FIW – Working Paper

FIW Working Paper N° 183
February 2018

Effect of International Trade on Wage Inequality with Endogenous Technology Choice

Tran Lam Anh Duong[1]

Abstract

This paper investigates how trade openness affects wage inequality of trading countries, both within and between them. Specifically, based on the theoretical literature on monopolistic competition between two asymmetric countries, we derive a new framework under the assumption of endogenous technology choice. This assumption implies that firms simultaneously choose to adopt different technology compositions which are appropriate for its labor composition. In other words, instead of utilizing standard constant technology as in most of other research, firms in this model are allowed to choose the technology system that maximizes their profits. With this framework, we find that firms in countries which are skilled-labor-abundant choose technologies that are appropriate for skilled labor, and vice versa for firms in unskilled-labor-abundant countries. The wage gap between different types of labor depends on the comparative level of technological capability, the skill composition in the two countries, and the skill bias. During the transition from autarky to free trade, if the size of the labor force and its composition in both countries satisfy a particular condition, we find that the decline in transport cost will increase the relative wage between one country and the other in both types of labor. Moreover, these effects on wage inequality in all phases, i.e., autarky, free trade, and the transition from autarky to free trade, are partially absorbed by the endogeneity in technology choice. In other words, if a firm utilizes a standard constant technology only, the effect on wage inequality is amplified. Based on calibration results utilizing data from 52 countries, we find that in some plausible scenarios, this amplification may generate different understandings of the role of trade openness on wage inequality.

Keywords: international trade, endogenous technology choice, transport cost, wage inequality.
JEL: F16, F11.

The author

1 Tran Lam Anh Duong, Faculty of Engineering, Information and Systems, University of Tsukuba, Tennodai 1-1-1, Tsukuba, Ibaraki 305-8573, Japan. Email address: anhduongtl (at) sk.tsukuba.ac.jp

The Research Centre International Economics FIW is a project of WIFO, wiiw and WSR on behalf of the Federal Ministry for Digital, Business and Enterprise. The FIW cooperation with Austrian Universities is supported by the Federal Ministry of Education, Science and Research.

Effect of International Trade on Wage Inequality with Endogenous Technology Choice

Tran Lam Anh Duong*

November 1, 2017

Abstract

This paper investigates how trade openness affects wage inequality of trading countries, both within and between them. Specifically, based on the theoretical literature on monopolistic competition between two asymmetric countries, we derive a new framework under the assumption of endogenous technology choice. This assumption implies that firms simultaneously choose to adopt different technology compositions which are appropriate for its labor composition. In other words, instead of utilizing standard constant technology as in most of other research, firms in this model are allowed to choose the technology system that maximizes their profits. With this framework, we find that firms in countries which are skilled-labor-abundant choose technologies that are appropriate for skilled labor, and vice versa for firms in unskilled-labor-abundant countries. The wage gap between different types of labor depends on the comparative level of technological capability, the skill composition in the two countries, and the skill bias. During the transition from autarky to free trade, if the size of the labor force and its composition in both countries satisfy a particular condition, we find that the decline in transport cost will increase the relative wage between one country and the other in both types of labor. Moreover, these effects on wage inequality in all phases, i.e., autarky, free trade, and the transition from autarky to free trade, are partially absorbed by the endogeneity in technology choice. In other words, if a firm utilizes a standard constant technology only, the effect on wage inequality is amplified. Based on calibration results utilizing data from 52 countries, we find that in some plausible scenarios, this amplification may generate different understandings of the role of trade openness on wage inequality.

Keywords: international trade, endogenous technology choice, transport cost, wage inequality
JEL classification codes: F16, F11

*Correspondence address: Tran Lam Anh Duong, Faculty of Engineering, Information and Systems, University of Tsukuba, Tennodai 1-1-1, Tsukuba, Ibaraki 305-8573, Japan. Email address: anhduongtl (at) sk.tsukuba.ac.jp

1 Introduction

Together with the rapid trade globalization in recent decades, there are increasing concerns about how trade openness affects wage inequality in trading partners, both within and between them. Early analyze first appeared in the Heckscher-Ohlin framework. They show that the rise in the skill premium - the relative wage of skilled to unskilled workers - is mainly due to cheaper unskilled-labor-intensive imports. Recently, trade economists have proposed more sophisticated trade models to examine the key determinant of the skill premium. For example, Feenstra and Hanson (1996) have shown that outsourcing unskilled-labor intensive production can raise the skill premium in both trade partners. Acemoglu (2003) shows how trade liberalization can induce skill-biased technological progress in models with endogenous innovation. Epifani and Gancia (2008) focus on the trade-induced scale effect. In this paper, we aim to examine the effect of trade openness on wage inequality under an assumption of endogenous technology choice.

The motivation for such assumption is the fact that in reality, different types of technology systems are appropriate for different inputs. Hence, together with choosing different combinations of labor, firms simultaneously choose to adopt different technology compositions which are appropriate for its labor composition. For example, a firm can choose to be unskilled-labor-intensive by having its factory mainly run by unskilled labor and supervised by a few number of skilled labor, or choose to be skilled-labor-intensive by introducing an automatic system operated by skilled labor. As a result, a firm can choose its particular technology system, which could be different from the selection of other firms in the same country.

Under the assumption of endogenous technology choice, a firm's decision of input volume and technology system will interact endogenously, leading to different results, compared to the case with the standard assumption of fixed technology system. Thus, applying this assumption to a trade model could lead to different effects of trade on wage inequality. For that reason, the core of the framework in this paper is a new version of a two-country general equilibrium trade model with monopolistic competition analyzed under the assumption of endogenous technology choice.

The use of this non-standard assumption has been developed since the late 1960s by Atkinson and Stiglitz (1969). Their paper introduces discrimination between labor-intensive and capital-intensive techniques and claims that a firm cannot choose its techniques solely due to factor prices, but must take into account the technical knowledge specific to each technique under the spillover effect. Since the pioneering work of Atkinson and Stiglitz (1969), endogeneity in technology choice has been discussed in several ways. Basu and Weil (1996) introduce the concept of appropriate technology into a learning-by-doing model where different technologies are specific to particular combinations of inputs. Acemoglu (2002) finds that technical change will be biased to optimize the conditions and factor suppliers in the country where the technology is developed.

Despite the importance of the endogenous technology choice assumption, not many trade models incorporate this important notion. In one of the most influential studies in the field, Yeaple (2005) builds a general equilibrium trade model where homogeneous firms in identical countries can choose its own technology and employees. He finds that a decline in trade costs induces firms to adopt new technologies, leading to wage premium expansion between highly and moderately skilled labor. The main difference between this paper and Yeaple (2005) is twofold. First, in Yeaple (2005) a single type of labor is hired by a firm that uses a specific type of technology. On the other hand, in this paper a firm can choose an optimal composition of unskilled and skilled labor along with an optimal composition of technology system that is appropriate for these two types of labor. Second, under the assumption of heterogeneous countries in the presence of variation in technological capability and labor composition, firms also take into account the labor endowment of other country in trade.

In particular, in this paper a firm is allowed to choose a large number of different technologies that differ in the use of unskilled and skilled labor. Firms choose their optimal compositions of technology, thus these sets are all non-dominated and located at the country's "technology frontier". Under these settings, the introduction of countries that are heterogeneous in technological capability and labor composition can lead to a very different effects of trade on wage inequality. A theoretical model of particular interest in the context of the production functions with endogenous technology choice is the model of Caselli and Coleman (2006). They adopt the idea that each type of labor could be more or less effective with different types of technology. They assume imperfect substitutions between unskilled and skilled labors, and find that in a given economy, an appropriate technology is chosen depending on the skill composition of labor. Their model incorporates the key features of factor-specific productivity, but is sufficiently simple to permit extension for the purpose of my analysis. This paper applies the specification of the production structure à la Caselli and Coleman (2006), in which skill bias in technology could arise endogenously, to a two-country general equilibrium trade model with monopolistic competition.

The paper yields some interesting results. In autarky, firms in countries which are skilled-labor-abundant choose technologies that are appropriate for skilled labor, and vice versa for firms in unskilled-labor-abundant countries. In trade, the wage gap between types of labor depends on the relative level of technological capability, the skill composition in both countries, and the skill bias. During the transition from autarky to free trade, if the labor force and labor composition in both countries satisfy a particular condition, we find that the decline in transport cost will increase the relative wage between the two countries in both types of labor. Moreover, these effects on wage inequality in all phases, i.e., autarky, free trade, and the transition from autarky to free trade, are also partially explained by the endogeneity in technology choice. In other words, if a firm only utilizes a standard constant technology, the effect on wage inequality is amplified. Furthermore, based on calibration results utilizing data from 52 countries, we find that in some plausible scenarios, the amplification derived from the standard constant technology assumption may generate different understandings of the role of openness on wage inequality.

The remainder of the paper is organized as follows. Section 2 lays out the model and characterizes the autarkic equilibrium. Section 3 solves for the free trade equilibrium in an asymmetric two-country setting. Section 4 provides analytical and numerical analysis on transport cost. Section 5 details the conclusions and extensions.

2 Autarky economy

In this paper, we utilize a general-equilibrium monopolistic competition model that emphasizes production differentiation. To highlight the mechanisms through which a firm's choice of technology and employment affect wages, we start with a closed economy and then examine the implications of opening the economy to international trade.

2.1 The setup

The economic environment assumes that in a country, there are N firms operating under monopolistic competition. Each firm produces a differentiated good and uses different technologies. The production requires two factors of production, unskilled and skilled labor. Each type of labor works with different technologies.

Firm i hires a combination of unskilled and skilled labor to produce only good i. The production function of good i is as follows

$$x_i = [(A_i^u l_i^u)^\gamma + (A_i^s l_i^s)^\gamma]^{\frac{1}{\gamma}}, \tag{1}$$

where γ is the substitutability between unskilled and skilled labor ($0 < \gamma < 1$), l_i^u and l_i^s are the number of unskilled and skilled laborers hired by firm i, respectively, and A_i^u and A_i^s are the appropriate technologies for the unskilled and skilled labor hired by firm i, respectively.

Firm i chooses A_i^u and A_i^s from a menu of a large number of different technologies, which vary in their applicability to unskilled and skilled labor. This means that a firm can choose which type of firm it wants to become, i.e., an unskilled-labor-intensive firm, or a skilled-labor-intensive firm. However, a country has its own level of technological capability, so that a firm faces limitations in choosing its technology. The menu of feasible technical choice is as follows

$$(1-\alpha)(A_i^u)^\beta + \alpha(A_i^s)^\beta \leq B, \tag{2}$$

where B is the level of technological capability ($B > 0$), α is skill bias parameter, and β is a parameter that determines the trade-off between A_i^u and A_i^s. Mathematically, the equation shows the curvature of the technology constraint curve. α, β, and B are strictly positive parameters. Specifically, for an unchanged B, a large α makes it difficult to access a skilled labor technology. When α is 0.5, the symmetric case applies. This setting of the production function is borrowed from Caselli and Coleman (2006), who introduce a general production function where the assumption of perfect substitutability of different types of labor is relaxed, and the technology used for each type of labor is endogenized. The authors show that this type of production function can explain real data well.

The population in the country is L. Skilled labor accounts for a share, σ, of the population and the reminder, $1-\sigma$, is unskilled labor, where $0 < \sigma < 1$. Let $\rho = \frac{1-\sigma}{\sigma}$ be the ratio of unskilled labor over skilled labor. Then, we have the following full employment conditions

Unskilled labor:

$$\sum_i^N l_i^u = L^u = (1-\sigma)L, \tag{3}$$

Skilled labor:

$$\sum_i^N l_i^s = L^s = \sigma L. \tag{4}$$

where N is the number of firms.

Goods enter symmetrically into demand. All consumers in the economy are assumed to have the same utility function:

$$U = \sum_{i=1}^N c_i^\theta, \tag{5}$$

where $0 < \theta < 1$. This corresponds to the constant elasticity of substitution utility function, which is homothetic and has an elasticity equal to $\frac{1}{1-\theta}(> 1)$.

Utility maximization for k-type labor is as follows

$$\begin{cases} \max \sum_i^N (c_i^k)^\theta \\ \text{s.t } \sum_i^N p_i c_i^k = w^k, \end{cases}$$

where k is unskilled or skilled labor ($k = u, s$) and w^k is the wage for k-type labor. Then, price is determined by the demand curve, as follows

$$p_i = \frac{\theta}{\lambda^k}(c_i^k)^{\theta-1}, \tag{6}$$

where λ^k is a Lagrange multiplier in the utility maximization problem of k-type labor. The price elasticity of the demand curve is $\frac{1}{\theta-1}$.

Given that the wages w^u and w^s must be positive, the problem of firm i is to maximize its profit under the technology constraint shown in equation (2). The profit function is computed by subtracting the labor cost from revenue, as follows

$$\begin{cases} \max\ p_i(x_i - f_e) - w^s l_i^s - w^u l_i^u \\ \text{s.t } (1-\alpha)(A_i^u)^\beta + \alpha(A_i^s)^\beta = B, \end{cases} \tag{7}$$

where f_e is the fixed cost required to set up a firm.[1]

Firms can freely enter the market. However, they do not choose to do so unless their expected profits are equal to the fixed cost. The free entry condition can be written as follows

$$\pi_i = p_i x_i - w^s l_i^s - w^u l_i^u = p_i f_e. \tag{8}$$

Under the goods market clearing condition, net output must equal the total consumption of all individual in the labor pool (unskilled and skilled labor)

$$x_i - f_e = L^s c_i^s + L^u c_i^u. \tag{9}$$

Here, we assume that firms are symmetric. Then, from equation (4), the labor market clearing conditions will become $Nl^u = (1-\sigma)L$ and $Nl^s = \sigma L$.

2.2 Closed economy equilibrium

Under the condition that parameter β is larger than $\frac{\gamma}{1-\gamma}$, there exists a unique interior solution. At the equilibrium, the technology and employment choices are[2]

$$A^s = \left(\frac{B}{\alpha[1+(\frac{\alpha}{1-\alpha}\rho^\beta)^{\frac{\gamma}{\beta-\gamma}}]}\right)^{\frac{1}{\beta}}, \ A^u = \left(\frac{B(\frac{\alpha}{1-\alpha}\rho^\beta)^{\frac{\gamma}{\beta-\gamma}}}{(1-\alpha)[1+(\frac{\alpha}{1-\alpha}\rho^\beta)^{\frac{\gamma}{\beta-\gamma}}]}\right)^{\frac{1}{\beta}},$$

$$l^u = \frac{f_e \alpha^{\frac{1}{\beta}} \rho}{(1-\theta)B^{\frac{1}{\beta}}\left[1+\left(\frac{\alpha}{1-\alpha}\rho^\beta\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}}}, \ l^s = \frac{f_e \alpha^{\frac{1}{\beta}}}{(1-\theta)B^{\frac{1}{\beta}}\left[1+\left(\frac{\alpha}{1-\alpha}\rho^\beta\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}}}.$$

The relative wage at the equilibrium for unskilled and skilled labor is computed as follows

$$\frac{w^u}{w^s} = \left(\frac{\alpha}{1-\alpha}\right)^{\frac{\gamma}{\beta-\gamma}} \rho^{\frac{\beta\gamma-\beta+\gamma}{\beta-\gamma}}.$$

The number of firms entering the market can be determined by using the condition of full employment. From equation (4), we have

$$N = \frac{\sigma L}{l^s} = \frac{(1-\theta)B^{\frac{1}{\beta}}\left[1+\left(\frac{\alpha}{1-\alpha}\rho^\beta\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}} L}{f_e(1+\rho)\alpha^{\frac{1}{\beta}}}.$$

[1] Here, the firm pays the fixed cost f_e from its production, rather than as an input. With this setting, the analysis on wage inequality is considerably simplified but the main features in the conclusion of the paper are maintained. Refer to propositions presented in Sections 2-4 to find that intuitive explanation for each proposition does not depend on the form of fixed cost. Clearly, if the firm pays the fixed cost by its input, some interesting aspects for discussion arise, and some quantitative effects may change. However, to focus on the consequences of the endogenous technology choice, which is the main motivation of this paper, further examination of this fixed cost setting is left for future work.

[2] See Appendix A.

Proposition 1. *The weight of the technology system appropriate for unskilled labor over that for skilled labor,* $\frac{A^u}{A^s}$*, increases with* α *and* ρ*.*

Mathematically, the weight of the technology system used for unskilled labor over that used for skilled labor $\left(\frac{A^u}{A^s}\right)$ is equal to $\left(\frac{\alpha}{1-\alpha}\rho^\gamma\right)^{\frac{1}{\beta-\gamma}}$. The exponent $\frac{1}{\beta-\gamma}$ is positive if β is larger than γ under the condition for existence of the interior solution. The intuitive explanation for this result is as follows. First, if the technology system for unskilled labor is relatively easier to access ($\alpha \uparrow$) compared with that for skilled labor, the firm will obviously choose to utilize more of the technology that is appropriate for unskilled labor, A^u. Second, if the country is unskilled-labor-abundant ($\rho \uparrow$), more firms tend to choose technology that is appropriate for unskilled labor. For example, a developing country that is unskilled-labor-abundant usually has more firms using technologies that are appropriate for this type of labor.

Proposition 2. *The increase in the rate of unskilled over skilled labor* ($\rho \uparrow$) *reduces the relative wage between these two types of labor* $\left(\frac{w^u}{w^s} \downarrow\right)$*. The change in this wage premium is partially absorbed by the endogeneity in technology choice.*

This feature is intuitive. However, compared to the case of standard constant technology (in which A_i^u and A_i^s are given), the decrease in the relative wage is smaller in the case of endogenous technology choice. The ability to endogenously select the technology partially absorbs this effect. For example, in a country which is abundant in unskilled labor, the wage for this type of labor is relatively low. However, because the technology system is endogenized, firms choose the technology system that can utilize the abundant resource, which is unskilled labor, as much as possible. As a result, the demand for unskilled labor increases and it partly absorbs the effects on the relative wage arising from a large number of unskilled laborers. Therefore, with the endogenous technology choice model, we find that the inequality between the two types of labor is not as serious as in the case of the fixed technology model. The same setting and result occurs in the case of the relative wage between skilled and unskilled labor, $\frac{w^s}{w^u}$.

3 Free trade

3.1 The setup

In this section, suppose that two countries trade with one another, with zero transportation costs. The two countries are the North country (N) and the South country (S), which differ in terms of their level of technological capability, B^J, and the ratio between unskilled and skilled labor, ρ^J, $J = N, S$.

The setting is similar to the autarky version. Each good is produced by only one firm in one country. A firm in each country hires unskilled and skilled labor, taking as given the wages of $w^{J,u}$ and $w^{J,s}$, to produce good i, with the following production function

$$x_i^J = [(A_i^{J,u} l_i^{J,u})^\gamma + (A_i^{J,s} l_i^{J,s})^\gamma]^{\frac{1}{\gamma}}. \tag{10}$$

The technology constraint has the form of

$$(1-\alpha)(A_i^{J,u})^\beta + \alpha(A_i^{J,s})^\beta \leq B^J. \tag{11}$$

The firm maximizes its profits under the technology constraint. We have the following profit maximization problem

$$\begin{cases} \max \ p_i^J(x_i^J - f_e) - w^{J,s} l_i^{J,s} - w^{J,u} l_i^{J,u} \\ \text{s.t } (1-\alpha)(A_i^{J,u})^\beta + \alpha (A_i^{J,s})^\beta = B^J. \end{cases} \tag{12}$$

The full employment condition is as follows

- Unskilled labor:

$$\sum_i^{N^J} l_i^{J,u} = N^J l^{J,u} = L^{J,u} = (1-\sigma^J) L^J, \tag{13}$$

- Skilled labor:

$$\sum_i^{N^J} l_i^{J,s} = N^J l^{J,s} = L^{J,s} = \sigma^J L^J. \tag{14}$$

The ratio of unskilled labor over skilled labor in country J, ρ^J, is defined as $\frac{1-\sigma^J}{\sigma^J}$.

Under the free entry condition, the firms' expected net profits become equal to the fixed cost

$$\pi_i^J = p_i^J x_i^J - w^{J,s} l_i^{J,s} - w^{J,u} l_i^{J,u} = p_i^J f_e. \tag{15}$$

The goods market clearing condition under free trade accounts for goods consumed both domestically and internationally, as follows

$$x_i^J - f_e = L^{J,u} c_i^{J,u} + L^{J,s} c_i^{J,s} + L^{-J,u} c_i^{J*,u} + L^{-J,s} c_i^{J*,s}, \tag{16}$$

where $-J$ means a country that is "not country J"; $c_i^{J,k}$ denotes consumption of a good, produced in country J, consumed by k-type labor living in country J; $c_i^{J*,k}$ is consumption of an imported good from country $-J$, consumed by k-type labor living in country J, and $k = u, s$.

The utility maximization problem of k-type labor in country J is as follows

$$\begin{cases} \max \ \sum_i^{N^J} (c_i^{J,k})^\theta + \sum_j^{N^{-J}} (c_j^{-J*,k})^\theta \\ \text{s.t } \sum_i^{N^J} p_i^J c_i^{J,k} + \sum_j^{N^{-J}} p_j^{-J} c_j^{-J*,k} = w^{J,k}. \end{cases} \tag{17}$$

The following trade balance condition shows that the export and import values of a country must be equal

$$\sum_i^{N^J} p_i^J (c_i^{J*,k} L^{-J,k} + c_i^{J*,-k} L^{-J,-k}) = \sum_j^{N^{-J}} p_j^{-J} (c_j^{-J*,k} L^{J,k} + c_j^{-J*,-k} L^{J,-k}). \tag{18}$$

3.2 Free trade equilibrium

The results for $A_i^{J,u}, A_i^{J,s}, l_i^{J,u}, l_i^{J,s}, \frac{w^{J,u}}{w^{J,s}}$, and N^J do not change from those in the autarky version above. Under free trade, the price indices between the two countries become equal. Thus, the relative real wage between the two countries with respect to unskilled and skilled labor is, respectively, as follows:[3]

$$\frac{w^{J,s}}{w^{-J,s}} = \left(\frac{B^J}{B^{-J}}\right)^{\frac{1}{\beta}} \left[\frac{1 + \left(\frac{\alpha}{1-\alpha}(\rho^J)^\beta\right)^{\frac{\gamma}{\beta-\gamma}}}{1 + \left(\frac{\alpha}{1-\alpha}(\rho^{-J})^\beta\right)^{\frac{\gamma}{\beta-\gamma}}}\right]^{\frac{\beta-\gamma-\beta\gamma}{\beta\gamma}}, \tag{19}$$

$$\frac{w^{J,u}}{w^{-J,u}} = \left(\frac{B^J}{B^{-J}}\right)^{\frac{1}{\beta}} \left[\frac{1 + \left(\frac{\alpha}{1-\alpha}(\rho^J)^\beta\right)^{\frac{-\gamma}{\beta-\gamma}}}{1 + \left(\frac{\alpha}{1-\alpha}(\rho^{-J})^\beta\right)^{\frac{-\gamma}{\beta-\gamma}}}\right]^{\frac{\beta-\gamma-\beta\gamma}{\beta\gamma}}. \tag{20}$$

Proposition 3. *The larger the gap in technological capability between the North and the South, $\frac{B^N}{B^S} \uparrow$, the larger the relative wage gap between the two countries for both types of labor, $\frac{w^{N,u}}{w^{S,u}} \uparrow$ and $\frac{w^{N,s}}{w^{S,s}} \uparrow$.*

This result is intuitively clear when we consider, e.g., the United States (US) and China. The level of technological capability in the US is higher than in China, and both unskilled and skilled labor in the US earn higher wages than do laborers in China.

Proposition 4. *If the North is less unskilled-labor-abundant than the South, $\rho^N < \rho^S$, the North's relative wage for unskilled labor is higher, $\frac{w^{N,u}}{w^{S,u}} \uparrow$, whereas its relative wage for skilled labor is lower, $\frac{w^{N,s}}{w^{S,s}} \downarrow$. The changes in these relative wages are partially absorbed by endogeneity in technology choice.*

The scarcity of unskilled labor in the North will increase the demand for this type of labor, thus raising the wage for unskilled labor in comparison to that for skilled labor. This result can be derived easily in a classical trade model, such as the Heckscher-Ohlin model. However, this paper shows that although the scarcity of one type of labor may affect the wage inequality, the magnitude of the change is not as large as it is in classical models. The effect of labor composition on wages is partially absorbed because a firm can choose its own technology and the number of laborers to hire.

Proposition 5. *If the technology appropriate for unskilled labor is relatively easier to access compared with that for skilled labor, $\alpha \uparrow$, the country that is more unskilled-labor-abundant, $\rho^S > \rho^N$, will have a higher relative wage for both types of labor, $\frac{w^{S,u}}{w^{N,u}} \uparrow$ and $\frac{w^{S,s}}{w^{N,s}} \uparrow$.*

Intuitively, when the technology appropriate for unskilled labor is relatively easier to access, $\alpha \uparrow$, compared with that for skilled labor, firms will utilize the technology appropriate for unskilled labor, A^u. This is especially effective for production in the country that is abundant in unskilled labor. Thus, wages for both types of labor in this country will be improved.

Proposition 6. *Under the condition that the difficulty in accessing technologies appropriate for both types of labor is the same, $\alpha = 0.5$, and both countries are unskilled-labor-abundant, $\rho^S, \rho^N > 1$, the country that has a higher unskilled-labor-abundant level, $\rho^S > \rho^N$, will exhibit larger wage inequality, $\frac{w^{S,s}}{w^{S,u}} > \frac{w^{N,s}}{w^{N,u}}$. The difference between these relative wages is also partially absorbed by the endogeneity in technology choice.*

This result is very intuitive. The country that is unskilled-labor-abundant has a relatively higher unskilled labor supply and a lower skilled labor supply; therefore, the wage gap between these two types of labor will be higher. Once again, this paper emphasizes that the magnitude of the effect on wage inequality in two countries trading with

[3] See Appendix B.

each other is not as large as in the classical literature. The firm in this unskilled-labor-abundant country will utilize more technology that is appropriate for unskilled labor; therefore, because of this demand for unskilled labor, the wage for unskilled labor will not be that low. As a result, the wage gap between unskilled and skilled labor is partially absorbed by this endogeneity in technology choice.

4 Transport costs

4.1 The setup

In this section, the model is extended to allow for transport costs. The main purpose of this extension is to determine how the transport costs affect wage inequality for both types of labor within and between two trading partners, when they can choose their technology system.

The world here consists of two countries that incur costs to trade with each other. This cost is assumed to be the "ice-berg" type, which means that only a fraction τ ($0 \leq \tau \leq 1$) of any good shipped arrives. The rest, a fraction $1 - \tau$, is lost during transportation. When $\tau = 0$, the economy is under autarky, and when $\tau = 1$, the economy is under free trade. The introduction of transport costs causes some changes in the settings of the model compared to free trade.

Whereas the price of a domestic good is the same as the payoff that the firm receives, the price of an imported good is the c.i.f. price (i.e. cost, insurance and freight price), which is calculated by dividing the producer's price by the transport cost. This means that consumers in country J pay $\hat{p}_j^{-J}$ $(= \frac{p_j^{-J}}{\tau})$ to buy good j produced in country $-J$ and consumers in country $-J$ pay $\hat{p}_i^J (= \frac{p_i^J}{\tau})$ for good i of country J. Thus, the individual budget constraint becomes

$$\sum_i^{N^J} p_i^J c_i^{J,k} + \sum_j^{N^{-J}} \hat{p}_j^{-J} c_j^{-J*,k} = w^{J,k}, \tag{21}$$

where p is the f.o.b. price (free on board price) and $\hat{p}$ $(= \frac{p}{\tau})$ is c.i.f price.

Because only a fraction, τ, of goods used for export arrives, the goods market clearing condition is

$$x_i^J - f_e = L^{J,u} c_i^{J,u} + L^{J,s} c_i^{J,s} + \frac{1}{\tau} L^{-J,u} c_i^{J*,u} + \frac{1}{\tau} L^{-J,s} c_i^{J*,s}. \tag{22}$$

The trade balance condition has the following form

$$\sum_i^{N^J} \hat{p}^J (L^{-J,s} c_i^{J*,s} + L^{-J,u} c_i^{J*,u}) = \sum_j^{N^{-J}} \hat{p}^{-J} (L^{J,s} c_j^{-J*,s} + L^{J,u} c_j^{-J*,u}). \tag{23}$$

4.2 The equilibrium

The solution for the equilibrium is described in Appendix C. This section focuses on the effect of transport costs on the relative real wage, both within and across trading partners.

First, in the equilibrium, the relative wage between skilled and unskilled labor in country J is calculated as follows:

$$\frac{w^{J,u}}{w^{J,s}} = \left(\frac{\alpha}{1-\alpha}\right)^{\frac{\gamma}{\beta-\gamma}} (\rho^J)^{\frac{\gamma+\beta\gamma-\beta}{\beta-\gamma}}.$$

The wage ratio between skilled and unskilled labor in country J only depends on labor specific to that country, not on any specific trading partner or transport costs because the change in the price and consumption of each good absorbs all the effects of trade in this case.

Next, let us focus on the relative real wage between two countries for both types of labor. Unlike the free trade case, where the relative wage depends only on the specifics of both trading countries, the wage rate in this case also depends on transport costs. To examine this relationship, we study the impact of transport costs on the relative nominal wage rate and the price index ratio between two countries.

First, the impact of transport costs on the relative nominal wage rate is shown in the following proposition.

Proposition 7. *In a world with two countries, when the size of the labor force and the ratio of unskilled over skilled labor in both countries satisfy $D^{J,-J} < 1$, a decline in transport costs ($\tau \uparrow$) will increase the wage ratio between the two countries for both types of labor $\left(\frac{w^{J,s}}{w^{-J,s}} \uparrow \text{ and } \frac{w^{J,u}}{w^{-J,u}} \uparrow\right)$.*

Here, $$D^{J,-J} \equiv \frac{\left[1+\left(\frac{\alpha}{1-\alpha}(\rho^J)^\beta\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}}}{\left[1+\left(\frac{\alpha}{1-\alpha}(\rho^{-J})^\beta\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}}} \frac{1+\rho^{-J}}{1+\rho^J} \frac{L^J}{L^{-J}}.$$

$D^{J,-J}$ consists of two aspects: the size of the labor force and the ratio of unskilled over skilled labor in both countries. Here, we analyze how each of these aspects affects the influence of transport costs on the relative nominal wage via $D^{J,-J}$. First, assume that the ratio of unskilled over skilled labor is the same in both countries, $\rho^J = \rho^{-J}$; if country J has a smaller labor force than country $-J$ ($L^J < L^{-J}$), $D^{J,-J}$ will be less than one. As Proposition 7 suggests, the decline in transport costs will increase the relative wage between country J and $-J$ for both types of labor. Intuitively, the lower transport costs are, the freer trade becomes. As a result, trade flows between the two countries will rise because of the increase in demand for imported goods. The demand for imported goods in both countries increases by the same amount because of trade balances. In relation to this point, the demand level being the same for imported goods in both countries, note that country J has a smaller labor force and wages for both types of labor in country J will be relatively higher than in country $-J$. Second, keeping the size of the labor force the same between the two countries ($L^J = L^{-J}$), assuming that the skill bias between the two types of labor is the same ($\alpha = 0.5$), and that both countries are unskilled-labor-abundant ($\rho^J, \rho^{-J} > 1$), if country J is more unskilled-labor-abundant than country $-J$ ($\rho^J > \rho^{-J}$), then $D^{J,-J}$ will be less than one. According to Proposition 7, the decline in transport costs will increase the relative wage between countries J and $-J$ for both types of labor. Intuitively, if both countries are unskilled-labor-abundant, both countries will choose technology systems that utilize unskilled labor as much as possible. As decreasing transport cost leads to an increase in demand for imported good in both countries, country J, which is more unskilled labor intensive, will be more effective in production, which raises wages for both types of labor.

We now turn to discussing the impact of transport costs on the price index ratio. As τ approaches one, the economy becomes closer to free trade, which means that the price indices between the two countries become equal. Thus, when transport costs fall to zero, the price index ratio between the two countries converges to one. Although these general remarks give a sense of the impacts, it is not possible to analyze the transition of the price index ratio from autarky to free trade. Instead, a numerical approach is required and this is described in Appendix E.

4.3 Calibration

In this section, the model is calibrated based on data from 52 countries, both developed and developing, to examine how the difference between the exogenous technology and the endogenous technology choice affects the impacts of the transport costs on the relative wage between the two countries.

4.3.1 Data

This paper uses a data set constructed by Caselli and Coleman (2006) covering a cross-section of 52 countries for a single year. In their data set, the wage premium between unskilled and skilled labor is constructed from data on the Mincerian rate of return[4] and the difference in schooling years between these two types of labor in 1985. Skilled laborers are defined as those who have achieved a high school diploma or higher ("secondary completed"), whereas unskilled laborers have not. The Mincerian rate of return is the marginal effect of an extra year of education on the wage. The difference in schooling years is estimated from the duration of primary, secondary, and tertiary schooling. The data uses gross domestic production (GDP) based on purchasing power parity in current international US dollars, and the population aged 15-64 from the World Development Indicators in 1990. The data on skilled and unskilled labor shares are calculated based on the educational attainment of the population aged 15 and over in 1990, provided in the data set by Barro and Lee (2001).[5]

4.3.2 Description of model parameters

There are eight model parameters, as follows: γ (substitutability between unskilled and skilled labor); σ (share of skill labor); ρ (the ratio of unskilled labor over skilled labor); θ (a preference parameter); f_e (fixed costs); β (the curvature of the technology constraint); α (the skill bias); and B (the level of technological capability). Below, each of these parameters is discussed in turn.

Substitutability between unskilled and skilled labor

Following Katz and Murphy (1992), the elasticity of substitution between unskilled and skilled labor (denoted by $\frac{1}{1-\gamma}$) is set at 1.4; therefore γ is equal to 0.286.

Labor share

Using the unskilled and skilled labor data, we can calculate the share of skilled labor in the total labor force, σ, for each country. The ratio of unskilled labor over skilled labor (ρ^J) for each country J is derived by dividing the share of unskilled labor in the total labor force by the share of skilled labor, $\rho^J = \frac{1-\sigma^J}{\sigma^J}$.

Preference parameter

According to Broda and Weinstein (2006), the elasticity of substitution (denoted by $\frac{\theta-1}{\theta}$) is assumed to be 2.7; therefore, $\theta = 0.63$.

Fixed cost

Assume that the fixed costs, f_e, equal one. Robustness will be checked with respect to alternative values.

[4]The Mincerian rate of return is estimated from the following equation: $\ln w_t = \lambda_0 + \lambda_1 s_i + \lambda_2 exp_i + \lambda_3 exp_i^2 + \epsilon_i$ where w is the wage, s is years of schooling, and exp is experience. Data used for the estimation is from 52 countries, with about 5,200 persons per country and a median sample size of 2,469 from 1970 to 1990.

[5]The skilled labor share = share of "secondary completed" + share of "total tertiary."

Parameters in the technology constraint equation

From the first-order condition regarding the demand for both types of labor, $l^{J,u}$ and $l^{J,s}$,[6] we have

$$\frac{A^{J,s}}{A^{J,u}} = \left(\frac{w^{J,s}}{w^{J,u}}\right)^{\frac{1}{\gamma}} \left(\frac{l^{J,s}}{l^{J,u}}\right)^{\frac{1-\gamma}{\gamma}}. \tag{24}$$

Using equation (24), the optimal technology ratio, $\frac{A^{J,s}}{A^{J,u}}$, can be calculated from the skill premium $\frac{w^{J,s}}{w^{J,u}}$ and the labor ratio $\frac{l^{J,s}}{l^{J,u}}$, which can be obtained from the data set.

From the first-order condition regarding the technology appropriate for both types of labor, $A^{J,u}$ and $A^{J,s}$, in the firm profit maximization problem,[7] we can derive the following

$$\frac{A^{J,s}}{A^{J,u}} = \left(\frac{1-\alpha}{\alpha}\right)^{\frac{1}{\beta-\gamma}} \left(\frac{l^{J,s}}{l^{J,u}}\right)^{\frac{\gamma}{\beta-\gamma}}.$$

Taking the logarithm of both sides, we have

$$\ln\left(\frac{A^{J,s}}{A^{J,u}}\right) = \frac{\gamma}{\beta-\gamma}\ln\left(\frac{l^{J,s}}{l^{J,u}}\right) + \frac{1}{\beta-\gamma}\ln\left(\frac{1-\alpha}{\alpha}\right). \tag{25}$$

Next, we estimate equation (25) by ordinary least squares with $\ln\left(\frac{A^{J,s}}{A^{J,u}}\right)$ as the dependent variable and $\ln\left(\frac{l^{J,s}}{l^{J,u}}\right)$ as the sole regressor. The estimation result gives the value of the slope, $\frac{\gamma}{\beta-\gamma}$; therefore, the parameter β can be calculated. We treat $\frac{1}{\beta-\gamma}\ln\left(\frac{1-\alpha}{\alpha}\right)$ as the intercept. Then, the skill bias, α, is derived.

From the aggregate production function in equation (10) in country J, we have $X^J = [(A^{J,u}L^{J,u})^\gamma + (A^{J,s}L^{J,s})^\gamma]^{\frac{1}{\gamma}}$ where X^J is total production. Combining this with the optimal technology ratio, $\frac{A^{J,s}}{A^{J,u}}$, which is calculated from equation (24), we can derive the value of each optimal technology, $A^{J,s}$ and $A^{J,u}$, for each country. Given these optimal technology values, we use the technology constraint in equation (11) to obtain the level of technological capability, B^J.

The estimation results

The results of estimated parameters are as follows: $\alpha = 0.408$, $\beta = 0.437$, $\gamma = 0.286$, and $\theta = 0.63$. Table 1 below shows these parameters for two countries, Indonesia and Malaysia, as an example, as well as the other parameters, the optimal technologies, $A^{J,s}$ and $A^{J,u}$, for these two countries.

Table 1

	σ	ρ	A^u	A^s	B	L
Indonesia	0.127	6.880	0.073	0.124	0.352	181,436,821
Malaysia	0.247	3.050	0.160	0.189	0.463	18,211,097

[6] See equations (C14) and (C15) in Appendix C.

[7] See equations (C12) and (C13) in Appendix C.

4.3.3 Findings

This section reports the results of the calibration. We show how transport costs matter in terms of the different effects of exogenous and endogenous technology choices.

Figure 1 shows the impact of transport costs on the relative real wage of both unskilled and skilled labor between Indonesia and Malaysia. In this figure, the horizontal axis corresponds to τ. Note that, because this variable measures the fraction of goods that reach the importing country safely, transport costs decrease as we move to the right along this axis. The vertical axis shows the real wage rate between the two countries. Figure 1A shows the results for unskilled labor and Figure 1B shows them for skilled labor. The solid lines represent the endogenous technology choice, whereas the dotted lines represent constant technology.[8]

Although the relative real wage curves between Indonesia and Malaysia in both cases are downward sloping, the differences between them have different implications in terms of the effect of trade openness on wage inequality. In the case of skilled labor, in Figure 1B, there is a horizontal line where the wages of skilled labor in the two countries are completely equal; in other words, the wage rate equals one for any transport costs. We call this line "line one." We find that part of this line lies between the solid line and the dotted line, corresponding to transport costs between point A and point B.[9]

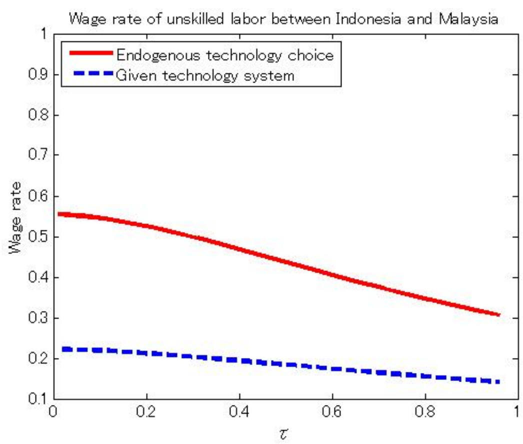

Fig 1A

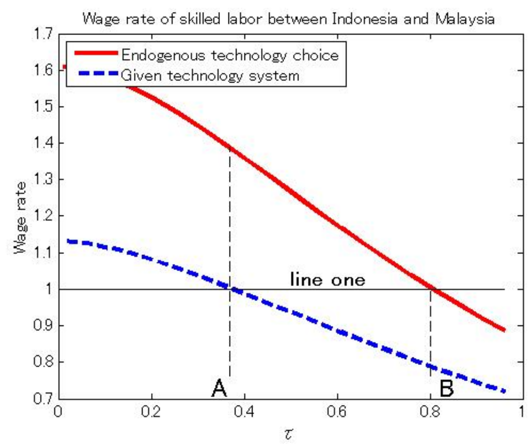

Fig 1B

Figure 1

Note: As τ measures the fraction of goods that reach the importing country safely, transport costs decrease as we move to the right along the horizontal axis.

Let us analyze the response of the relative real wage to transport costs when the cost decreases from point A to point B. In the case of standard constant technology (the dotted line), the relative real wage curve between the two countries diverges far away from "line one"; in other words, the two countries become less equal in terms of the

[8] The setting and solution of the standard model with exogenous technology are shown in Appendix C. Here, the constant technologies for both types of labor in Indonesia and Malaysia are $\bar{A}^{IND,u} = 0.088, \bar{A}^{IND,s} = 0.09, \bar{A}^{MYS,u} = 0.17$, and $\bar{A}^{MYS,s} = 0.173$, where IND and MYS are the acronyms for Indonesia and Malaysia, respectively.

[9] Points A and B correspond to transport costs equaling 0.37 and 0.8, respectively.

wages for skilled labor as τ increases from point A to point B. In contrast, the solid line decreases toward "line one," indicating that, in the case of endogenous technology choice, the relative wage for skilled labor between Indonesia and Malaysia becomes more equal as transport costs fall. Therefore, whether technology choice is exogenous or endogenous matters in terms of the impact of trade openness on wage inequality between the two countries analyzed.

Similar results can be found for other pairs of countries, including Sweden and Switzerland, Chile and Peru, and Greece and Hongkong, as shown in Figure 2. We find that the dotted lines and solid lines move in the same direction, and lie around or intersect partly or wholly with "line one." This results in trade openness having significantly different impacts on wage inequality when technology choice is endogenous rather than exogenous.

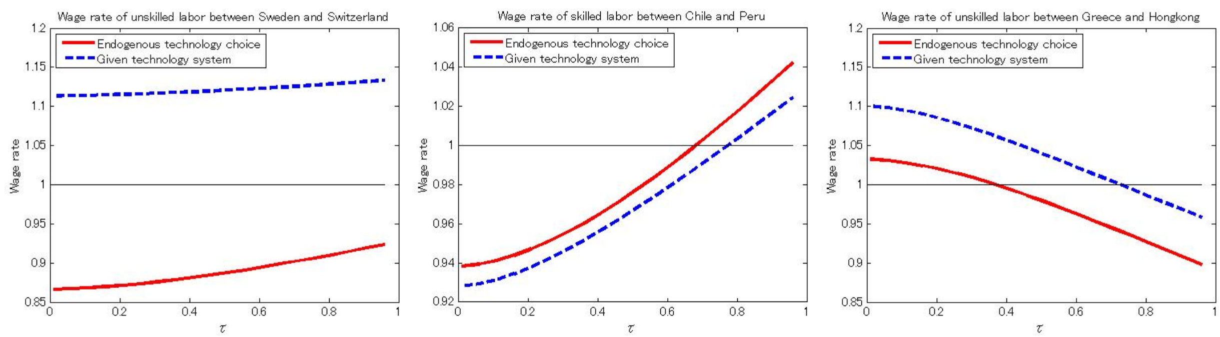

Fig 2A Fig 2B Fig 2C

Figure 2

Note: As τ measures the fraction of goods that reach the importing country safely, transport costs decrease as we move to the right along the horizontal axis.

The dotted lines and the solid lines in each of the figures lie around or intersect with "line one." This is because both countries within each pair have a similar labor composition and technological capacity. However, even if the dotted lines and the solid lines did not lie around or intersect with "line one," it remains the case that trade openness will have significant different impacts on wage inequality when technology choice is endogenous rather than exogenous. An example of this situation is discussed below.

The examples above share the same following feature: the solid line and the dotted line slope in the same direction, whether they are upward sloping or downward sloping. However, there is also a case where the solid lines and the dotted lines slope in different directions. This occurs for France and Italy, as shown in Figure 3. Specifically, for both unskilled and skilled workers, the dotted line is downward sloping, whereas the solid line is upward sloping. In the case of unskilled workers, shown in Figure 3A, both lines lie above "line one." Therefore, as transport costs fall, the relative real wage for unskilled labor between France and Italy in the endogenous technology choice model becomes less equal, whereas in the constant technology case, the relative real wage becomes more equal. However, in the case of skilled workers, shown in Figure 3B, both lines lie below "line one"; therefore, the opposite outcome occurs. As transport costs fall, the relative real wage for skilled labor between the two countries becomes more equal when the technology choice is endogenous, whereas under constant technology, it becomes less equal. In short, endogenous technology choice and constant technology have different implications for the impact of trade openness on real wage inequality.

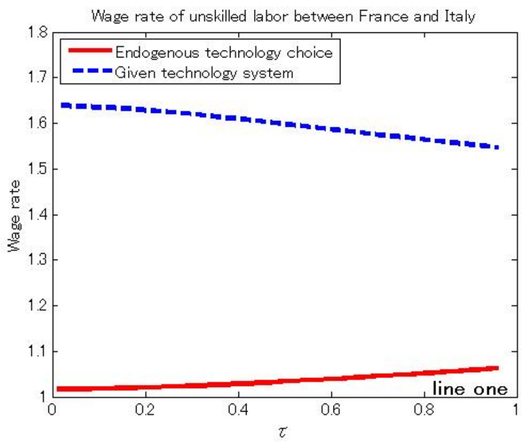

Fig 3A

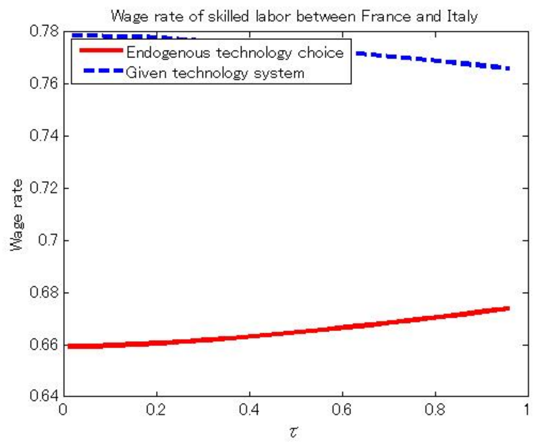

Fig 3B

Figure 3

Note: As τ measures the fraction of goods that reach the importing country safely, transport costs decrease as we move to the right along the horizontal axis.

5 Conclusions and extensions

This paper attempts to explain how trade openness affects wage inequality, both domestically and internationally, under endogenous technology choice. Building on the theoretical literature on a two-country general equilibrium trade model with monopolistic competition, the paper proposes a new assumption of endogenous technology choice, under which firms can choose which technology system to adopt to maximize their profits. The effect of trade openness is examined by considering the impact of endogenous technology choice on the wage rate, both within and across trading partners, when the two countries move from autarky to free trade.

Under autarky, we find that firms in skilled-labor-abundant countries choose technologies that are appropriate for skilled labor, and vice versa for firms in unskilled-labor-abundant countries. Furthermore, the effect of labor composition on the skill premium between unskilled and skilled labor is partially absorbed by the endogeneity in technology choice. In other words, in the case of standard constant technology, skill composition has a strong influence on wage inequality, whereas in the case of endogenous technology choice, this effect is not as strong. In the case of trade, wage inequality between the two types of labor is influenced by the comparative level of technological capability, the labor composition in both countries, and the skill bias. Moreover, countries with a higher ratio of unskilled labor will exhibit a larger wage inequality. Compared to the case of standard constant technology, these effects on wage inequality are also weaker. In addition, we also analyze the transition from autarky to free trade, to determine the impact of declining transport costs on wage inequality. If the size of the labor force and its skill composition in both countries satisfies a particular condition, the decline in transport costs will increase the relative wage between the two countries for both types of labor.

Furthermore, we run a calibration using data from 52 countries to examine the difference between the standard model with exogenous technology and the new model with endogenous technology choice. As suggested by the results of the calibration, the impact of trade openness on real wage inequality is both qualitatively and quantitatively different in the case of endogenous technology choice compared to standard constant technology for some pairs of countries.

The model presented in this paper can be extended in some directions. First, two parameters play very important roles in the model: the skill bias (α) and the parameter that determines the curvature of the technology constraint (β). Thus, introducing differences in these parameters across countries may provide interesting results. Second, transport costs are the same for all goods in this model; therefore, in future extensions, we could allow different goods to face different transport costs. For example, transport costs in the service sector may be lower than those in the manufacturing sector. Additionally, each sector is more or less intensive in different types of labor; therefore, the extension will be more meaningful in analyzing the effect of endogeneity in technology choice on wage inequality. Third, except in regard to labor, the two countries in this model do not differ in their levels of technological capability. Firm i in any country can choose any set of A_i^u and A_i^s from a menu of feasible technical choice, as shown in equation (11). In fact, a firm in a country with a low level of technological capability may find it difficult to access a high A_i^s, the appropriate technology for skilled labor, even when it is eager to give up all A_i^u, the technology appropriate for unskilled labor. Thus, introducing a limitation on the choice of the appropriate technology for skilled labor, A_i^s, may bring the model closer to reality.

Appendix A. Solution for autarky equilibrium

k-type labor's utility maximization

$$\begin{cases} \max \sum_i^N (c_i^k)^\theta \\ \text{s.t } \sum_i^N p_i c_i^k = w^k. \end{cases}$$

Solve the utility maximization, we have

$$p_i = \frac{\theta}{\lambda^k}(c_i^k)^{\theta-1}. \tag{A1}$$

Apply for both types of labor

$$c_i^u = \left(\frac{\lambda^u}{\lambda^s}\right)^{\frac{1}{\theta-1}} c_i^s. \tag{A2}$$

Substitute equation (A1) into good market clearing condition in equation (9), we have

$$\begin{aligned} x_i - f_e &= L^s c_i^s + L^u c^u \\ &= L^s c_i^s + L^u \left(\frac{\lambda^u}{\lambda^s}\right)^{\frac{1}{\theta-1}} c_i^s \\ &= \left[\sigma + (1-\sigma)\left(\frac{\lambda^u}{\lambda^s}\right)^{\frac{1}{\theta-1}}\right] c_i^s L. \end{aligned}$$

c_i^s can be rewritten as follows

$$c_i^s = \frac{x_i - f_e}{\left[\sigma + (1-\sigma)\left(\frac{\lambda^u}{\lambda^s}\right)^{\frac{1}{\theta-1}}\right]L}.$$

Substitute this into equation (6), we get

$$p_i = \frac{\theta}{\Lambda}\left(\frac{x_i - f_e}{L}\right)^{\theta-1}, \tag{A3}$$

where $\Lambda = [\sigma(\lambda^s)^{\frac{1}{\theta-1}} + (1-\sigma)(\lambda^u)^{\frac{1}{\theta-1}}]^{\theta-1}$.

Firm i's profit maximization

$$\begin{cases} \max\ p_i(x_i - f_e) - w^s l_i^s - w^u l_i^u \\ \text{s.t}\ (1-\alpha)(A_i^u)^\beta + \alpha(A_i^s)^\beta = B. \end{cases}$$

The Lagrangian is written as

$$\mathscr{L} = p_i(x_i - f_e) - w^s l_i^s - w^u l_i^u - \mu[(1-\alpha)(A_i^u)^\beta + \alpha(A_i^s)^\beta - B].$$

Firms are symmetry. Substitute the price in equation (A3) into the Lagrangian, we have

$$\mathscr{L} = \frac{\theta}{\Lambda}\left(\frac{1}{L}\right)^{\theta-1}(x - f_e)^\theta - w^s l^s - w^u l^u - \mu[(1-\alpha)(A^u)^\beta + \alpha(A^s)^\beta - B].$$

The first-order conditions

$$\frac{\partial\mathscr{L}}{\partial A^u} = 0 \Leftrightarrow \frac{\theta^2}{\Lambda}\left(\frac{x - f_e}{L}\right)^{\theta-1} x^{1-\gamma}(A^u l^u)^{\gamma-1} l^u = (1-\alpha)\mu\beta(A^u)^{\beta-1}, \tag{A4}$$

$$\frac{\partial\mathscr{L}}{\partial A^s} = 0 \Leftrightarrow \frac{\theta^2}{\Lambda}\left(\frac{x - f_e}{L}\right)^{\theta-1} x^{1-\gamma}(A^s l^s)^{\gamma-1} l^s = \alpha\mu\beta(A^s)^{\beta-1}, \tag{A5}$$

$$\frac{\partial\mathscr{L}}{\partial l^u} = 0 \Leftrightarrow \frac{\theta^2}{\Lambda}\left(\frac{x - f_e}{L}\right)^{\theta-1} x^{1-\gamma}(A^u l^u)^{\gamma-1} A^u = w^u, \tag{A6}$$

$$\frac{\partial\mathscr{L}}{\partial l^s} = 0 \Leftrightarrow \frac{\theta^2}{\Lambda}\left(\frac{x - f_e}{L}\right)^{\theta-1} x^{1-\gamma}(A^s l^s)^{\gamma-1} A^s = w^s. \tag{A7}$$

Substitute price in equation (A3) into the free entry condition in equation (8) and aggregate to the whole economy, we have

$$\frac{\theta}{\Lambda L^\theta} N(x - f_e)^\theta = \sigma w^s + (1-\sigma) w^u. \tag{A8}$$

Let w^s to be numeraire, $w^s = 1$.

Using the technology constraint in equation (2), full employment condition in equations (3) and (4), first order condition of profit maximization in equations (A4)-(A7), and free entry condition in equation (A8) to solve for $A^u, A^s, l^u, l^s, \mu, \Lambda, N$ and w^u.

Appendix B. Solution for free trade equilibrium

Utility maximization of k-type labor in country J

$$\begin{cases} \max \ \sum_i^{N^J} (c_i^{J,k})^\theta + \sum_j^{N^{-J}} (c_j^{-J*,k})^\theta \\ \text{s.t} \ \sum_i^{N^J} p_i^J c_i^{J,k} + \sum_j^{N^{-J}} p_j^{-J} c_j^{-J*,k} = w^{J,k}. \end{cases}$$

The same setting is applied to country $-J$. Solve the utility maximization problem for both countries, we have

$$p_i^J = \frac{\theta}{\lambda^{J,k}}(c_i^{J,k})^{\theta-1} = \frac{\theta}{\lambda^{-J,k}}(c_i^{J*,k})^{\theta-1}. \tag{B1}$$

Using equation (B1) applied for two countries, we get

$$\left(\frac{c_i^{J,k}}{c_i^{J,-k}}\right)^{\theta-1} = \frac{\lambda^{J,k}}{\lambda^{J,-k}} \text{ and } \left(\frac{c_i^{J*,k}}{c_i^{J*,-k}}\right)^{\theta-1} = \frac{\lambda^{-J,k}}{\lambda^{-J,-k}}, \tag{B2}$$

$$\left(\frac{c_i^{J,k}}{c_i^{J*,k}}\right)^{\theta-1} = \frac{\lambda^{J,k}}{\lambda^{-J,k}}. \tag{B3}$$

Substitute equations (B2), (B3) into good market clearing equation (16), we get

$$\begin{aligned} x_i^J - f_e &= L^{J,u}c_i^{J,u} + L^{J,s}c_i^{J,s} + L^{-J,u}c_i^{J*,u} + L^{-J,s}c_i^{J*,s} \\ &= L^J\left[\sigma^J + (1-\sigma^J)\left(\frac{\lambda^{J,u}}{\lambda^{J,s}}\right)^{\frac{1}{\theta-1}}\right]c_i^{J,s} + L^{-J}\left[\sigma^{-J} + (1-\sigma^{-J})\left(\frac{\lambda^{-J,u}}{\lambda^{-J,s}}\right)^{\frac{1}{\theta-1}}\right]\left(\frac{\lambda^{-J,s}}{\lambda^{J,s}}\right)^{\frac{1}{\theta-1}} c_i^{J,s} \\ &= \Bigg[\underbrace{[\sigma^J(\lambda^{J,s})^{\frac{1}{\theta-1}} + (1-\sigma^J)(\lambda^{J,u})^{\frac{1}{\theta-1}}]}_{\Lambda^J} L^J + \underbrace{[\sigma^{-J}(\lambda^{-J,s})^{\frac{1}{\theta-1}} + (1-\sigma^{-J})(\lambda^{-J,u})^{\frac{1}{\theta-1}}]}_{\Lambda^{-J}} L^{-J}\Bigg]\frac{c_i^{J,s}}{(\lambda^{J,s})^{\frac{1}{\theta-1}}} \\ &= [\Lambda^J L^J + \Lambda^{-J}L^{-J}]\frac{c_i^{J,s}}{(\lambda^{J,s})^{\frac{1}{\theta-1}}}. \end{aligned}$$

Thus, we have

$$c_i^{J,s} = \frac{(x_i^J - f_e)(\lambda^{J,s})^{\frac{1}{\theta-1}}}{\Lambda^J L^J + \Lambda^{-J}L^{-J}}.$$

Using equations (B2), (B3), we have

$$c_i^{J,k} = \frac{(x_i^J - f_e)(\lambda^{J,k})^{\frac{1}{\theta-1}}}{\Lambda^J L^J + \Lambda^{-J}L^{-J}} \text{ and } c_i^{J*,k} = \frac{(x_i^J - f_e)(\lambda^{-J,k})^{\frac{1}{\theta-1}}}{\Lambda^J L^J + \Lambda^{-J}L^{-J}}. \tag{B4}$$

Substitute into equation (B1),

$$p_i^J = \frac{\theta}{\lambda^{J,k}}(c_i^{J,k})^{\theta-1} = \frac{\theta}{\Lambda}(x_i^J - f_e)^{\theta-1}, \tag{B5}$$

where $\Lambda = [\Lambda^J L^J + \Lambda^{-J}L^{-J}]^{\theta-1}$.

Remind the individual budget constraints:

$$\sum_i^{N^J} p_i^J c_i^{J,k} + \sum_j^{N^{-J}} p_j^{-J} c_j^{-J*,k} = w^{J,k}.$$

Substitute the price in equation (B5) into the budget constraints

$$\frac{\theta}{\Lambda^{\frac{\theta}{\theta-1}}}(\lambda^{J,k})^{\frac{1}{\theta-1}}[N^J(x_i - f_e)^\theta + N^{-J}(x_j - f_e)^\theta] = w^{J,k}. \tag{B6}$$

Firm i in country J maximize its profit

$$\begin{cases} \max\ p_i^J(x_i^J - f_e) - w^{J,s}l_i^{J,s} - w^{J,u}l_i^{J,u} \\ \text{s.t } (1-\alpha)(A_i^{J,u})^\beta + \alpha(A_i^{J,s})^\beta = B^J. \end{cases}$$

The Lagrangian is written as

$$\mathscr{L}^J = p_i^J(x_i^J - f_e) - w^{J,s}l_i^{J,s} - w^{J,u}l_i^{J,u} - \mu^J[(1-\alpha)(A_i^{J,u})^\beta + \alpha(A_i^{J,s})^\beta - B^J].$$

Firms in country J are symmetry. Substitute the price in equation (B5) into the Lagrangian, we have

$$\mathscr{L}^J = \frac{\theta}{\Lambda}(x^J - f_e)^\theta - w^{J,s}l_i^{J,s} - w^{J,u}l_i^{J,u} - \mu^J[(1-\alpha)(A_i^{J,u})^\beta + \alpha(A_i^{J,s})^\beta - B^J].$$

The first-order conditions

$$\frac{\partial\mathscr{L}^J}{\partial A^{J,u}} = 0 \Leftrightarrow \frac{\theta^2}{\Lambda}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(A^{J,u}l^{J,u})^{\gamma-1}l^{J,u} = (1-\alpha)\mu^J\beta(A^{J,u})^{\beta-1}, \tag{B7}$$

$$\frac{\partial\mathscr{L}^J}{\partial A^{J,s}} = 0 \Leftrightarrow \frac{\theta^2}{\Lambda}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(A^{J,s}l^{J,s})^{\gamma-1}l^{J,s} = \alpha\mu^J\beta(A^{J,s})^{\beta-1}, \tag{B8}$$

$$\frac{\partial\mathscr{L}^J}{\partial l^{J,u}} = 0 \Leftrightarrow \frac{\theta^2}{\Lambda}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(A^{J,u}l^{J,u})^{\gamma-1}A^{J,u} = w^{J,u}, \tag{B9}$$

$$\frac{\partial\mathscr{L}^J}{\partial l^{J,s}} = 0 \Leftrightarrow \frac{\theta^2}{\Lambda}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(A^{J,s}l^{J,s})^{\gamma-1}A^{J,s} = w^{J,s}. \tag{B10}$$

Let $w^{S,s}$ to be numeraire, $w^{S,s} = 1$.

Using the technology constraint in equation (11), full employment condition in equations (13) and (14), first order condition of profit maximization problem in equations (B7)-(B10) for both countries, budget constraint in equation (B6) for both countries and both types of labor, and trade balance condition in equation (18) (all 19 equations) to solve for 19 variables as follows: $A^{N,s}$, $A^{N,u}$, $A^{S,s}$, $A^{S,u}$, $l^{N,s}$, $l^{N,u}$, $l^{S,s}$, $l^{S,u}$, μ^S, μ^N, N^S, N^N, $w^{N,s}$, $w^{N,u}$, $w^{S,u}$, $\lambda^{N,s}$, $\lambda^{N,u}$, $\lambda^{S,s}$ and $\lambda^{S,u}$.

Note that from trade balance in equation (18), budget constraint in equation (B6), and good market clearing in equation (16), we can derive the following free entry condition:

$$\frac{\theta}{\Lambda}N^J(x^J - f_e)^\theta = [\sigma w^{J,s} + (1-\sigma)w^{J,u}]L^J. \tag{B11}$$

Appendix C. Solution for transport cost

Consumption side

Utility maximization of k-type labor in country J

$$\begin{cases} \max \ \sum_i^{N^J} (c_i^{J,k})^{\theta} + \sum_j^{N^{-J}} (c_j^{-J*,k})^{\theta} \\ \text{s.t } \sum_i^{N^J} p_i^J c_i^{J,k} + \sum_j^{N^{-J}} \hat{p}_j^{-J} c_j^{-J*,k} = w^{J,k}. \end{cases}$$

Solve the utility maximization, price of good i produced in country J will be as follows

$$p_i^J = \frac{\theta}{\lambda^{J,k}} (c_i^{J,k})^{\theta-1} = \tau \frac{\theta}{\lambda^{-J,k}} (c_i^{J*,k})^{\theta-1}. \tag{C1}$$

Using equation (C1) applying for both countries, we have

$$\frac{c_i^{J,k}}{c_i^{J,-k}} = \frac{c_j^{-J*,k}}{c_j^{-J*,-k}} = \left(\frac{\lambda^{J,k}}{\lambda^{J,-k}}\right)^{\frac{1}{\theta-1}} \text{ and } \frac{c_i^{J*,k}}{c_i^{J*,-k}} = \frac{c_j^{-J,k}}{c_j^{-J,-k}} = \left(\frac{\lambda^{-J,k}}{\lambda^{-J,-k}}\right)^{\frac{1}{\theta-1}}, \tag{C2}$$

$$\frac{c_i^{J*,k}}{c_i^{J,k}} = \left(\frac{\lambda^{-J,k}}{\tau\lambda^{J,k}}\right)^{\frac{1}{\theta-1}} \text{ and } \frac{c_j^{-J*,k}}{c_j^{-J,k}} = \left(\frac{\lambda^{J,k}}{\tau\lambda^{-J,k}}\right)^{\frac{1}{\theta-1}}. \tag{C3}$$

Substitute this into good market clearing condition in equation (22), we get

$$\begin{aligned} x_i^J - f_e &= L^{J,u} c_i^{J,u} + L^{J,s} c_i^{J,s} + \frac{1}{\tau} L^{-J,u} c_i^{J*,u} + \frac{1}{\tau} L^{-J,s} c_i^{J*,s} \\ &= \Bigg[\underbrace{[\sigma^J (\lambda^{J,s})^{\frac{1}{\theta-1}} + (1-\sigma^J)(\lambda^{J,u})^{\frac{1}{\theta-1}}]}_{\Lambda^J} L^J + \frac{1}{\tau^{\frac{\theta}{\theta-1}}} \underbrace{[\sigma^{-J} (\lambda^{-J,s})^{\frac{1}{\theta-1}} + (1-\sigma^{-J})(\lambda^{-J,u})^{\frac{1}{\theta-1}}]}_{\Lambda^{-J}} L^{-J} \Bigg] \frac{c_i^{J,s}}{(\lambda^{J,s})^{\frac{1}{\theta-1}}} \\ &= [\Lambda^J L^J + \tau^{\frac{\theta}{1-\theta}} \Lambda^{-J} L^{-J}] \frac{c_i^{J,s}}{(\lambda^{J,s})^{\frac{1}{\theta-1}}}. \end{aligned}$$

The same for production in country $-J$ as follows

$$x_j^{-J} - f_e = [\tau^{\frac{\theta}{1-\theta}} \Lambda^J L^J + \Lambda^{-J} L^{-J}] \frac{c_j^{-J,s}}{(\lambda^{-J,s})^{\frac{1}{\theta-1}}}.$$

Thus, we have

$$c_i^{J,k} = \frac{(x_i^J - f_e)(\lambda^{J,k})^{\frac{1}{\theta-1}}}{(\tilde{\Lambda}^J)^{\frac{1}{\theta-1}}}, \tag{C4}$$

and

$$c_j^{-J,k} = \frac{(x_j^{-J} - f_e)(\lambda^{-J,k})^{\frac{1}{\theta-1}}}{(\tilde{\Lambda}^{-J})^{\frac{1}{\theta-1}}}, \tag{C5}$$

where

$$\tilde{\Lambda}^{-J} \equiv (\tau^{\frac{\theta}{1-\theta}} \Lambda^J L^J + \Lambda^{-J} L^{-J})^{(\theta-1)}, \tag{C6}$$

$$\tilde{\Lambda}^J \equiv (\Lambda^J L^J + \tau^{\frac{\theta}{1-\theta}} \Lambda^{-J} L^{-J})^{(\theta-1)}. \tag{C7}$$

Substitute into equation (C4) into equation (C1),

$$p_i^J = \frac{\theta}{\tilde{\Lambda}^J}(x_i^J - f_e)^{\theta-1}. \tag{C8}$$

The same for price in country $-J$

$$p_j^{-J} = \frac{\theta}{\tilde{\Lambda}^{-J}}(x_j^{-J} - f_e)^{\theta-1}. \tag{C9}$$

Substitute the price in equations (C8), (C9), and consumption in equations (C1), (C3)-(C5) into the budget constraint in equation (21), we get:

$$\theta(\lambda^{J,k})^{\frac{1}{\theta-1}}\left(\frac{N^J(x^J - f_e)^\theta}{(\tilde{\Lambda}^J)^{\frac{\theta}{\theta-1}}} + \frac{N^{-J}(x^{-J} - f_e)^\theta}{\tau^{\frac{\theta}{\theta-1}}(\tilde{\Lambda}^J)^{\frac{\theta}{\theta-1}}}\right) = w^{J,k}. \tag{C10}$$

Let $w^{S,s}$ to be numeraire, $w^{S,s} = 1$. [10]

Price index

Utility maximization of k-type labor in country J

$$\begin{cases} \max \ \sum_i^{N^J}(c_i^{J,k})^\theta + \sum_j^{N^{-J}}(c_j^{-J*,k})^\theta \\ \text{s.t } \sum_i^{N^J} p_i^J c_i^{J,k} + \sum_j^{N^{-J}} \hat{p}_j^{-J} c_j^{-J*,k} = w^{J,k}. \end{cases}$$

This utility maximization problem has similar form with that in Dixit-Stiglitz model. The price index can be calculated as

$$P^J = \left(\sum_i^{N^J}(p_i^J)^{\frac{\theta}{\theta-1}} + \sum_j^{N^{-J}}(\hat{p}_j^{-J})^{\frac{\theta}{\theta-1}}\right)^{\theta-1}. \tag{C11}$$

Production side

Endogenous technology choice model

Firm i in country J maximize its profit as follows

$$\begin{cases} \max\limits_{l_i^{J,u}, l_i^{J,s}, A_i^{J,u}, A_i^{J,s}} p_i^J(x_i^J - f_e) - w^{J,s}l_i^{J,s} - w^{J,u}l_i^{J,u} \\ \text{s.t } (1-\alpha)(A_i^{J,u})^\beta + \alpha(A_i^{J,s})^\beta = B^J. \end{cases}$$

The Lagrangian is written as

$$\mathscr{L}_i^J = p_i^J(x_i^J - f_e) - w^{J,s}l_i^{J,s} - w^{J,u}l_i^{J,u} - \mu^J[(1-\alpha)(A_i^{J,u})^\beta + \alpha(A_i^{J,s})^\beta - B^J].$$

Firms in country J are symmetry. Substitute the price in equation (C8) into the Lagrangian, we have:

$$\mathscr{L}^J = \frac{\theta}{\tilde{\Lambda}^J}(x^J - f_e)^\theta - w^{J,s}l_i^{J,s} - w^{J,u}l_i^{J,u} - \mu^J[(1-\alpha)(A_i^{J,u})^\beta + \alpha(A_i^{J,s})^\beta - B^J].$$

[10] In calibration, in order to convert other variables in the model into numeraire equivalent, it is necessary to calculate the wage of skilled labor for each country. The average wage of a country can be calculated in two ways. First, assume that all 52 countries have the same labor share in income as of 65%, then the average wage of a labor will be $\frac{0.65\times GDP}{\text{Total population}}\left(= \frac{0.65X^J}{L^J}\right)$. Second, this average wage can also be calculated as $\sigma^J w^{J,s} + (1-\sigma^J)w^{J,u}$. Equalizing these two calculations, we have $\sigma^J w^{J,s} + (1-\sigma^J)w^{J,u} = \frac{0.65\times X^J}{L^J}$. Given the share of each type of labor, the skill premium $\frac{w^{J,s}}{w^{J,u}}$, GDP, and total population, the wage of skilled labor in each country can be derived.

The first-order conditions:

$$\frac{\partial \mathscr{L}^J}{\partial A^{J,u}} = 0 \Leftrightarrow \frac{\theta^2}{\tilde{\Lambda}^J}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(A^{J,u}l^{J,u})^{\gamma-1}l^{J,u} = (1-\alpha)\mu^J\beta(A^{J,u})^{\beta-1}, \tag{C12}$$

$$\frac{\partial \mathscr{L}^J}{\partial A^{J,s}} = 0 \Leftrightarrow \frac{\theta^2}{\tilde{\Lambda}^J}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(A^{J,s}l^{J,s})^{\gamma-1}l^{J,s} = \alpha\mu^J\beta(A^{J,s})^{\beta-1}, \tag{C13}$$

$$\frac{\partial \mathscr{L}^J}{\partial l^{J,u}} = 0 \Leftrightarrow \frac{\theta^2}{\tilde{\Lambda}^J}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(A^{J,u}l^{J,u})^{\gamma-1}A^{J,u} = w^{J,u}, \tag{C14}$$

$$\frac{\partial \mathscr{L}^J}{\partial l^{J,s}} = 0 \Leftrightarrow \frac{\theta^2}{\tilde{\Lambda}^J}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(A^{J,s}l^{J,s})^{\gamma-1}A^{J,s} = w^{J,s}. \tag{C15}$$

Using the technology constraint in equation (11), full employment condition in equations (13) and (14), first order condition of profit maximization in equations (C12)-(C15) for both countries, budget constraint in equation (C10) for both countries and both types of labor, and trade balance condition in equation (23) (all 19 equations) to solve for 19 variables as follows: $A^{N,s}$, $A^{N,u}$, $A^{S,s}$, $A^{S,u}$, $l^{N,s}$, $l^{N,u}$,$l^{S,s}$, $l^{S,u}$, μ^S, μ^N, N^S, N^N, $w^{N,s}$, $w^{N,u}$, $w^{S,u}$, $\lambda^{N,s}$, $\lambda^{N,u}$, $\lambda^{S,s}$ and $\lambda^{S,u}$.

Standard constant technology model

In this model, the world technology combination, $\frac{\bar{A^s}}{\bar{A^u}}$, is constant. This technology combination is the weighted average of the logarithm of $\frac{A^{J,s}}{A^{J,u}}$ of each country, which is derived from equation (24). Each weight involved in this weighted average equals the share of the labor force of each country in the total labor force of all 52 countries provided in the data. From the data on the unskilled and skilled labor shares, the relative wage rate between these two types of labor, and the labor force, which are described in Section 4.3.1, the world technology combination, $\frac{\bar{A^s}}{\bar{A^u}}$, is 1.02 by calculation. Given this world technology combination, using aggregate production function of each country $X^J = [(\bar{A^{J,u}}L^{J,u})^\gamma + (\bar{A^{J,s}}L^{J,s})^\gamma]^{\frac{1}{\gamma}}$, we can compute the technology appropriate for unskilled and skilled labor in country J in the standard model with exogenous technology, $\bar{A^{J,u}}$ and $\bar{A^{J,s}}$. Now, firms in each country adopt the same technology system and simply choose different combinations of labor. Firm i in country J maximize its profit

$$\max_{l_i^{J,u}, l_i^{J,s}} p_i^J(x_i^J - f_e) - w^{J,s}l_i^{J,s} - w^{J,u}l_i^{J,u}.$$

Substitute price in equation (C8) into profit maximization problem above, we have

$$\max_{l_i^{J,u}, l_i^{J,s}} \frac{\theta}{\tilde{\Lambda}^J}(x^J - f_e)^\theta - w^{J,s}l_i^{J,s} - w^{J,u}l_i^{J,u}.$$

The first-order conditions:

$$\frac{\theta^2}{\tilde{\Lambda}^J}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(l^{J,u})^{\gamma-1}(\bar{A^{J,u}})^\gamma = w^{J,u}, \tag{C16}$$

$$\frac{\theta^2}{\tilde{\Lambda}^J}(x^J - f_e)^{\theta-1}(x^J)^{1-\gamma}(l^{J,s})^{\gamma-1}(\bar{A^{J,s}})^\gamma = w^{J,s}. \tag{C17}$$

Using full employment condition in equations (13) and (14), first order condition of profit maximization in equations (C16), (C17) for both countries, budget constraint in equation (C10) for both countries and both types of labor, and trade balance condition in equation (23) (all 13 equations) to solve for 13 variables as follows: $l^{N,s}$, $l^{N,u}$,$l^{S,s}$, $l^{S,u}$, N^S, N^N, $w^{N,s}$, $w^{N,u}$, $w^{S,u}$, $\lambda^{N,s}$, $\lambda^{N,u}$, $\lambda^{S,s}$ and $\lambda^{S,u}$.

Appendix D. Proof of proposition 7

Substitute price and consumption in equations (C1), (C3)-(C5) into trade balance in equation (23), we have

$$\frac{\Lambda^J}{\Lambda^{-J}} = \frac{N^J L^{-J}}{N^{-J} L^J}\left(\frac{\tilde{\Lambda}^J}{\tilde{\Lambda}^{-J}}\right)^{\frac{\theta}{1-\theta}}.$$

Substitute N^J and N^{-J} which is solved in Appendix C into the previous equation, we have

$$\frac{\Lambda^J L^J}{\Lambda^{-J} L^{-J}} = D\left(\frac{\tilde{\Lambda}^J}{\tilde{\Lambda}^{-J}}\right)^{\frac{\theta}{1-\theta}}, \tag{D1}$$

where D[11] is denoted as

$$D \equiv \frac{\left[1 + \left(\frac{\alpha}{1-\alpha}(\rho^J)^\beta\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}}}{\left[1 + \left(\frac{\alpha}{1-\alpha}(\rho^{-J})^\beta\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}}} \frac{1+\rho^{-J}}{1+\rho^J} \frac{L^J}{L^{-J}}.$$

Using definition of $\tilde{\Lambda}^J$ and $\tilde{\Lambda}^{-J}$ in equations (C6) and (C7) we can derive the following equation

$$\frac{\Lambda^J L^J}{\Lambda^{-J} L^{-J}} = \frac{\left(\frac{\tilde{\Lambda}^J}{\tilde{\Lambda}^{-J}}\right)^{\frac{1}{\theta-1}} - \tau^{\frac{\theta}{1-\theta}}}{1 - \tau^{\frac{\theta}{1-\theta}}\left(\frac{\tilde{\Lambda}^J}{\tilde{\Lambda}^{-J}}\right)^{\frac{1}{\theta-1}}}. \tag{D2}$$

Let $y \equiv \left(\frac{\tilde{\Lambda}^J}{\tilde{\Lambda}^{-J}}\right)^{\frac{1}{1-\theta}}$ and $\kappa = \tau^{\frac{\theta}{1-\theta}}$.

Then, from equations (D1) and (D2), we have

$$Dy^\theta = \frac{1-\kappa y}{y-\kappa},$$

or

$$Dy^{\theta+1} - D\kappa y^\theta + \kappa y - 1 = 0. \tag{D3}$$

Left hand side of equation (D3) is a function of y and κ: $g(y,\kappa) = Dy^{\theta+1} - D\kappa y^\theta + \kappa y - 1$. Thus equation (D3) will be $g(y,\kappa) = 0$. Differentiate function $g(y,\kappa)$ by y,

$$\begin{aligned} g'_y(y,\kappa) &= D(\theta+1)y^\theta - \theta\kappa D y^{\theta-1} + \kappa \\ &= D\theta y^\theta - \theta\kappa D y^{\theta-1} + \frac{Dy^{\theta+1} + \kappa y}{y} \end{aligned}$$

[11] In the main body of the paper, this D is clearly denoted as $D^{J,-J}$ to avoid any misunderstanding.

$$= D\theta y^{\theta} - \theta\kappa D y^{\theta-1} + \frac{D\kappa y^{\theta}+1}{y} \text{ (by equation (D3))}$$

$$= D\theta y^{\theta} + \frac{1}{y} + D\kappa y^{\theta-1}(1-\theta) > 0. \tag{D4}$$

Thus, function $g(y,\kappa)$ is monotonic increasing in y. At $y = \kappa$, function $g(y,\kappa) = \kappa^2 - 1 < 0$. At $y = \frac{1}{\kappa}$, function $g(y,\kappa) = D\kappa^{-(\theta+1)}(1-\kappa^2) > 0$. Thus, solution y of equation (D3) will lie between κ and $\frac{1}{\kappa}, \kappa < y < \frac{1}{\kappa}$.

Differentiate function $g(y,\kappa)$ by κ and use equation (D3), we have

$$g'_{\kappa}(y,\kappa) = \frac{y^2-1}{y-k}. \tag{D5}$$

Because $y > k$, sign of $g'_{\kappa}(y,\kappa)$ depends on sign of (y^2-1).

$$g'_{\kappa}(y,\kappa) = \begin{cases} > 0 & \text{when } y > 1 \\ \leq 0 & \text{when } y \leq 1. \end{cases}$$

Using implicit function theorem, we can derive $\frac{dy}{dk} = -\frac{g'_{\kappa}(y,\kappa)}{g'_{y}(y,\kappa)}$, thus

$$\frac{dy}{d\kappa} = \begin{cases} \leq 0 & \text{when } y > 1 \\ > 0 & \text{when } 0 < y \leq 1. \end{cases} \tag{D6}$$

Back to equation (D3)

$$\begin{cases} y = 1 \Longrightarrow g(y,\kappa) = D - D\kappa + \kappa - 1 = \underbrace{(1-\kappa)}_{>0}(D-1) \\ y = \kappa \Longrightarrow g(y,\kappa) = \kappa^2 - 1 < 0 \\ y = \frac{1}{\kappa} \Longrightarrow g(y,\kappa) = D\left(\frac{1}{\kappa}\right)^{\theta+1}[1-\kappa^2] > 0. \end{cases} \tag{D7}$$

Treat κ as a parameter,

$$\text{If } D^{J,-J} > 1 \Longrightarrow \begin{array}{l} y = 1 \Longrightarrow g(y,\kappa) > 0 \\ y = \kappa \Longrightarrow g(y,\kappa) < 0 \end{array} \Longrightarrow \text{Solution of equation (D3) } y \in (\kappa, 1) \xrightarrow{\text{eq.(D6)}} \frac{dy}{d\kappa} > 0$$

$$\text{If } D^{J,-J} < 1 \Longrightarrow \begin{array}{l} y = 1 \Longrightarrow g(y,\kappa) < 0 \\ y = \frac{1}{\kappa} \Longrightarrow g(y,\kappa) > 0 \end{array} \Longrightarrow \text{Solution of equation (D3) } y \in (1, \tfrac{1}{\kappa}) \xrightarrow{\text{eq.(D6)}} \frac{dy}{d\kappa} < 0.$$

Wage rate between two countries for skilled labor can be calculated by $\frac{\tilde{\Lambda}^{J}}{\tilde{\Lambda}^{-J}}$ by equations (C14), (C15) as follows

$$\frac{w^{J,s}}{w^{-J,s}} = \frac{\tilde{\Lambda}^{-J}}{\tilde{\Lambda}^{J}} \underbrace{\left[\frac{1 + \left(\frac{\alpha}{1-\alpha}(\rho^{J})^{\beta}\right)^{\frac{\gamma}{\beta-\gamma}}}{1 + \left(\frac{\alpha}{1-\alpha}(\rho^{-J})^{\beta}\right)^{\frac{\gamma}{\beta-\gamma}}}\right]^{\frac{\beta-\gamma-\beta\gamma}{\beta-\gamma}}}_{>0} \Longrightarrow \text{sign}\left[\frac{\partial \frac{w^{J,s}}{w^{-J,s}}}{\partial\tau}\right] = -\text{sign}\left[\frac{\partial \frac{\tilde{\Lambda}^{J}}{\tilde{\Lambda}^{-J}}}{\partial\tau}\right] = -\text{sign}\left[\frac{dy}{d\kappa}\right].$$

The same for wage rate between two countries for unskilled labor, we can also find that

$$\mathrm{sign}\left[\frac{\partial \frac{w^{J,u}}{w^{-J,u}}}{\partial \tau}\right] = -\mathrm{sign}\left[\frac{\partial \frac{\tilde{\Lambda}^{J}}{\tilde{\Lambda}^{-J}}}{\partial \tau}\right] = -\mathrm{sign}\left[\frac{dy}{d\kappa}\right].$$

Thus, knowing sign of $\frac{dy}{d\kappa}$, we can find how transport cost τ affects wage rate of labor type k, $\frac{w^{J,k}}{w^{-J,k}}$. The result will be as follows

$$\frac{\partial \frac{w^{J,s}}{w^{-J,s}}}{\partial \tau} = \begin{cases} < 0 & \text{when } D > 1 \\ > 0 & \text{when } D < 1. \end{cases} \tag{D8}$$

□

Discussion of D We rewrite D here for convenience.

$$D \equiv \frac{\left[1 + \left(\frac{\alpha}{1-\alpha}(\rho^{J})^{\beta}\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}}}{\left[1 + \left(\frac{\alpha}{1-\alpha}(\rho^{-J})^{\beta}\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}}} \frac{1+\rho^{-J}}{1+\rho^{J}} \frac{L^{J}}{L^{-J}}.$$

There are two aspects to the calculation of D: the size of the labor force (L) and the ratio of unskilled over skilled labor (ρ) for both countries, J and $-J$.

First, assuming that the ratio of unskilled over skilled labor is the same in both countries, $\rho^{J} = \rho^{-J}$, if country J has a smaller labor force than does country $-J$ ($L^{J} < L^{-J}$), D will be smaller than one.

Second, assuming that the size of the labor force is the same in both countries, $L^{J} = L^{-J}$, if country J is more unskilled-labor-abundant than is country $-J$ ($\rho^{J} > \rho^{-J}$), then whether D is smaller or larger than one depends on the characteristics of function $h(\rho) = \left[1 + \left(\frac{\alpha}{1-\alpha}(\rho^{J})^{\beta}\right)^{\frac{\gamma}{\beta-\gamma}}\right]^{\frac{\beta-\gamma}{\beta\gamma}} (1+\rho^{J})^{-1}$. Under the conditions that the skill bias between the two types of labor is the same ($\alpha = 0.5$) and both countries are unskilled-labor-abundant ($\rho^{J}, \rho^{-J} > 1$), function $h(\rho)$ is found to be monotonically decreasing, $h'(\rho) < 0$. Thus, if $\rho^{J} > \rho^{-J}$, then $h(\rho^{J}) < h(\rho^{-J})$. Consequently, D is less than one.

Appendix E. Some extra calibration results for the impact of transport costs

To understand the impact of transport costs on the relative real wage fully, the sections below discuss the impact of transport costs on the relative nominal wage and the price index ratio separately.

Impact of transport costs on the relative nominal wage

This section reports calibration results for the impact of transport costs on the relative nominal wage. Figure E1 shows the impact of transport costs on the relative nominal wage for both unskilled and skilled labor between Indonesia and Malaysia.

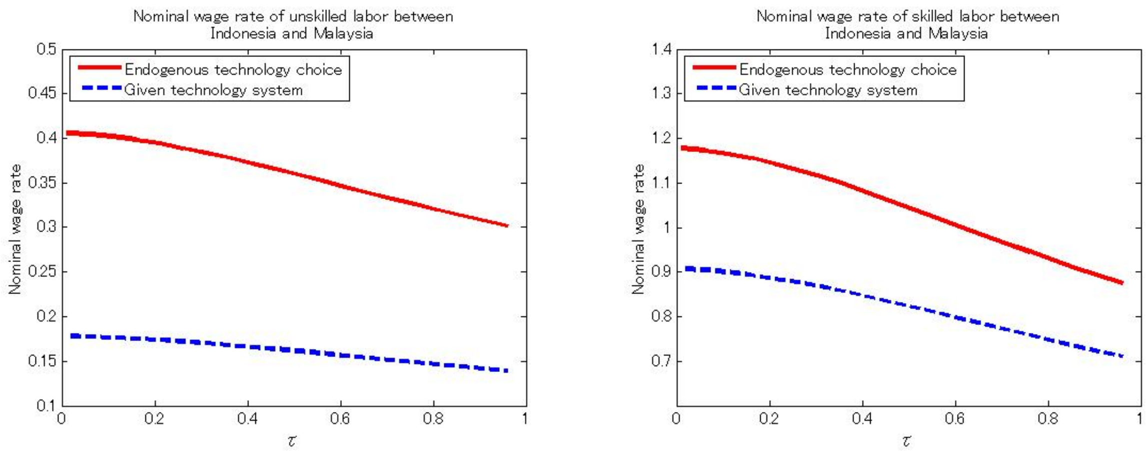

Fig E1A

Fig E1B

Figure E1

Note: As τ measures the fraction of goods that reach the importing country safely, transport costs decrease as we move to the right along the horizontal axis.

In this figure, the horizontal axis corresponds to τ. Note that, because τ measures the fraction of goods that reaches the importer country safely, the transport cost decreases as we move to the right along this axis. The vertical axis shows the relative nominal wage between the two countries. Figure E1A shows the case of unskilled labor, whereas Figure E1B shows the case of skilled labor. The solid lines represent endogenous technology choice, whereas the dotted lines represent constant technology. The result is consistent with Proposition 7, which states that relative nominal wage increases monotonically as transportation costs are reduced. In this case, the factor $D^{IND,MYS}$ denoted in Proposition 7 between Indonesia and Malaysia is 5.384, which is larger than one; therefore, thus the relative nominal wage curves are downward sloping for both types of labor as transport costs decrease.

Impact of transport costs on the price index ratio

This section reports the calibration results for the impact of transport costs on the price index ratio. Figure E2 shows the impact of transport cost on the price index ratio between two pairs of countries: Indonesia and Malaysia, and France and Italy.

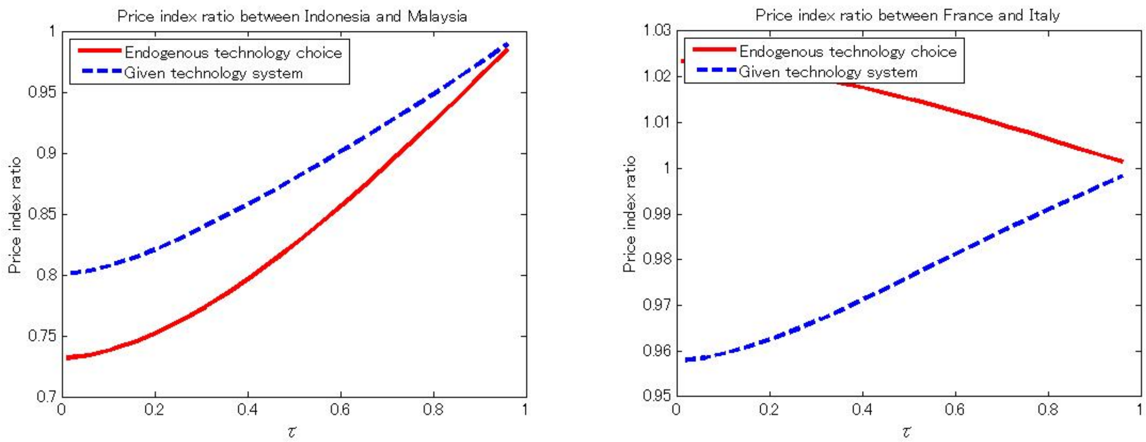

Fig E2A

Fig E2B

Figure E2

Note: As τ measures the fraction of goods that reach the importing country safely, transport costs decrease as we move to the right along the horizontal axis.

In this figure, the horizontal axis corresponds to τ. The vertical axis shows the price index ratio between the two countries. The solid lines represent endogenous technology choice, whereas the dotted lines represent constant technology. Figure E2A shows the case of Indonesia and Malaysia. In both exogenous and endogenous technology choice models, the price index ratios between these two countries are monotonically increasing and converge to one during the transition from autarky to free trade. However, in Figure E2B, which shows the impact of transport costs on the price index ratio between France and Italy, the price index ratios are monotonically increasing for the case of exogenous technology but decreasing in the case of endogenous technology choice. However, as the economies are close to free trade, these ratios also converge to one as discussed in Section 4.2. This convergence narrows the gap in terms of the impact of transport costs on the relative real wage between the two models as the economies become closer to free trade.

References

Acemoglu, D. 2002. “Directed Technical Change”, *Review of Economic Studies* 69(4): 781-809.

Acemoglu, D. 2003. “Patterns of Skill Premia”, *Review of Economic Studies* 70(2): 199-230.

Atkinson, A. B. and J. E. Stiglitz. 1969. “A New View of Technological Change”, *The Economic Journal* 79(4): 573-578.

Basu, S. and D. Weil. 1998. “Appropriate Technology and Growth”, *Quarterly Journal of Economics* 113: 1025-1054.

Broda, C. and D. E. Weinstein. 2006. “Globalization and the Gains from Variety”, *Quarterly Journal of Economics* 121(2): 541-585.

Caselli, F. and W. J. Coleman. 2006. “The World Technology Frontier”, *American Economic Review* 96(3): 499-522.

Epifani P. and Gancia G. 2008. “The Skill Bias of World Trade”, *The Economic Journal* 118: 927-960.

Feenstra, R. C. and G. H. Hanson. 1996. “Globalization, Outsourcing, and Wage Inequality”, *American Economic Review* 86(2): 240-245.

Katz, L. F. and K. M. Murphy. 1992. “Changes in Relative Wages, 1963-1987: Supply and Demand Factors”, *The Quarterly Journal of Economics* 107(1): 35-78.

World Bank. 1990-2012. World Development Indicators database, World Bank.

Yeaple, S. R. 2005. “A Simple Model of Firm Heterogeneity, International Trade, and Wages”, *Journal of International Economics* 65(1): 1-20.