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Specialization Patterns and the Factor Bias of Technology

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Abstract

Development accounting exercises based on an aggregate production function find technology is biased in favor of a country's abundant production factors. We provide an explanation to this finding based on the Heckscher-Ohlin model. Countries trade and specialize in the industries that use intensively the production factors they are abundantly endowed with. For given factor endowment ratios, this implies smaller international differences in factor price ratios than under autarky. Thus, when measuring the factor bias of technology with the same aggregate production function for all countries, they appear to have an abundant-factor bias in their technologies.

Keywords: International Trade, Heckscher-Ohlin, Simulation, Development Accounting.

JEL codes: F1, F4, O4.

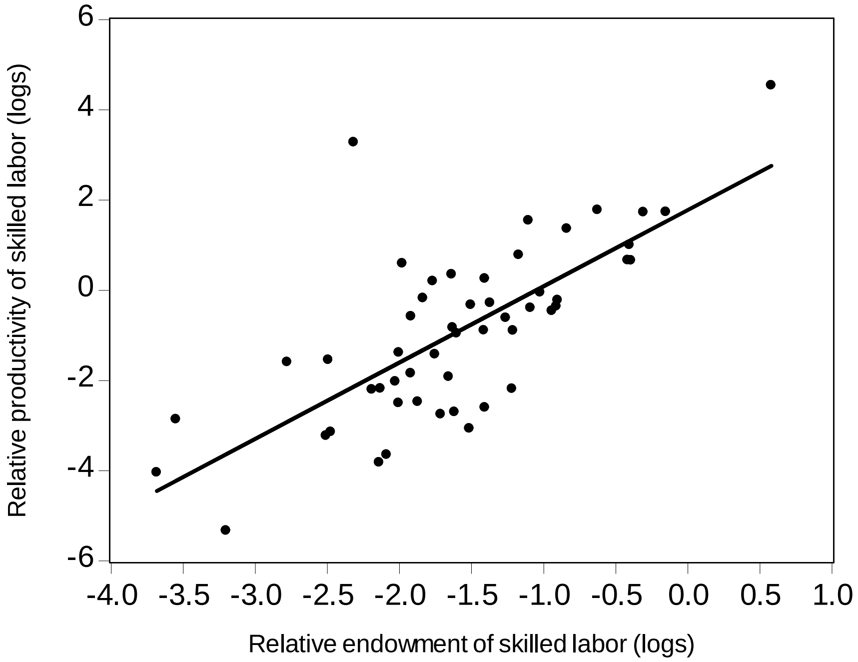

Figure 1: The relative factor bias of productivity.

1 Introduction

Recent empirical evidence suggests there are systematic international differences in the technologies countries use.[1] In the spirit of the growth accounting literature, these "development accounting" exercises use information on aggregate variables (GDP, factor endowments, factor income shares, factor price ratios, etc.) typically for a cross-section of countries, and estimate or calibrate the parameters of an aggregate production function. In an important contribution to this literature, in particular, Caselli and Coleman (2006) find that countries use technologies that tend to be biased in favor of the production factors they are abundantly endowed with. Figure 1 reproduces their main empirical finding by plotting the relative productivity of skilled to unskilled labor they measure against the relative endowment of skilled to unskilled labor.[2] This suggests countries deliberately choose the technologies that are best suited for them.

This paper provides an explanation to this finding, which is based on a standard Heckscher-Ohlin model. If countries trade with each other and specialize according to their comparative advantages, they will display different production structures. In the Heckscher-Ohlin model this translates into skill abundant countries specializing in skill intensive industries, and unskilled labor abundant countries specializing in unskilled labor intensive industries. Thus, when looking at these specialized countries from an aggregate

[1] See, among others, Caselli and Coleman (2006), Hall and Jones (1999), and Klenow and Rodríguez-Clare (1997). Caselli (2005) provides a thorough review of this literature.

[2] The data are described in detail in Caselli and Coleman (2006). The sample spans a cross-section of 52 developed and developing countries for the year 1988. Section 2 below describes the exercise by Caselli and Coleman (2006) in detail. Caselli (2005) also finds a similar pattern when focusing on physical capital and skilled labor: the technologies of skill abundant countries are biased in favor of skilled labor, and similarly for physical capital.

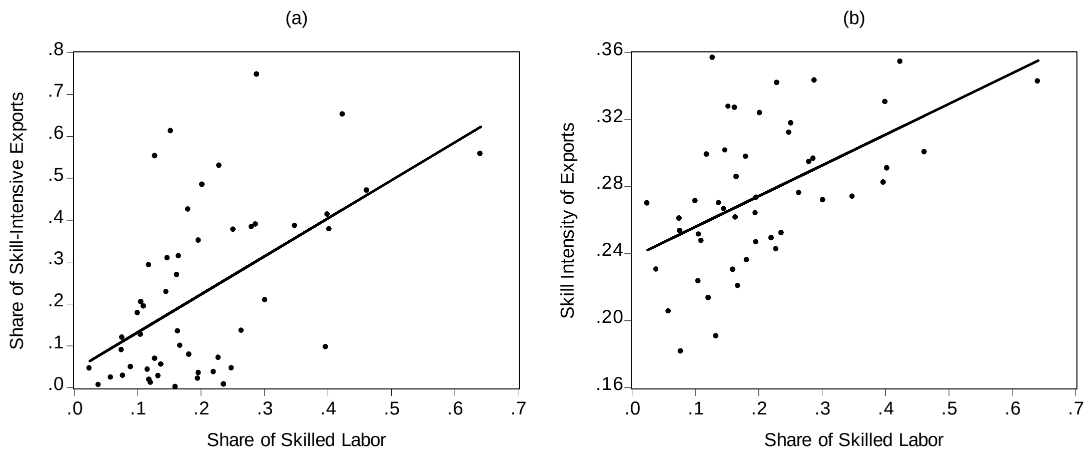

Figure 2: Relative factor endowments and export patterns

perspective, they seem to have an abundant-factor bias in their technologies. However, this is not the result of the deliberate choices of countries, but the unavoidable consequence of comparative advantage and international competition.

Figure 2 provides some empirical evidence supporting the idea that the production structures of countries vary systematically with relative skill abundance.[3] The left panel of figure 2 plots the share of skill-intensive exports in total manufacturing exports against the share of skilled labor in total employment (as computed by Caselli and Coleman (2006)).[4] Notice there is quite an evident positive relationship between specialization patterns and relative endowments. The right panel of figure 2 provides an alternative way of looking at the specialization patterns of countries: it plots the average skill intensity of a country's exports against the share of skilled labor in total employment.[5] Once again, countries that are more skill abundant seem to have their export patterns biased towards skill intensive industries.

In the light of this evidence, we produce a many-good model in which all countries have access to identical technologies. Industries vary in skill intensity, and countries vary in relative skill abundance, which gives rise to comparative advantage and some specialization when countries trade. Our exercise consists in using this standard Heckscher-Ohlin model as the process generating the 'data' to which we apply the development-accounting machinery. We find a measured factor bias positively correlated with factor abundance when

[3]See, among others, Cuñat and Melitz (2006) and Romalis (2004) for econometric evidence on the link between skill abundance and specialization.

[4]Data on exports for 3-digit SITC categories for the year 1988 and the same 52 countries examined in Caselli and Coleman (2006) come from the UNCTAD online database. The SITC categories considered span from 511 to 961. To identify high-skill categories, we follow the classification presented in UNCTAD (2002), p. 131. We compute the ratio between high-skill exports (*i.e.* exports for all SITC categories from 511 to 961) and total manufacturing exports.

[5]The average skill intensity of a country's exports is computed as

$$S_j = \sum_z \frac{x_{jz}}{\sum_z x_{jz}} s_z,$$

where x_{jz} denotes country j's sector-z exports, and s_z is a measure of a sector's skill intensity. To proxy for s_z, we use the ratio of non-production workers to total employment in each industry. Data for s_z are for the US; their source is the *US Census of Manufactures*.

applying the same aggregate production function to all countries in our development-accounting 'empirical' exercise.

The key intuition underlying this result is the 'flatter' relationship between skill premia and skill abundance implied by the trade equilibrium, in comparison with that of the autarky equilibrium, in which all countries have got identical production structures: when countries specialize according to their relative factor abundance, relative factor demand varies across countries in favor of each country's abundant factor. Thus, a development accounting exercise that does not account for differences in production structures will attribute the flat relationship between skill premia and skill abundance to a positive cross-country correlation between the skill bias of technology and the skill abundance of countries.

The rest of the paper is structured as follows. Section 2 reviews the Caselli-Coleman methodology and finding. Section 3 presents a stylized model that highlights the essence of our argument: we compare the model's implications for factor prices, production structures, and the measured factor bias of technology under autarky and free trade. In section 4 we simulate a more realistic version of our model in which we allow for trade frictions; we use this setup to assess the quantitative relevance of the arguments put forth in the paper, and find that a reasonable parametrization of our model generates an important measured factor bias of technology. Section 5 concludes, and the appendix discusses technical details.

2 The Factor Bias of Technology

Caselli and Coleman (2006) use the following aggregate production function to assess the factor bias of technology:

$$y = k^{\alpha}\left[\left(A^h h\right)^{\gamma} + \left(A^l l\right)^{\gamma}\right]^{\frac{1-\alpha}{\gamma}}, \tag{1}$$

where y denotes GDP; k is the physical capital stock; h and l denote, respectively, skilled and unskilled labor; A^h and A^l are factor-specific productivity augmenting factors; finally, $\alpha, \gamma \in (0,1)$. The parameter γ determines the elasticity of substitution between skilled and unskilled labor, which is given by $\delta = 1/(1-\gamma)$. If production factors are paid their marginal productivities, we can express the skill premium as

$$\frac{v}{w} = \left(\frac{A^l}{A^h}\right)^{\frac{1-\delta}{\delta}}\left(\frac{l}{h}\right)^{\frac{1}{\delta}}, \tag{2}$$

where v and w denote the prices of skilled labor and unskilled labor, respectively.

The system of equations (1) and (2) can be solved for the technology pair $\left(A^h, A^l\right)$. Using data for y, k, h, l, and v/w, and making standard assumptions about the values of parameters α and γ, Caselli and Coleman (2006) obtain values for $\left(A^h, A^l\right)$ for a sizable cross-section of countries. Their results imply a positive relationship between the ratio A^h/A^l and the factor endowment ratio h/l; that is, the skill bias of technology is positively correlated with the skill abundance of countries. Figure 3, constructed with the data in Caselli and Coleman (2006), provides some interpretation for this finding: a constant A^h/A^l would yield too steep a relationship between the log of the skill premium $\ln(v/w)$, and the log of the skill abundance ratio, $\ln(h/l)$, such as depicted by the steep (theoretical) line. To reconcile the theory (*i.e.*, equations (1) and (2)) with the data (the fitted line in figure 3), A^h/A^l must grow with h/l.

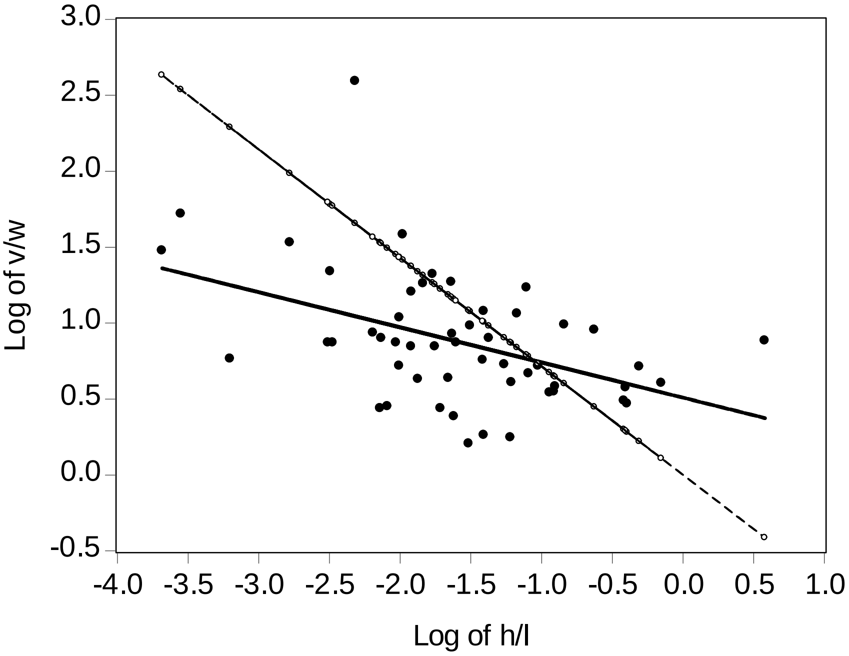

Figure 3: Skill premium vs. skill abundance.

3 The Model

Let us now discuss a many-sector model that will highlight the essence of our argument. Consider a world with many countries, denoted by $j = 1, ..., N$, $N \geq 2$. Countries are endowed with two productions factors, skilled labor h and unskilled labor l.[6] We label countries according to their skilled to unskilled labor ratios: the higher j, the higher h_j/l_j. Production factors are internationally immobile, and supplied ineslastically All markets are competitive.

Consumers maximize consumption of a non-traded final good y, which is made from a continuum of intermediate goods with the following production function:

$$y_j = \kappa \left[\int_0^1 x_j (z)^\rho \, dz \right]^{\frac{1}{\rho}}, \tag{3}$$

where $x(z)$ denotes the use of intermediate good z in the production of the final good; $\kappa > 0$; $\rho \in (0, 1)$; and $\varepsilon \equiv 1/(1 - \rho)$ is the elasticity of substitution between intermediates.

Intermediate good z is made with production function

$$q_j (z) = \left[\beta (z) \left[\phi_j^h h_j (z) \right]^\sigma + \left[1 - \beta (z) \right] \left[\phi_j^l l_j (z) \right]^\sigma \right]^{\frac{1}{\sigma}}, \tag{4}$$

where $q_j (z)$ denotes production of intermediate good z. $\beta (z) \in [0, 1]$ is the parameter that rules the factor intensity $h (z) / l (z)$ for a given skill premium. We rank goods so that $\beta' (\cdot) > 0$. For simplicity, we impose some symmetry on $\beta (z)$: for all z, $\beta (z) =$

[6] The third factor, physical capital, is not key. We will nevertheless consider it in an extension of the model below.

$1 - \beta(1-z)$.[7] We denote with $\eta \equiv 1/(1-\sigma)$ the elasticity of substitution between h and l, $\sigma \in (0,1)$. Finally, ϕ_j^h and ϕ_j^l are factor-augmenting productivity shifters.

3.1 Autarky

Let us consider autarky as a benchmark. In the appendix we show that in this case, and under the assumption that $\varepsilon = \eta$,[8] the skill premium is given by

$$\frac{v_j}{w_j} = \left(\frac{\phi_j^l}{\phi_j^h}\right)^{\frac{1-\eta}{\eta}} \left(\frac{l_j}{h_j}\right)^{\frac{1}{\eta}}. \tag{5}$$

Notice that this equation is isomorphic to equation (2). Hence, assuming that the autarky model is the 'data generating process' and provided $\delta = \varepsilon = \eta$, we would find $A_j^h/A_j^l = \phi_j^h/\phi_j^l$. In other words, under autarky there is a one-to-one relationship between the 'true' or theoretical factor bias, ϕ_j^h/ϕ_j^l, and its empirical counterpart, A_j^h/A_j^l.

3.2 Free Trade

For the rest of our discussion, we assume away the theoretical possibility of a factor bias in technology, although we let total factor productivity vary across countries: $\phi_j^h = \phi_j^l = \phi_j$. We also assume that intermediate goods can be traded freely. We distinguish two scenarios here: factor price equalization, which applies when the factor endowment ratios of countries are similar enough; and complete specialization, which applies when differences in factor endowment ratios are large.

3.2.1 Factor Price Equalization

If factor endowment ratios h_j/l_j are not very different across countries, then international trade in commodities equalizes factor prices across countries: $v_j/w_j = v/w \; \forall j$. In this case, one can show that the trade equilibrium is equivalent to the so-called 'integrated equilibrium', where both intermediate goods and production factors (measured in efficiency units) are internationally mobile. The integrated equilibrium is equivalent therefore to an autarky equilibrium.[9]

Assuming again $\varepsilon = \eta$,

$$\frac{v}{w} = \left(\frac{\sum_j \phi_j l_j}{\sum_j \phi_j h_j}\right)^{\frac{1}{\eta}}, \tag{6}$$

where $\sum_j \phi_j h_j$ and $\sum_j \phi_j l_j$ are the world endowments in efficiency units of skilled and unskilled labor, respectively.

This is obviously an extreme case, but it highlights the key role of international trade (as opposed to autarky) in the determination of relative factor prices. Notice that in this

[7] In a sense, this symmetry is in line with the CES part of the aggregate production function (1), since it enables us to produce an isomorphism between the autarky version of our many-good model and the Caselli-Coleman model.

[8] Although arbitrary, this assumption enables us to find an analytical solution for the equilibrium. In section 4 we allow for differences between ε and η, and show that our arguments do not depend on these parameters being equal.

[9] See Dixit and Norman (1980) for a formal discussion on factor price equalization and the integrated equilibrium. See also Trefler (1993) for an empirical analysis of factor price equalization.

case the relationship between $\ln(v_j/w_j)$ and $\ln(h_j/l_j)$ is completely flat. Therefore, if we took this factor price equalization model as the 'data generating process' and applied the methodology in Caselli and Coleman (2006), we would still measure a technology factor bias despite the assumption $\phi_j^h = \phi_j^l = \phi_j$: given a constant skill premium, equation (2) implies a positive relationship between A_j^h/A_j^l and h_j/l_j, provided $\delta > 1$.

3.2.2 Complete Specialization

Let us consider, for simplicity, the two-country case: $N = 2$. Assume $h_1/l_1 << h_2/l_2$, so that factor price equalization does not hold. In this case, we will have complete specialization: country 1 will specialize in the range of unskilled-intensive industries $z \in [0, \bar{z}]$, and country 2 will specialize in the range of skill-intensive industries $z \in (\bar{z}, 1]$.[10] Assuming once again $\varepsilon = \eta$, the factor market clearing conditions imply the following skill premia:

$$\frac{v_1}{w_1} = \left[\frac{\int_0^{\bar{z}} \beta(z)^\eta\, dz}{\int_0^{\bar{z}} [1-\beta(z)]^\eta\, dz}\right]^{\frac{1}{\eta}} \left(\frac{l_1}{h_1}\right)^{\frac{1}{\eta}}, \tag{7}$$

$$\frac{v_2}{w_2} = \left[\frac{\int_{\bar{z}}^1 \beta(z)^\eta\, dz}{\int_{\bar{z}}^1 [1-\beta(z)]^\eta\, dz}\right]^{\frac{1}{\eta}} \left(\frac{l_2}{h_2}\right)^{\frac{1}{\eta}}. \tag{8}$$

Obviously, $v_1/w_1 > v_2/w_2$; otherwise, the equilibrium specialization pattern would not hold.

Taking this complete specialization model as the 'data generating process', and provided $\delta = \varepsilon = \eta$, we would find

$$\left(\frac{A_1^l}{A_1^h}\right)^{\frac{1-\delta}{\delta}} = \left[\frac{\int_0^{\bar{z}} \beta(z)^\eta\, dz}{\int_0^{\bar{z}} [1-\beta(z)]^\eta\, dz}\right]^{\frac{1}{\eta}} < \left[\frac{\int_{\bar{z}}^1 \beta(z)^\eta\, dz}{\int_{\bar{z}}^1 [1-\beta(z)]^\eta\, dz}\right]^{\frac{1}{\eta}} = \left(\frac{A_2^l}{A_2^h}\right)^{\frac{1-\delta}{\delta}}. \tag{9}$$

In comparison with the autarky model, international trade makes countries specialize in industries that use their abundant factor intensively. This reduces the premium received by each economy's scarce factor, "flattening" the relationship between $\ln(v_j/w_j)$ and $\ln(h_j/l_j)$. Provided $\delta = \varepsilon = \eta > 1$, this model would also yield a positive correlation between A_j^h/A_j^l and h_j/l_j.

4 A Quantitative Experiment

In order to assess the quantitative relevance of our trade-based explanation of the factor bias of technology, we attempt to make our model more realistic by considering a third factor, physical capital, and trade frictions.[11] Intermediate goods are now made with production functions of the type

$$q_j(z) = \phi_j [k_j(z)]^\alpha \{\beta(z) [h_j(z)]^\sigma + [1-\beta(z)] [l_j(z)]^\sigma\}^{\frac{1-\alpha}{\sigma}}, \tag{10}$$

where $\alpha \in (0,1)$. Regarding trade frictions, we assume that $\tau > 1$ units of a good must be shipped for one unit to arrive from one country to another, with $\tau - 1$ units being lost on the way.[12] Notice that we are preventing capital abundance from giving rise to

[10] See Dornbusch, Fischer, and Samuelson (1980).

[11] The model is a generalization of the static trade model in Cuñat and Maffezzoli (2007).

[12] Below we identify $\tau > 1$ with the existence of import tariffs. However, we abstract from tariff revenue, as it has virtually no impact on the numerical results we report.

comparative advantage, since the power α is not indexed in z. Assuming $\alpha = 0$ and τ sufficiently high would bring us back to the autarky model discussed in section 3.1. Assuming $\alpha = 0$ and $\tau = 1$ yields the free-trade model discussed in section 3.2.

We consider the two-country case: $N = 2$. The model leads to a specialization pattern similar to that of the complete specialization model discussed above: in general, the equilibrium is characterized by two cut-off values z_1, z_2, $0 < z_2 < z_1 < 1$, that divide the range $[0, 1]$ in three subranges. For $z \in [0, z_2)$ z is produced exclusively by country 1. For $z \in [z_2, z_1]$ z is produced in both countries, and nontraded. Finally, for $z \in (z_1, 1]$ z is produced exclusively by country 2.

The appendix summarizes the model's equilibrium conditions. We are unable to solve for the equilibrium analytically, and therefore solve the model numerically.[13]

4.1 Calibration

Our benchmark parametrization is pinned down by the following calibration strategy. First of all, the elasticities of substitution ε and η are both assumed to be equal to $\delta = 1.4$, for consistency with Caselli and Coleman (2006). For the same reason, we set $\alpha = 1/3$. We set $\beta(z) = z$, which preserves the symmetry assumed above.

The trade cost τ is set to the benchmark value 1.21, which corresponds to one plus the unweighted average of the 1988 import tariff for a large subset of the countries in the Caselli and Coleman (2006) sample as reported by the World Bank.[14] Without loss of generality, we normalize the world capital stock and population to unity. We attribute 20% of world population and 70% of world capital to the skill-abundant country (country 2 in our notation). These figures correspond to the shares computed for OECD countries in the Caselli and Coleman (2006) sample. We assume that the share of skilled labor over total labor is equal to 83% in country 2 and 42% in country 1. Again, these figures correspond to the average shares for OECD countries against non-OECD countries. Finally, we normalize $\phi_1 = 1$ and set $\phi_2 = 3.47$ so as to let our calibrated model replicate the observed fact that OECD countries produce 61% of world output.

To summarize:

$$\begin{gathered}
\alpha = 1/3, \quad \beta(z) = z, \\
\delta = \varepsilon = \eta = 1.4, \\
\tau = 1.21 \\
\phi_1 = 1 < \phi_2 = 3.47, \\
k_1 = 0.3 < k_2 = 0.7, \\
h_1 = 0.336 < h_2 = 0.166, \\
l_1 = 0.464 > l_2 = 0.034.
\end{gathered}$$

For discussion purposes, we let τ vary from 1.01, which approximates the free-trade complete-specialization equilibrium of section 3.2, to 1.60, which yields the autarky equilibrium of section 3.1: given the factor endowment ratios h_j/l_j assumed above, comparative-

[13] We employ a globally stable trust-region algorithm to solve the non-linear system of equilibrium conditions; the integrals are approximated using a standard adaptive quadrature scheme.

[14] See the online database *Data on Trade and Import Barriers* published by the World Bank Trade Department and available on http://econ.worldbank.org. Note that for some countries the tariff for 1988 is not reported: where available, we use the observations for 1987 or 1989. Four countries do not have data on tariffs at all: Botswana, Dominican Republic, Honduras, and Panama.

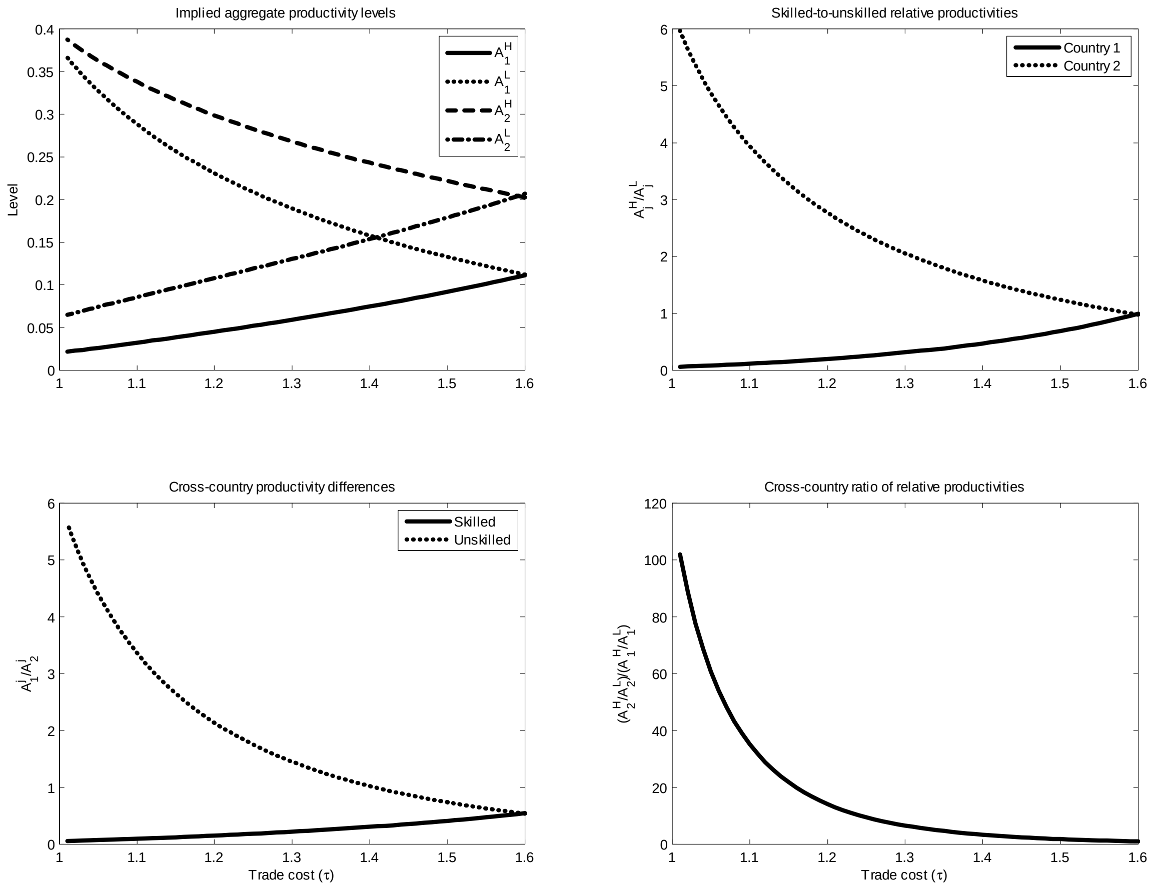

Figure 4: Openness and implied productivity differences

advantage driven gains from trade are compensated by the magnitude of trade frictions for $\tau \geq 1.60$.

4.2 Results

For each value of τ, we compute the resulting trade equilibrium, and use it as 'data' to compute the technology pair $\left(A_j^h, A_j^l\right)$ as discussed in section 2.[15] The top-left panel of Figure 4 plots the technology pairs $\left(A_j^h, A_j^l\right)$ thus obtained against τ. The other three panels report different ratios constructed with these data. The model produces the technology bias uncovered by Caselli and Coleman (2006), both in its 'absolute' (A_j^h rises with h_j/l_j, and A_j^l falls with h_j/l_j) and 'relative' (A_2^h/A_2^l rises with h_j/l_j) versions. Only when τ is prohibitively high ($\tau \geq 1.60$) and therefore countries have the same production structures do we obtain no factor bias of any kind: $A_2^h/A_1^h = A_2^l/A_1^l$ and $A_2^h/A_2^l = A_1^h/A_1^l = 1$.[16] The fact that $\tau = 1.60$ amounts to autarky can be read from the left panel of Figure 5, which reports the predicted trade shares (defined as the value of exports plus imports over GDP) of both countries: notice these are zero for $\tau = 1.60$.

The intuition here is similar to the one we discussed in Section 3.2: in the trade equi-

[15] To be precise, we normalize the computed factor biases of technology $\left(A_j^h, A_j^l\right)$ by the total factor productivity parameters ϕ_j assumed in our calibration.

[16] Notice that A_2^h/A_1^h and A_2^l/A_1^l need not equal one under autarky, as capital-labor ratios differ across countries.

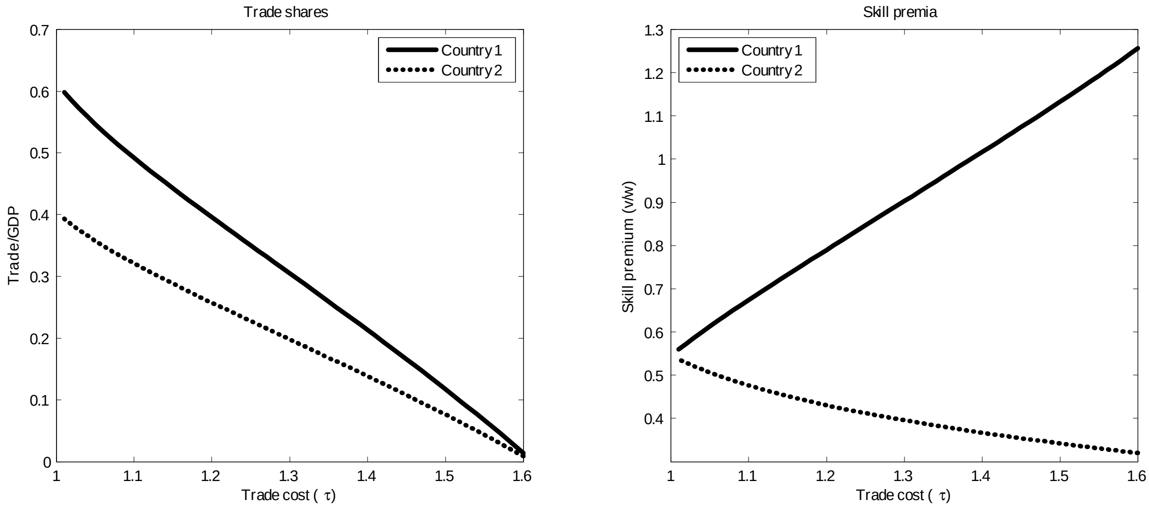

Figure 5: Trade shares and skill premia.

librium, countries specialize in industries that use their abundant factor intensively. This raises relative demand for their abundant factor, and reduces the premium received by each economy's scarce factor. In comparison with the autarky case, in which all countries have the same production structures, or with the aggregate production function of section 2, the cross-country differences in skill premia resulting from the trade equilibrium are not that large; this leads to a measured skill bias that is positively correlated with skill abundance. This intuition is corroborated by the right panel of Figure 5, which plots the trade equilibrium's skill premium against τ: *ceteris paribus*, cross-country differences in skill premia rise with τ.

Notice that our benchmark value for trade frictions, $\tau = 1.21$, yields reasonable magnitudes (0.39 in country 1 and 0.25 in country 2) for the trade shares of both countries;[17] for $\tau = 1.21$, the ratio $\left(A_2^h/A_2^l\right) / \left(A_1^h/A_1^l\right)$ is in the neighborhood of 13. These magnitudes illustrate the quantitative relevance of the mechanism highlighted in our model.

As a final comparative statics exercise, we let h_2 vary while keeping all other parameters constant. For comparison purposes, we report the corresponding results for two different trade regimes: trade with frictions ($\tau = 1.21$) and autarky ($\tau \geq 1.60$). Figure 6 plots $\log(v_2/w_2)$ against $\log(h_2/l_2)$, expressed in percentage deviations from their mean. It is apparent that the ability to trade 'flattens' the relationship between the log of the skill premium and the log of the skill-abundance ratio.

4.3 Sensitivity Analysis

Figure 7 reports how our main results change for different values of the elasticity of substitution between goods ε. We let ε vary between 1 and 4.[18] Again, we keep the benchmark parametrization, including $\tau = 1.21$, for all other parameters. It is apparent that a higher elasticity of substitution raises the measured factor bias of technology, as

[17] The trade shares for OECD countries and non-OECD countries in Caselli and Coleman (2006) are respectively 0.27 and 0.35. These figures have been computed by taking weighted averages of the openness indicator in constant prices reported in the *Penn World Tables 6.2*, using nominal GDP levels as weights.

[18] Yi (2003) reviews the CGE literature and finds that the 'elasticities that are typically estimated or employed in simulations/calibrations are on the order of two or three.'

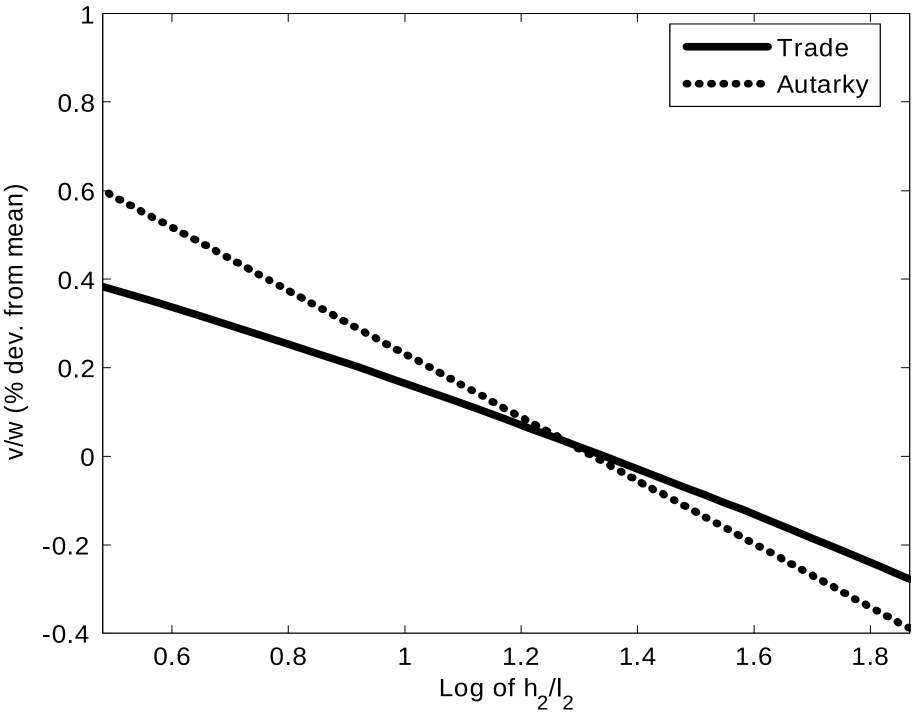

Figure 6: Skill premium vs. skill abundance in the model.

skill premia become less responsive to factor endowment differences. Notice, however, that doubling ε (for example, from 1 to 2) does not change the measured relative factor bias $\left(A_2^h/A_2^l\right)$ / $\left(A_1^h/A_1^l\right)$ dramatically.

Figure 8 reports the results from performing a similar exercise with η. We let this parameter vary between 1 and 2.[19] Once again, the measured relative factor bias of technology $\left(A_2^h/A_2^l\right)$ / $\left(A_1^h/A_1^l\right)$ rises with η: the better substitutes production factors are, the less responsive equilibrium skill premia are to differences in relative factor endowments. Notice that in this case doubling η (from 1 to 2) doubles the relative factor bias $\left(A_2^h/A_2^l\right)$ / $\left(A_1^h/A_1^l\right)$, which is quite sizable over the entire range $\eta \in (1, 2)$.

5 Concluding Remarks

This paper shows that international differences in production structures due to comparative advantage can explain the aggregate factor bias of technology uncovered in the development accounting literature. If countries specialize in industries that use their abundant factor intensively, relative demand for their abundant factor will be higher than under autarky, reducing the premium received by each economy's scarce factor. In comparison with the autarky case, in which all countries have the same production structures, the cross-country differences in skill premia resulting from the trade equilibrium are not that large. This leads to a measured skill bias that is positively correlated with skill abundance. Countries do display important differences in their production structures, which makes us think that the mechanism highlighted in this paper is indeed important from an empirical perspective. In fact, our numerical simulations suggests that the quantitative

[19] Caselli and Coleman (2006) review the labor economics literature and conclude that the elasticity of substitution between skilled and unskilled labor is very unlikely to fall outside of the interval $(1, 2)$.

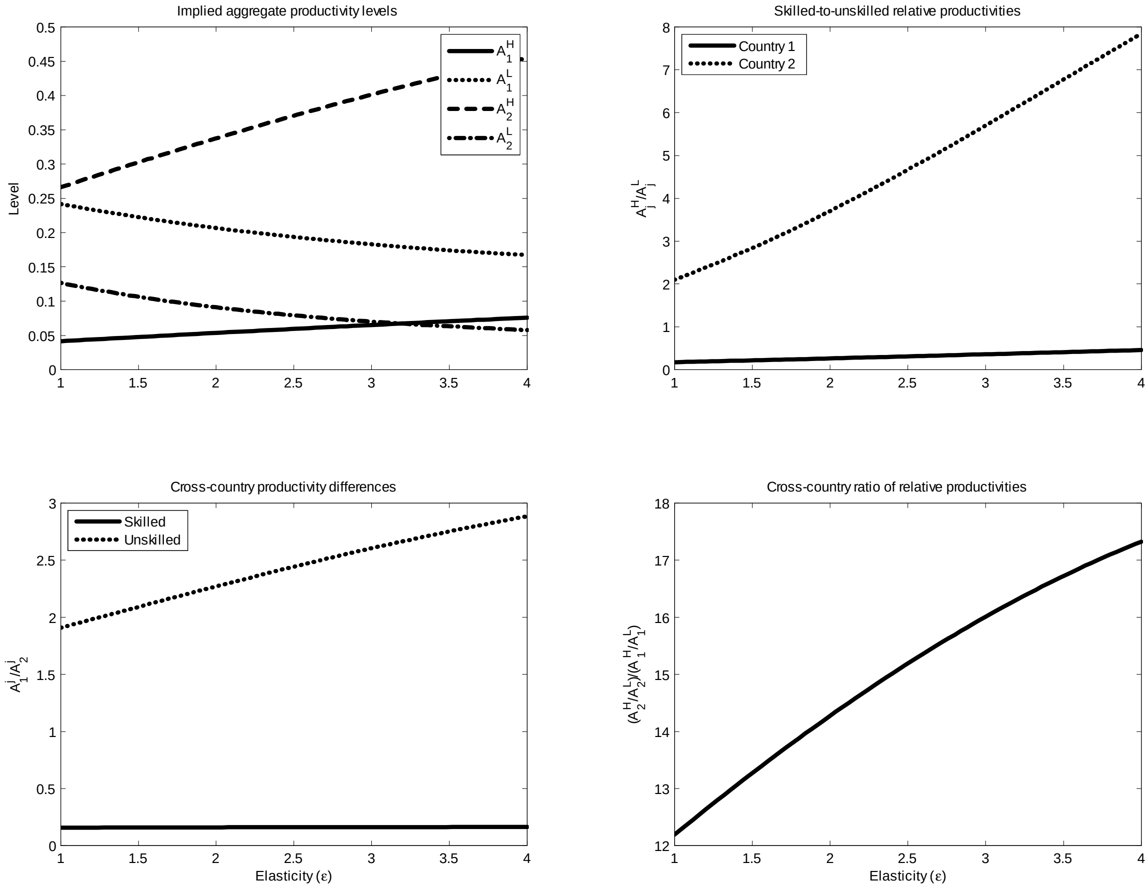

Figure 7: Sensitivity analisys: changes in ε, *ceteris paribus*.

effect of the mechanism we highlight is far from trivial.

The relevance of our results is twofold. First, as a matter of interpretation, our results imply that the measured factor bias of technology may not be the outcome of deliberate choices about technology by economic agents, but the result of specialization in an open-economy environment. Second, it suggests the need for disaggregate exercises to assess whether the factor bias of technology is indeed a genuine feature of the data.

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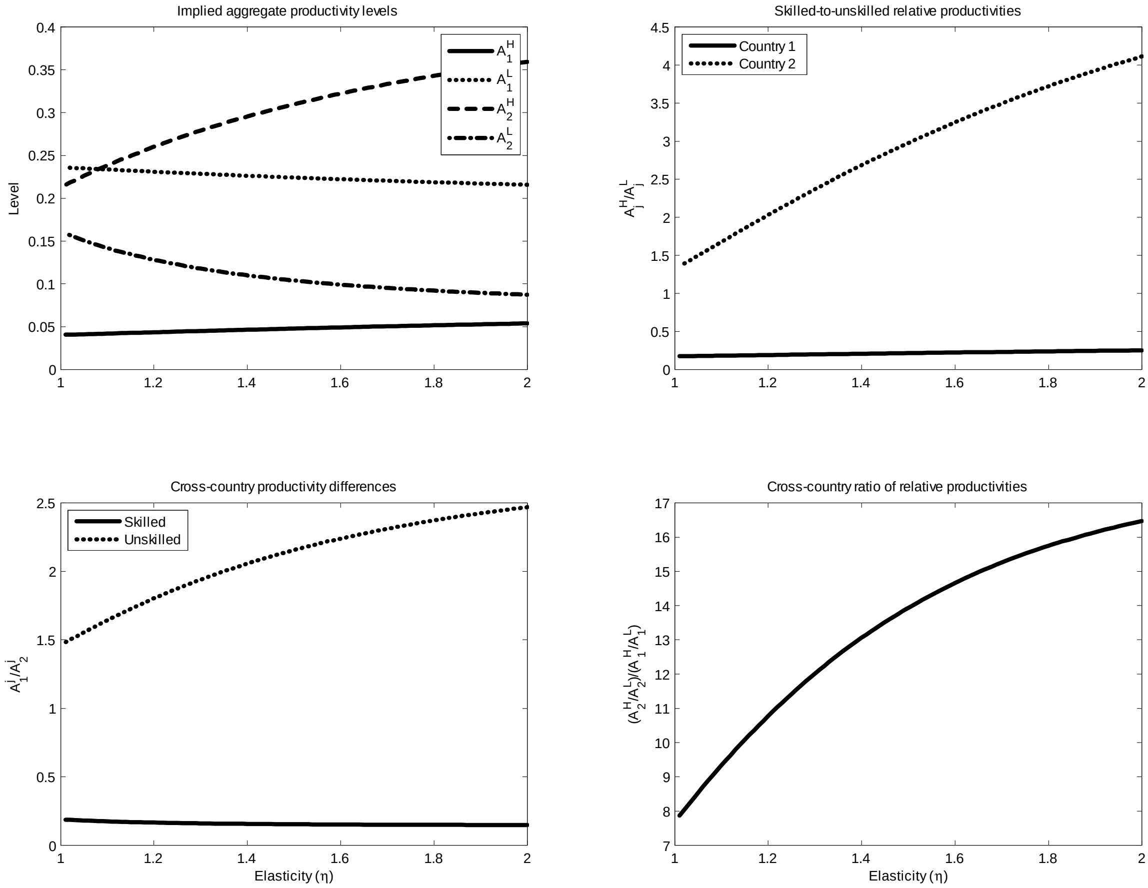

Figure 8: Sensitivity analisys: changes in η, *ceteris paribus*.

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6 Appendix

6.1 Autarky Equilibrium

The equilibrium conditions of the autarky model discussed in section 3.1 are:

$$p_j(z) = b_j(z), \tag{11}$$

$$q_j(z) = x_j(z), \tag{12}$$

$$h_j = \int_0^1 \frac{\partial b_j(z)}{\partial v} q_j(z)\,dz, \tag{13}$$

$$l_j = \int_0^1 \frac{\partial b_j(z)}{\partial w} q_j(z)\,dz, \tag{14}$$

$$x_j(z) = \left[\frac{p_j(z)}{p_j}\right]^{-\varepsilon} y_j = \frac{p_j(z)^{-\varepsilon}}{p_j^{1-\varepsilon}} Y_j, \tag{15}$$

$$p_j = \kappa^{-1}\left[\int_0^1 p_j(z)^{1-\varepsilon}\,dz\right]^{\frac{1}{1-\varepsilon}}. \tag{16}$$

for all z, j, where $Y_j \equiv p_j y_j = v_j h_j + w_j l_j$. Equation (11) sets the price of intermediate good z equal to its unit cost;[20] equation (12) is good z market clearing condition; equations (13) and (14) are the factor market clearing conditions; equation (15) gives the demand for good z; and equation (16) sets the price of the final good equal to its unit cost.

In general, this system does not have an analytical solution, but assuming $\varepsilon = \eta$ simplifies the algebra drastically: manipulating the system under this assumption yields

$$\frac{h_j}{l_j} = \frac{\int_0^1 \beta(z)^\eta\,dz}{\int_0^1 [1-\beta(z)]^\eta\,dz}\left(\frac{\phi_j^l}{\phi_j^h}\right)^{1-\eta}\left(\frac{w_j}{v_j}\right)^\eta. \tag{17}$$

The symmetry we imposed on $\beta(z)$ implies

$$\int_0^1 \beta(z)^\eta\,dz = \int_0^1 [1-\beta(z)]^\eta\,dz. \tag{18}$$

6.2 Trade with Frictions

The production function in equation (10) is associated to the following unit cost function:

$$b\left(z,\phi_j,r_j,v_j,w_j\right) = \phi_j^{-1}\left(\frac{r_j}{\alpha}\right)^\alpha\left[\frac{\left[[\beta(z)]^{\frac{1}{1-\sigma}} v_j^{\frac{\sigma}{\sigma-1}} + [1-\beta(z)]^{\frac{1}{1-\sigma}} w_j^{\frac{\sigma}{\sigma-1}}\right]^{\frac{(\sigma-1)}{\sigma}}}{1-\alpha}\right]^{1-\alpha}, \tag{19}$$

[20] Associated to production function (4) is the following unit cost function:

$$b_j(z) \equiv b\left(z,\phi_j^h,\phi_j^l,v_j,w_j\right) = \left[\beta(z)^\eta\left(\frac{v_j}{\phi_j^h}\right)^{1-\eta} + [1-\beta(z)]^\eta\left(\frac{w_j}{\phi_j^l}\right)^{1-\eta}\right]^{\frac{1}{1-\eta}}.$$

where r, v, and w denote the prices of capital, skilled labor and unskilled labor, respectively.

In general, the equilibrium is characterized by two cut-off values z_1, z_2, $0 < z_2 < z_1 < 1$, that divide the range $[0,1]$ in three subranges:

1. For $z \in [0, z_2)$, z is produced exclusively by country 1. Therefore:

$$p_1(z) = b_1(z), \tag{20}$$
$$p_2(z) = \tau p_1(z). \tag{21}$$

   Market clearing implies:

$$q_1(z) = \frac{p_1(z)^{-\varepsilon}}{p_1^{1-\varepsilon}} Y_1 + \tau \frac{p_2(z)^{-\varepsilon}}{p_2^{1-\varepsilon}} Y_2 = \frac{p_1^{\varepsilon-1} Y_1 + \tau^{1-\varepsilon} p_2^{\varepsilon-1} Y_2}{b_1(z)^{\varepsilon}}, \tag{22}$$
$$q_2(z) = 0. \tag{23}$$

   where $Y_j = r_j k_j + v_j h_j + w_j l_j$.

2. For $z \in [z_2, z_1]$, z is produced in both countries, and nontraded. Therefore:

$$p_1(z) = b_1(z), \tag{24}$$
$$p_2(z) = b_2(z). \tag{25}$$

   Market clearing implies:

$$q_1(z) = \frac{p_1(z)^{-\varepsilon}}{p_1^{1-\varepsilon}} Y_1 = \frac{p_1^{\varepsilon-1} Y_1}{b_1(z)^{\varepsilon}}, \tag{26}$$
$$q_2(z) = \frac{p_2(z)^{-\varepsilon}}{p_2^{1-\varepsilon}} Y_2 = \frac{p_2^{\varepsilon-1} Y_2}{b_2(z)^{\varepsilon}}. \tag{27}$$

3. For $z \in (z_1, 1]$, z is produced exclusively by country 2. Therefore:

$$p_1(z) = \tau p_2(z), \tag{28}$$
$$p_2(z) = b_2(z). \tag{29}$$

   Market clearing implies:

$$q_1(z) = 0, \tag{30}$$
$$q_2(z) = \tau \frac{p_1(z)^{-\varepsilon}}{p_1^{1-\varepsilon}} Y_1 + \frac{p_2(z)^{-\varepsilon}}{p_2^{1-\varepsilon}} Y_2 = \frac{\tau^{1-\varepsilon} p_1^{\varepsilon-1} Y_1 + p_2^{\varepsilon-1} Y_2}{b_2(z)^{\varepsilon}} \tag{31}$$

Let us choose $p(0) = 1$ as our numeraire. Given ϕ_j, k_j, h_j, l_j, and τ, the unknowns of the model are r_j, v_j, w_j, and z_j. We can solve for the unknowns from the following system of equations:

1. Factor market clearing conditions:[21]

$$\int_0^{z_1} \frac{\partial b_1(z)}{\partial r} q_1(z)\, dz = k_1, \tag{32}$$

$$\int_0^{z_1} \frac{\partial b_1(z)}{\partial v} q_1(z)\, dz = h_1, \tag{33}$$

$$\int_0^{z_1} \frac{\partial b_1(z)}{\partial w} q_1(z)\, dz = l_1, \tag{34}$$

$$\int_{z_2}^{1} \frac{\partial b_2(z)}{\partial r} q_2(z)\, dz = k_2, \tag{35}$$

$$\int_{z_2}^{1} \frac{\partial b_2(z)}{\partial v} q_2(z)\, dz = h_2, \tag{36}$$

$$\int_{z_2}^{1} \frac{\partial b_2(z)}{\partial w} q_2(z)\, dz = l_2. \tag{37}$$

2. Marginal commodity conditions:

$$b_j(z_j) = \tau b_{-j}(z_j). \tag{38}$$

3. Numeraire:

$$p_1(0) = 1 = b_1(0). \tag{39}$$

Assuming $\beta(z) = z$ and expanding the system of factor market clearing conditions yields

$$p_1^{\varepsilon-1} Y_1 \int_0^{z_1} b_1(z)^{1-\varepsilon}\, dz + \left(\frac{p_2}{\tau}\right)^{\varepsilon-1} Y_2 \int_0^{z_2} b_1(z)^{1-\varepsilon}\, dz = \frac{r_1 k_1}{\alpha}, \tag{40}$$

$$p_2^{\varepsilon-1} Y_2 \int_{z_2}^{1} b_2(z)^{1-\varepsilon}\, dz + \left(\frac{p_1}{\tau}\right)^{\varepsilon-1} Y_1 \int_{z_1}^{1} b_2(z)^{1-\varepsilon}\, dz = \frac{r_2 k_2}{\alpha}, \tag{41}$$

$$p_1^{\varepsilon-1} Y_1 \int_0^{z_1} b_1(z)^{1-\varepsilon} \Omega_1(z)\, dz + \left(\frac{p_2}{\tau}\right)^{\varepsilon-1} Y_2 \int_0^{z_2} b_1(z)^{1-\varepsilon} \Omega_1(z)\, dz = \frac{v_1 h_1}{1-\alpha}, \tag{42}$$

$$p_2^{\varepsilon-1} Y_2 \int_{z_2}^{1} b_2(z)^{1-\varepsilon} \Omega_2(z)\, dz + \left(\frac{p_1}{\tau}\right)^{\varepsilon-1} Y_1 \int_{z_1}^{1} b_2(z)^{1-\varepsilon} \Omega_2(z)\, dz = \frac{v_2 h_2}{1-\alpha}, \tag{43}$$

$$p_2^{\varepsilon-1} Y_2 \int_{z_2}^{1} b_2(z)^{1-\varepsilon} \left[1 - \Omega_2(z)\right] dz + \tag{44}$$
$$\left(\frac{p_1}{\tau}\right)^{\varepsilon-1} Y_1 \int_{z_1}^{1} b_2(z)^{1-\varepsilon} \left[1 - \Omega_2(z)\right] dz = \frac{w_2 l_2}{1-\alpha},$$

[21] One of these is redundant.

where

$$
\begin{aligned}
Y_j &= r_j k_j + v_j h_j + w_j l_j, & (45)\\
p_1 &= \kappa^{-1}\left[\int_0^{z_1} b_1(z)^{1-\varepsilon}dz + \tau^{1-\varepsilon}\int_{z_1}^{1} b_2(z)^{1-\varepsilon}dz\right]^{\frac{1}{1-\varepsilon}}, & (46)\\
p_2 &= \kappa^{-1}\left[\tau^{1-\varepsilon}\int_0^{z_2} b_1(z)^{1-\varepsilon}dz + \int_{z_2}^{1} b_2(z)^{1-\varepsilon}dz\right]^{\frac{1}{1-\varepsilon}}, & (47)\\
b_j(z) &= \phi_j^{-1}\left(\frac{r_j}{\alpha}\right)^{\alpha}\left[\frac{\left[z^{\eta}v_j^{1-\eta} + (1-z)^{\eta}w_j^{1-\eta}\right]^{\frac{1}{1-\eta}}}{1-\alpha}\right]^{1-\alpha}, & (48)\\
\Omega_j(z) &\equiv \frac{z^{\eta}v_j^{1-\eta}}{z^{\eta}v_j^{1-\eta} + (1-z)^{\eta}w_j^{1-\eta}} & (49)
\end{aligned}
$$

The system (40)-(44), along with

$$
\begin{aligned}
b_1(z_1) &= \tau b_2(z_1), & (50)\\
b_2(z_2) &= \tau b_1(z_2), & (51)\\
w_1 &= (1-\alpha)\left[\phi_1\left(\frac{\alpha}{r_1}\right)^{\alpha}\right]^{\frac{1}{1-\alpha}}, & (52)
\end{aligned}
$$

yields the equilibrium factor prices, and z_1 and z_2. The volume of trade is easy to compute once one has got a solution to the equilibrium. For example, the value of imports by country 2 is given by

$$
M_2 = \int_0^{z_2} p_2(z)\,\tau\frac{p_2(z)^{-\varepsilon}}{p_2^{1-\varepsilon}}Y_2 dz = \frac{\tau Y_2}{p_2^{1-\varepsilon}}\int_0^{z_2} p_2(z)^{1-\varepsilon}dz, \qquad (53)
$$

where we are valuing the traded quantities at c.i.f. prices.