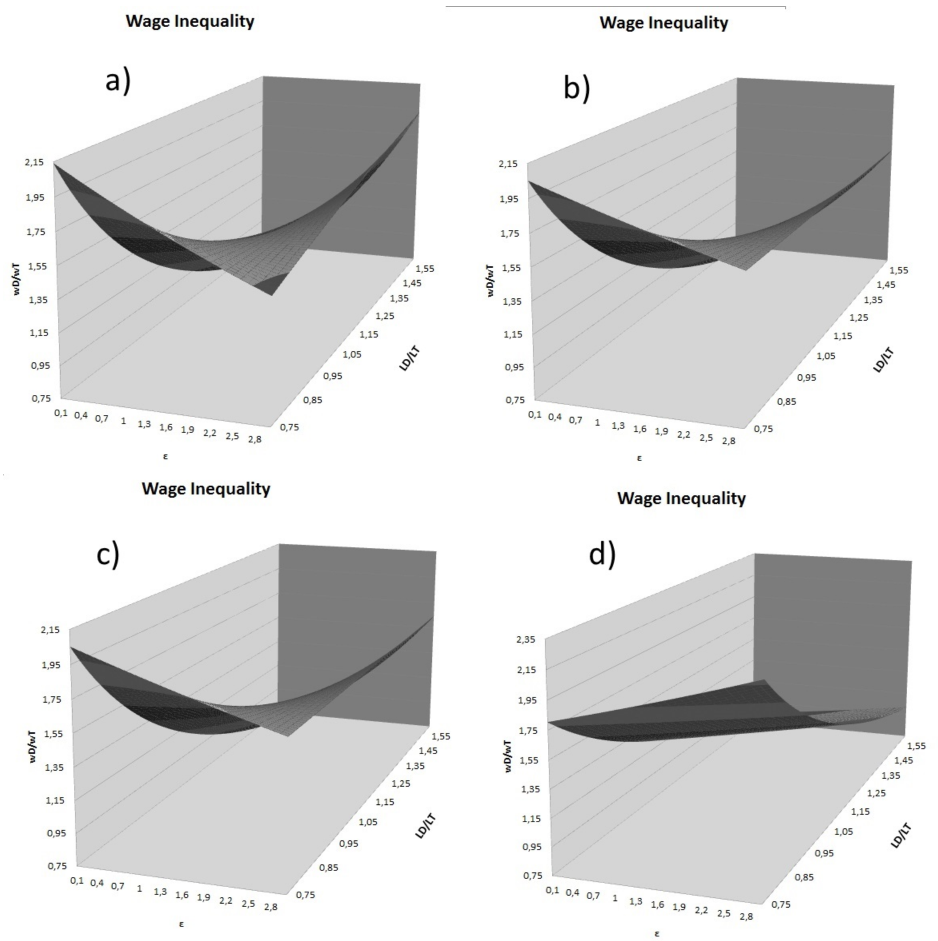

Figure 4: Steady-state wage inequality as a function of the elasticity of substitution and labor ratios for different scale effects; i.e., $\frac{w_D}{w_T}$ as a function of ϵ and $\frac{L_D}{L_T}$ for a) $\delta = 0$, b) $\delta = 0.25$, c) $\delta = 0.5$, d) $\delta = 1$.

labor. This effect can be seen in Figures 4a, 4b, and 4c.

In general, for a relatively developed economy – in which scale effects tend to be less important, further specialization in the nontradable sector tends to decrease the wage premium. On the contrary, for economies in which scale effects are important, specialization in the nontradable sector may increase inequality, especially if the tradable sector and the nontradable sector are strong substitutes.

Real exchange rate tends to depreciate with an increase in labor allocated to the nontradable sector, a depreciation that is more sloped when both sectors are complements – see Figures 5a, 5b, and 5c. With higher scale effects, this effect of the labor ratio and complementarity on the terms of trade are greater. In fact, as scale effects become more important, the variations in the elasticity of substitution also become more important in governing the relationship between the labor ratio and the terms of trade. The higher the scale effect and the lower the substitubility, the greater the benefits of the sector with more abundant labor and then the technological-knowledge

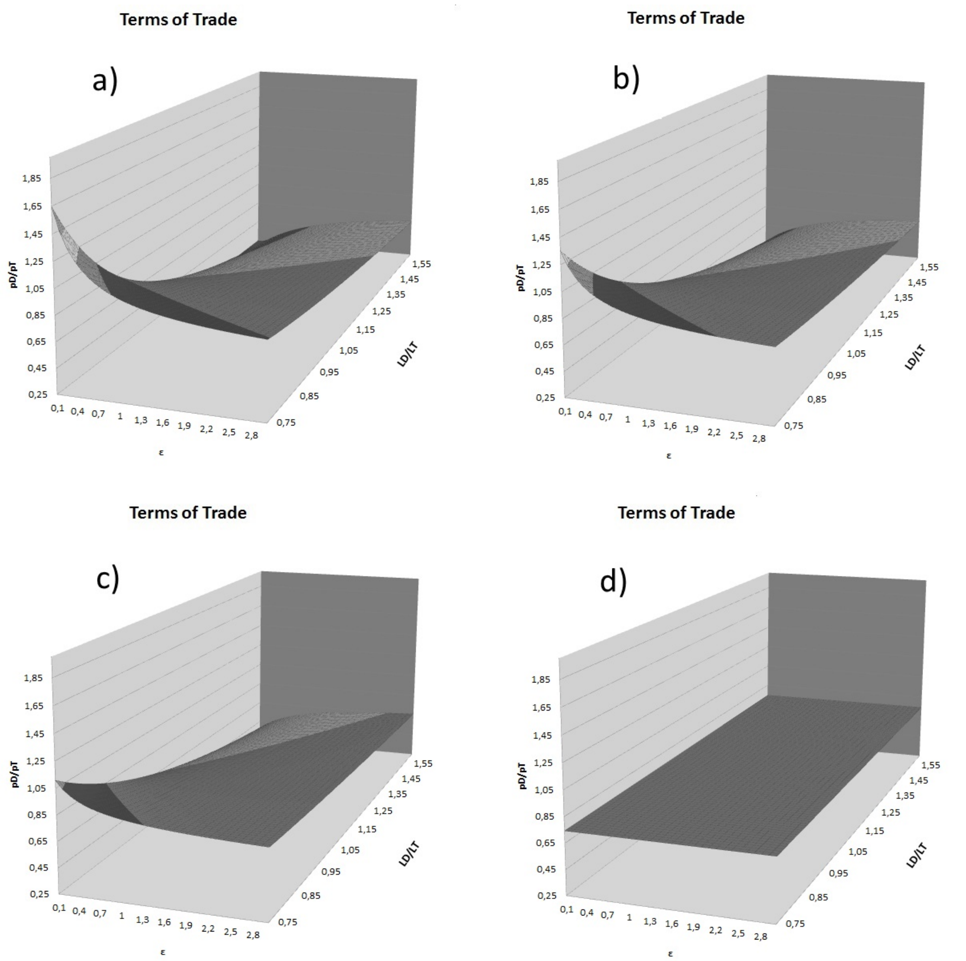

Figure 5: Steady-state terms of trade as a function of the elasticity of substitution and labor ratios for different scale effects; i.e., $\frac{P_D}{P_T}$ as a function of ϵ and $\frac{L_D}{L_T}$ for a) $\delta = 0$, b) $\delta = 0.25$, c) $\delta = 0.5$, d) $\delta = 1$.

bias toward that sector, which increase production and decrease the relative price. With complete removal of the scale effects, the real exchange rate is not sensitive to the labor ratio or to the elasticity of substitution – see equation (23). In this case, specialization in the nontradable sector does not deteriorate terms of trade.

As a policy implication, for economies in which scale is not important – namely for more developed economies – more specialization in the nontradable sector will not deteriorate terms of trade. For economies in which scale is important, then specialization in the nontradable sector may depreciate the real exchange rate, an effect that is more evident with low substitutability between both sectors.

5 Concluding remarks

By using a directed technical change approach between tradable and nontradable sectors, we want to reconcile the major trends in relative prices (real exchange rate or terms of trade), intra-country wage inequality, and economic growth rate.

We develop a directed technical change endogenous growth model with different degrees of substitutability between the employed labor level in each sector as well as with distinct intensity of scale effects. The productivity mechanism, induced by the bias of the technological-knowledge progress, is especially important in explaining the emphasized major trends. As a result, (i) the relative advantage to entry through horizontal innovation, (ii) the relative supply of labor, (iii) the elasticity of substitution, and (iv) the degree of scale effects emerge as determinants of productivity.

With a lower skilled labor ratio and a higher relative wage in the tradable sector in most countries, the application of the directed technical change framework would point to the price mechanism as the main one in determining productivity differences between sectors and thus wage premium between sectors. This suggests that the real exchange rate (or the terms of trade) should be crucial in explaining the higher relative skilled labor force and the lower relative wage in the nontradable sector.

The relative price of the nontradable sector – "the real exchange rate" – accommodates the Balassa-Samuelson hypothesis; indeed, after the adjustment of the technological-knowledge bias, the real exchange rate is negatively related with the relative advantage to entry through horizontal innovation in the sector and with the relative labor level in the sector, but only when scale effects are present or are partially removed.

The wage premium increases as a result of an increase in the relative labor level in the nontradable sector under substitutability with scale effects or under complementarity without scale effects. It is independent of the relative labor level when, under the dominance of the market size (price) channel, the substitutability (complementarity) has particular values. In all other cases the wage premium decreases as a result of an increase in the relative supply of labor in the nontradable sector. The wage premium is also positively related with the relative importance of the nontradable sector in the production of the final good and, under substitutability, with the relative productivity of developing intermediate goods for the nontradable sector.

It is now worth mentioning some policy implications. Our research indicates that real exchange rate reaction to reallocation of labor between sectors relies on fundamentals such as the elasticity of substitution between the tradable sector and the nontradable sector inside countries as well as the existence (or not) of scale effects. For example, for developed economies in which scale is not important, more specialization in the nontradable sector will not deteriorate terms of trade, whereas for developing economies in which scale is important, specialization in the nontradable sector may depreciate the real exchange rate, an effect that is more evident with low substitutability between both sectors. International trade policy should be aware of these fundamentals in order to adjust itself to the "natural" mechanisms of the real exchange rate. In particular, exchange-rate adjustments may be made considering the economic adjustment of the relative price that is due to modifications in the relative importance of tradable and nontradable sectors, for instance.

Our framework is still quite stylized and encourages extensions in several directions. The use of our model, which allows for simultaneous scale and price effects as well as substitutability and complementarity effects, in future research should be able to assess the strength of each effect following international trade. Since in this paper, the relative-wage paths hinge upon the assumption of fixed endowments, among other factors, we intend to explore the effects of endogenous human-capital accumulation. Finally, still another promising extension of the research follows from a recent characterization, by Aghion et al. (2003), of the explanations for rising wage inequality, stressing the importance of institutions. Our framework can accommodate the North-South spread of exogenous innovations of the general-purpose-technology type, which is interpretable and, thus, can be modeled as an institutional change.

References

Acemoglu, D. (1998). "Why do new technologies complement skills? directed technical change and wage inequality." Quarterly Journal of Economics 113(4), 1055-1090.

Acemoglu, D. (2002). "Directed technical change." Review of Economic Studies 69(4), 781-809.

Acemoglu, D. (2003). "Cross-country inequality trends." Economic Journal 113(485), 121-149.

Acemoglu, D. (2008). Introduction to modern economic growth. Princeton University Press.

Acemoglu, D. and J. Ventura (2002). "The world income distribution." Quarterly Journal of Economics 117(2), 659-694.

Acemoglu, D. and F. Zilibotti (2001). "Productivity differences." Quarterly Journal of Economics 116, 563-606.

Afonso, O. (2012). "Scale-independent North-South trade effects on the technological-knowledge bias and on wage inequality." Review of World Economics 148(1), 181-207.

Balassa, B. (1964). "The purchasing-power parity doctrine: a reappraisal." Journal of Political Economy 72(6), 584-596.

Barro, R. and X. Sala-i-Martin (2004). Economic growth, MIT Press (second edition), Cambridge, Massachusetts.

Berka, M. and M.B. Devereux (2010). "What determines European real exchange rates?" NBER Working Paper 15753.

Berka, M. and M.B. Devereux (2013). "Trends in European real exchange rates." Economic Policy 28(74), 193-242.

Borensztein, E., J. D. Gregorio, and J.-W. Lee (1998). "How does foreign direct investment affect economic growth?" Journal of International Economics 45, 115-135.

Bound, J. and J. George (1992). "Changes in the structure of wages in the 1980s: an evaluation of alternative explanations." American Economic Review 88(3), 371-392.

Caselli, F. and W. J. Coleman (2006). "The world technology frontier." American Economic Review 96(3), 499-522.

Chong, Y., O. Jordà, and A.M. Taylor (2012). "The Harrod-Balassa-Samuelson hypothesis: real exchange rates and their long-run equilibrium." International Economic Review 53(2), 609-633.

De Gregorio, J. and H. Wolf (1994). "Terms of trade, productivity, and the real exchange rate." NBER Working Paper 4807, National Bureau of Economic Research, Cambridge, MA July.

Dinopoulos, E. and P. Thompson (2000). "Endogenous growth in a cross-section of countries." Journal of International Economics 51, 335-362.

Epifani, P. and G. Gancia (2009). "Openness, government size and the terms of trade." Review of Economic Studies 76(2), 629-668.

Erosa, P., T.A Koreshkova, and D. Restuccia (2010). "How important is human capital? A quantitative theory assessment of world income inequality." Review of Economic Studies 01, 1-32.

Fadinger, H. and K. Mayr (2014). "Skill-biased technological change, unemployment, and brain drain." Journal of the European Economic Association 12(2), 397-431.

Gancia, G. and A. Bonfiglioli (2008). "North-South trade and directed technical change." Journal of International Economics 76(2), 276-295.

Gancia, G., A. Muller, and F. Zilibotti (2013). "Structural development accounting." In Advances in Economics and Econometrics: Tenth World Congress (Vol. 2, p. 373). Cambridge University Press. Chicago.

Gómez, M. A. and T. N. Sequeira (2014). "Should the US increase subsidies to R&&D? Lessons from an endogenous growth theory." Oxford Economic Papers 66(1), 654-682.

Grossman, G.M. and E. Helpman (1991). Innovation and growth in the global economy. Cambridge, Massachusetts: MIT Press.

Grossman, G.M. and C. Shapiro (1982). “A theory of factor mobility.” Journal of Political Economy 90(5), 1054-1069.

Grossmann, V., T. Steger, and T. Trimborn (2013). “Dynamically optimal R&D subsidization.” Journal of Economic Dynamics and Control 37, 516-534.

Hassler, J. and J. Rodriguez-Mora (2000). “Intelligence, social mobility and growth.” American Economic Review 90(4), 888-908.

Jones, C.I. (1995a). “R&D based models of economic growth.” Journal of Political Economy 103(4), 759-784.

Jones, C.I. (1995b). “Time series tests of endogenous growth models.” Quarterly Journal of Economics 110(2), 495-525.

Jones, C. and J. Williams (2000). “Too much of a good thing? The economics of investment in R&D.” Journal of Economic Growth 5, 65-85.

Juhn, C., K.M. Murphy, and B. Pierce (1993). “Wage inequality and the rise in returns to skill.” Journal of Political Economy 101(3), 410-442.

Katz, L. and K. Murphy (1992). “Changes in relative wages, 1963-1987: supply and demand factors.” Quarterly Journal of Economics 107(1), 35-78.

Krugman, P. (1995). “Growing world trade: causes and consequences.” Brookings Papers on Economic Activity 1995(1), 327-362.

Laincz, C.A. and P. Peretto (2006). “Scale effects in endogenous growth theory: an error of aggregation not specification.” Journal of Economic Growth 11, 263-288.

Lothian, R. and M.P. Taylor (2008). “Real exchange rates over the past two centuries: how important is the Harrod-Balassa-Samuelson effect?” The Economic Journal 118(532), 1742-1763.

MacDonald, R. and L.A. Ricci (2007). “Real exchange rates, imperfect substitutability, and imperfect competition.” Journal of Macroeconomics 29(4), 639-664.

Mincer, J. (1993). Studies in human capital: collected essays of Jacob Mincer. Edward Elgar, Cambridge.

Rabanal, P. and V. Tuesta (2013). “Nontradable goods and the real exchange rate.” Open Economies Review 24(3), 495-535.

Rogoff, K. (1996). “The purchasing power parity puzzle.” Journal of Economic Literature 34(2), 647-668.

Samuelson, P. (1964). “Theoretical notes on trade problems.” Review of Economics and Statistics 46(2), 145-154.

Strauss, J. and M.E. Ferris (1996). “The role of nontradable wages in the productivity differential model.” Southern Economic Journal 63(2), 327-338.

Strulik, H. (2007). “Too much of a good thing? The quantitative economics of R&D-driven growth revisited.” Scandinavian Journal of Economics 109, 369-386.

Van Zon, Adriaan and Roberto Antonietti (2004). “On the role of education and training as drivers of growth.” MERIT, May. Available at: http://degit.sam.sdu.dk/papers/degit_09/C009_027.pdf

Zeugner, S. (2013). “Tradable vs. nontradable: an empirical approach to the classification of sectors.” European Commission, October 2013. Available online at (accessed in January 2014): http://www.zeugner.eu/studies/research/TradedShares_zeugner.pdf