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The undersigned

SURNAME *Marvi*
FIRST NAME *Ramezan Ali*
PhD Registration Number *1461250*

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SURNAME *Marvi*
FIRST NAME *Ramezan Ali*

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Abstract

This dissertation tries to rationalize some new stylized facts related to the rising of Global Value Chains (GVCs) during recent years, as well as the special nature of trade happening inside value chains.

The first essay develops a model aimed at capturing some of the features of the recent trade collapse which took place across countries between 2008 and 2009. We consider a multinational firm producing in a global value chain whose headquarter faces three possible ways to procure the intermediate input: vertical FDI, outsourcing and market-based procuring. Using queueing theory, we derive the time costs for each of these organizational structures. Incorporating these costs in the traditional cost minimization problem of the headquarter enables us to explain the mechanisms under which a sudden trade collapse might occur with a different speed across sector, as a function of the intensity of the respective organizational form. It also helps us to address the motivation for the existence of north-north vertical FDI. Simulating the model we are able to reproduce the main qualitative features of US monthly trade data during the recent trade collapse.

The second essay focuses on the pattern of task and income distribution within a GVC. Using the recently developed WIOD database, collecting data on the trade in value added within a world Input/Output matrix, we reveal a high heterogeneity of countries in terms of their trends of skill premia. The latter is a stylized fact at odds with the assumption of a recent theoretical model of Global Value Chains (Costinot et al. [2013]), which we extend by allowing for different types of labor and different types of production stages. The model generates a pattern of vertical specialization in which the position of each country in the chain is a function of two factors: its productivity and skill intensity of its labor endowments. Moreover, the wage of each labor type depends on the position of the country, its skill intensity and productivity of skilled workers. As a result, depending on the model parameters and labor endowments, technological innovations will induce various trends in the relative position of countries, prices, wages and exports, in line with the stylized fact. The model thus represents a suitable candidate for addressing the heterogeneity of countries in terms of skill premia.

Chapter 1

Introduction

The spectacular increase in the level of international sequential production during recent decades, have created enough space for investigating the role of GVCs in the World trade. A variety of terms including: “global supply chains”, “international outsourcing”, “international production sharing”, “global production networks”, “fragmentation of the production process” and “global production sharing” have been used in the literature to refer to this phenomenon. Since today a major share of the world trade happens inside GVCs, the characteristics of the same GVCs can influence most of the new and unprecedent stylized facts on the evolution of trade flows worldwide. The 2008/09 episode of sudden trade collapse at the world level is a good example of this pattern. As Baldwin [2009a] points out, GVCs are key in understanding the channels through which the recent trade collapse happened in a synchronized manner across countries and was larger than the drop in the world GDP. On top of these shift from traditional arm’s length to GVC-related trade, a notable number of leading technological innovations occur within GVCs, and thus the same position of countries in GVCs, as dictated by technology, can account for a number of stylized facts taking place within countries beyond trade (e.g. wage dynamics, skill premia, etc.).

Motivated by these facts, this dissertation attempts to shed some light on the theoretical aspects of GVCs. The first essay, co-authored with Professor Altomonte from Bocconi University, is devoted to address the ”suddenness” of the last trade collapse by focusing on the organizational decisions across different linkages of a GVC. We We consider a multinational firm producing in a global value chain whose headquarter faces three possible ways to procure the intermediate input: vertical FDI, outsourcing and market-based procuring. Using queueing theory, we derive the time costs for each of these organizational structures. Incorporating these costs in the traditional cost minimization problem of the headquarter enables us to explain the mechanisms under which a sudden trade collapse might occur with a different speed across sector, as a function of the intensity of the respective organizational form. It also helps us to address the motivation for the existence of north-north vertical FDI. Simulating the model we are able to reproduce the main qualitative features of US monthly trade data during the recent trade collapse.

In the second essay, we try to rationalize the interdependence of countries participating in a GVC and define the pattern of task and income distribution within the GVC. Moreover, we provide a theoretical support for the heterogeneity of countries in their trends of skill premia, now explained through the channel of the effect of technological changes on the GVC. This heterogeneity is derived from the WIOD1 database. Theoretical framework is based on the Costinot, Vogel and Wang (2013)'s model (hereafter, CVW).

CVW's framework consists of a world with an arbitrary number of countries, one type of labor, a continuum of intermediate goods and one final good produced sequentially in a multistage production. Each stage of production is subject to a mistake rate which is different across countries. The authors find that such a framework yields a unique free trade equilibrium in which there is full employment across countries and countries with lower mistake rates at all stages specialize in later stages. In other words, there is a vertical specialization based on the mistake rates of countries in the unique equilibrium. Their study establishes interesting results on the interdependence of countries within a GVC and the effect of technological innovations on this interdependence. However, it is silent on the observations related to the heterogeneity of labor including the stylized fact on skill premia. In addition, as we will see in chapter 3, their setting allows limited proxies for global technological changes.

This paper thus extends CVW's model by allowing for two different types of labor and two different types of stages. The new setting yields richer tools for analyzing the role of GVCs on the patterns of task and income distribution across countries and the impact of technological change on international trade. In this framework, the vertical specialization is preserved, but these modifications result in some new results about the position of countries in the chain and the effect of technological changes on the skill premia within countries. In our model, the position of countries depends not only on mistake rates, but also on the endowment of skilled and unskilled labor. Moreover, the contribution level of each country to both type of stages is a function of these two factors. The lower is the mistake rate of a country, the more downstream is the position of that country and the higher is the skill ratio of a country, the bigger is the share of high-tech stages that it produces. In turn, the wage of labor factors and skill premium are defined by the position of the country in the chain, the share of high-tech stages produced by the country and the productivity ratio of skilled labor over unskilled labor in high-tech stages.

Chapter 2

Global Value Chains (GVCs) as network of queues and the Great Trade Collapse

2.1 Introduction

The “recent trade collapse”is characterized as severe, sudden and synchronized (Baldwin [2009a]). Several studies have tried to explain the main causes of these features. They focus on three factors: compositional effects (Baldwin [2009b], Levchenko et al. [2011]), credit constraints (Mora and Powers [2009]) and GVCs (Bullwip effect (Altomonte et al. [2012] and Alessandria et al. [2011]) and multiple accounting (Yi [2009], Bergoeing et al. [2004]). Levchenko et al. [2010] show that compositional effects can explain greatly the severity of the trade collapse. Mora and Powers [2009] and Levchenko et al. [2011] argue that credit constraints did not play a significant role in the trade collapse, whereas, Chor and Manova [2012] find that credit conditions were important in the trade crisis. Bems et al. [2011] justify the synchronicity feature by highlighting the role of GVCs. However, there is a sparse literature on the suddenness of this event.

The present paper tries to shed light on this dimension by taking into account the ”time concerns” of the key players of a GVC. By time concerns, we mean the costs associated with the time lasts from ordering an intermediate good by a headquarter to availability of that good for using (without the need for further processing) in the production of the final good. The model focuses on three types of organizational structure by which a headquarter can procure the intermediate component from a foreign country: establishing a subsidiary (vertical FDI), outsourcing and buying from the foreign market. The headquarter analyzes costs associated with these time concerns besides the wellknown costs in the literature (e.g. efficiency costs, the degree of contractibility of the intermediate input, the institutional quality of the host country, ...) to decide on the type of organizational structure for providing intermediate good. In the vertical FDI method of procuring, the headquarter should finance the total costs of producing the intermediate component. In this case, time costs refer to the time-discounting in the monetary value of these expenditures. In the outsourcing case, the headquarter should undertake a share of input production costs. It also runs a process to purify the input produced by the supplier because of its partial-specificity. Here, time costs consists of two elements: the time-discounting in the resources devoted to the production of intermediate good and time-discounting in the input value during the purifying process. Finally, if the headquarter relies on market, it should undertake the time-discounting costs of the input value during the search activity in the market and the refining stage. The time of getting full-specific inputs, in each organizational type, is derived by queueing theory. The main theoretical result is that the decision of headquarter on the organizational structure is positively related to the minimization of the time costs. So, the suddenness of the great trade collapse, considering the rise of international activities in the recent decades, is no longer a puzzle.

Embodying the time concerns of the headquarter in the model also helps us to address an unanswered question about the internalization (make-or-buy) decision of MNEs. In fact, as Alfaro and Charlton [2009] discuss, there is a type of vertical FDI (within-industry vertical FDI) that is not justified by the existing theories of FDI. This type of FDI is undertaken in similar countries and thus might be incorrectly accounted for as horizontal FDI. We show that it is possible to have situations in which the host country has a high level of institutional quality, like the headquarter's country, and vertical FDI dominates other methods in procuring the intermediate component. In fact, if the product-contractibility is low enough and the trade costs are not so much large, establishing a subsidiary in a country with high enough degree of institutional quality is more profitable than other types of organizational structures.

We also loosely assess the empirical performance of our model. For this aim, first we extract the main features of the data on the US monthly trade during the crisis. Then, simulating the model implies that the model has the capability to generate the main features of these data.

This paper is related to several strands of the literature on international trade. First, it could be included in the studies that focus on the importance of time for the trade activity (e.g. Alessandria et al. [2011] and Hummels and Schaur [2012]). Second, it contributes to the well-grown literature on the role of GVCs in the recent trade collapse (e.g. Bems et al. [2011], Altomonte and Ottaviano [2009] and Altomonte et al. [2012]). Next, it could be categorized in the research on analyzing the internalization decision of multinational firms (e.g. Antràs [2003], Antràs and Helpman [2004], Antràs and Helpman [2008] and Grossman and Helpman [2002]). Finally, it relates to the newborn literature on modeling GVCs (Baldwin and Venables [2010], Antràs and Chor [2013] and Costinot et al. [2013]).

The rest of the paper is organized as follows. Section II explains the model and its implications in details. Section III describes the data and their main features. The empirical analysis including the simulation results are presented in section IV and finally, section V states some concluding remarks.

2.2 The model

In this section, we start by brief introduction of queueing theory. We use this theory for endogenizing the time of procuring the full specific input. Then, we state the model setup. Next, we solve the model by assuming that time of procuring is given. After that, we use queueing theory to address this time term. Finally, we derive some implications of the model.

2.2.1 A brief introduction to queueing theory

Before going through the model, it is helpful to briefly introduce the theory of queues[1]. This theory relates to the situations in which customers are certainly bound to wait in a line before getting served by a server (station). Examples of these situations include a bank, an airport security check point, a post office, computer-communication networks, production systems and transportation services. There are four different types of queueing systems depending on types of consumers (one or many) and number of stations (one or multiple). Regarding our model, we just need to analyze the basic queueing system characterized by homogenous consumers and one server. So, we only explain this type of queueing systems.

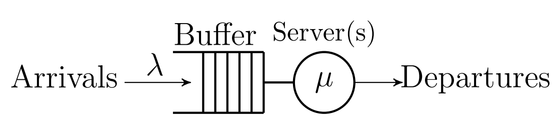

Figure 2.1: The basic queue and its elements

Figure (2.1) presents a schematic view of a single server queue. As depicted in the figure, a queue models any service station with one or multiple servers and a waiting room

[1]We have benefited from Bolch et al. [2006] and Cooper [1981] for writing this introduction.

(or buffer). Customers arrive to receive service and if all servers are busy, they should wait in the waiting room. In a word, each queue is defined by five elements: number of servers (S), buffer size (b), service discipline/scheduling (SD), arrival process (AP) and service time distribution (ST). S can be one, multiple or infinite; b can take any non-negative integer; SD describes the service order, for instance First Come First Served (FCFS) which is the default, Last Come Fist Served (LCFS), etc., and Finally, AP and ST are specific distributions such as exponential (M), Erlang (E_k), deterministic (D), etc. It is usual in the queueing literature to assume that customer inter-arrival times (the time between arrivals) are independent and identically distributed. Let t_n denotes the inter-arrival time between customers n and $n+1$. t_n is a random variable and $\{t_n, n \geq 1\}$ is a stochastic process. according to this assumption, inter-arrival times have a common mean:

$$E(t_n) = E(t) = \frac{1}{\lambda}$$

λ is called the average arrival rate. The similar assumption goes to the service times. Denote the service time of customer n at the server by s_n. Again, $\{s_n, n \geq 1\}$ is a stochastic process and service times are independently and identically distributed with a common mean:

$$E(s_n) = E(s) = \mu$$

in which μ is called the average service rate.

There is a standard notation to describe queues: $AP/ST/S/Cap/SD$. In this notation, Cap is the maximum number of customers allowed in the whole system (with a default value of infinite). For example, $M/M/1$ refers to a queue with Poisson arrivals, exponentially distributed service times, one server, infinite capacity and FCFS service discipline. Since our model only uses this class of queues, we devote the rest of this part to them.

There are four main counting process for queues: number of customers in the queue system at time t, number of customer arrivals till time t ($a(t)$), number of customer departures till time t ($\gamma(t)$) and time spent in system by the i^{th} customer (T_i). We can define the time average of these processes over interval $[0, t]$:

$$N_t = \frac{1}{t}\int_0^t N(s)ds$$

$$\lambda_t = \frac{a(t)}{t}$$

$$T_t = \frac{1}{a(t)} \sum_{i=1}^{a(t)} T_i$$

$$\gamma_t = \frac{\gamma(t)}{t}$$

In addition, we can determine the steady states of these time averages (in case of existence):

$$N = \lim_{t \to \infty} N_t$$

$$\lambda = \lim_{t \to \infty} \lambda_t$$

$$T = \lim_{t \to \infty} T_t$$

$$\gamma = \lim_{t \to \infty} \gamma_t$$

The number of customers in the system at time t, for this class of queues, can be modeled as a continuous time Markov chain. So, the condition for stability of the $M/M/1$ queue is:

$$\rho = \frac{\lambda}{\mu} < 1$$

where ρ is called traffic intensity. This is intuitive because the server is able to serve all arrivals only if the average arrival rate does not exceed its ability at which it can process on an average. Assuming that the service rates are independent of the current state of the system, we can derive the average number of customers in the system as:

$$N = \frac{\lambda}{\mu - \lambda}$$

Applying Little's theorem[2], we can obtain the average time that each customer spends in the system:

$$T = \frac{N}{\lambda} = \frac{1}{\mu - \lambda}$$

Besides knowing about single queues, we require the knowledge on the two-stage tandem network of queues for solving our model. As a typical example, consider figure (2.2) in which the departures of the first queue enter the second queue and the service times are exponentially distributed and mutually independent. Moreover, they are independent of the arrival processes.

[2] Little's theorem says that

$$N = \lambda \cdot T$$

in which N is the average number of customers in a queue, T is the average time of waiting in queue and receiving service per customer and λ is the average rate of arrivals.

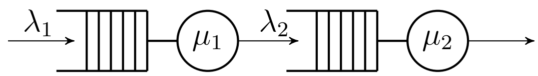

Figure 2.2: A tandem network of queues

If the arrival process for node 1 is Poisson with the arrival rate of λ, then based on Burke's theorem [3] the arrival process at node 2 is also Poisson. The rate of this Poisson process is the same as departure rate of node 1, i.e. λ. Stability conditions impose $\mu_1 < \lambda$ and $\mu_2 < \lambda$. With these inputs, we can derive the average number of customers in each queue:

$$N_i = \frac{\rho_i}{1-\rho_i} \quad i = 1, 2 \tag{2.1}$$

which yields below average time that each customer spends in the whole system:

$$T = \frac{1}{\mu_1 - \lambda_1} + \frac{1}{\mu_2 - \lambda_2} \tag{2.2}$$

Now, we can go through the model.

2.2.2 Setup

There is a final good (q) that needs two types of inputs to be produced: headquarter services (H) and intermediate good (m). We assume that the headquarter's country has comparative disadvantage in production of m compare to some foreign countries. So, it is not economic for the headquarter to produce the intermediate good domestically. It can provide m from the foreign country in three different ways: establishing a subsidiary (vertical FDI), outsourcing and buying form the market.

We summarize all trade barriers in the iceberg form of trade costs. Thus, for obtaining 1 unit of m in the destination country, $\tau > 1$ unit of it should be traded.

There are some trade-offs across these different organizational structures. For instance, in the case of vertical FDI, the price of the intermediate component is not observable to the multinational firm (hereafter, MNE) and the efficiency of the subsidiary is at the lowest possible level, but it is completely specific to the production of q and the informational problems are at the lowest possible level. In the outsourcing method, the efficiency of the supplier is higher than Vertical FDI (due to incentive effects) and the price is observable to the headquarter but the intermediate input is not completely specific

[3] This theory states that for $M/M/1$, $M/M/m$ or $M/M/\infty$ queues with Poisson arrivals (rate λ), we have the following conditions in the steady state:

i. The departure process is a Poisson process with rate λ.

ii. At time t the number of customers in the queue is independent of the departures prior to time t.

to the production of q and it needs a further processing stage during which a fraction of it is thrown away. Finally, by relying on the foreign market, the headquarter can acquire m with the lowest possible price but the informational asymmetries are at the highest level. We can summarize these trade-offs as below.

Define $\overline{p}_m^V$, p_m^O and p_m^M as the shadow price of m in the case of vertical FDI, the price of m if the headquarter relies on outsourcing and the price of m if it is procured from the market, respectively. In addition, note by α_i the ratio of intermediate good that is not usable in the production of q if the organizational structure is i ($\in \{V, O, M\}$). Then we have:

$$\overline{p}^{mV} > p^{mO} > p^{mM} \tag{2.3}$$

$$\alpha_V = 0 < \alpha_O < \alpha_M < 1 \tag{2.4}$$

$$\theta_m^V < \theta_m^O \tag{2.5}$$

$$\overline{m}_i = (\frac{1-\alpha_i}{\tau})m_i \tag{2.6}$$

in which $\overline{m}_t^i$ is the amount of intermediate good that is completely specific to the production of q and m_i is the gross amount of it. Since our model is dynamic, these trade-offs will be adjusted as follows. We can divide the process of producing q by two different stages: procuring m and transforming m to q. The latter stage is actually composed of two different processes: purifying m (and getting $\overline{m}$) and physical transformation of $\overline{m}$ to q. We neglect the second process because it is common and similar across all organizational structures. Imagine the timing of the whole activity of obtaining $\overline{m}$ as what is shown in figure (2.3).

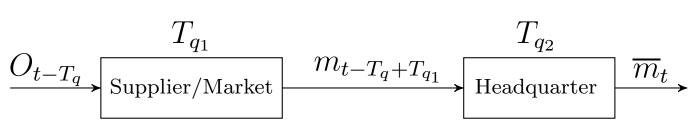

Figure 2.3: The timing of producing q

where O_{t-T_q} represents the orders at time $t - T_q$ and $T_q = T_{q_1} + T_{q_2}$. So, we can modify equation (2.6) as:

$$\overline{m}_t = \frac{(1-\alpha_i)}{\tau} m^i_{t-T_q+T_{q_1}} \tag{2.7}$$

The demand function for q_t is:

$$q_t = A_t p_t^{-\frac{1}{1-\rho}} \quad where \quad A_t = A + u_t \tag{2.8}$$

Here, A is a constant and u_t is the stochastic term that has an arbitrary distribution $F(.)$ with average 0 and variance σ.

The production function for q is a constant returns to scale Cobb-Douglas function:

$$q_t = \theta_H \overline{m}_t^{\beta} h_t^{1-\beta} \tag{2.9}$$

here, θ_H is the productivity level of the headquarter. If the headquarter procures m from the market or via outsourcing, it should pay the relevant price. Otherwise, the production function of intermediate component would be:

$$m^V_{t-T^V_q+T^V_{q_1}} = \theta^V_m [L^{\alpha}_{t-T^V_q} + K^{\alpha}_{t-T^V_q}]^{\frac{1}{\alpha}} \tag{2.10}$$

in which θ^V_m is the productivity of the subsidiary and L and K are two factors of production for m (e.g. labor and capital).

The cost function for each method of providing m consists of three elements: H-services' expenditures, costs associated with the production of m and costs arising from the time discounting of the value of intermediate good during procuring period. If the headquarter chooses vertical FDI, the cost function would be:

$$C^V_t(h_t, L_{t-T^V_q}, K_{t-T^V_q}) = p^h_t h_t + w_{t-T^V_q} L_{t-T^V_q} + r_{t-T^V_q} K_{t-T^V_q} + \delta T^V_q (w_{t-T^V_q} L_{t-T^V_q} + r_{t-T^V_q} K_{t-T^V_q}) \tag{2.11}$$

that p^h_t is the price of headquarter services (h) at time t; w and r are the prices of production factors; and T^V_q corresponds to T_q when the headquarter provide m in-house and will be formally defined later. For the other types of organizational structures, the cost function is:

$$C^j_t(h_t, m_{t-T^j_q}) = p^h_t h_t + p^{mj}_{t-T^j_q} m^j_{t-T^j_q} + C^{Tj}_t(T^j_q), \quad j \in \{O, M\} \tag{2.12}$$

Here, T^j_q represents T_q when the method of obtaining m is j. If the headquarter relies on outsourcing, it should pay a fraction of the value of the ordered input. Suppose this fraction is s_O. We can write:

$$C^{TO}_t(T^O_q) = s_O \delta T^O_{q_1} p^{mO}_{t-T^O_q+T^O_{q_1}} m^O_{t-T^O_q+T^O_{q_1}} + \delta T^O_{q_2} p^{mO}_{t-T^O_q+T^O_{q_1}} m_{t-T^O_q+T^O_{q_1}} \tag{2.13}$$

in which $T^O_{q_1}$ is the time of producing m by the supplier and $T^O_{q_2}$ is the time of further processing of m to make it completely specific ($\overline{m}$) to the production of the final good. Finally, in the case of obtaining m from the foreign market, we have:

$$C^{TM}_t(T^M_q) = \delta T^M_q p^{mM}_{t-T^M_q} m^M_{t-T^M_q} \tag{2.14}$$

in this equation, T^M_q consists of two elements: the time of searching in the market and the time of transforming m to $\overline{m}$.

We solve the model in two steps. First, we solve the headquarter's problem by taking T_q in each case as given. Then, we endegenize them and solve the model by applying queueing theory.

2.2.3 Solving the model taking T_q^i as given

If the risk-neutral headquarter chooses to make m, it should solve this problem:

$$\max_{q_t} \quad E_{t-T_q^V}\{\pi_t^V(q_t) = R_t^V(q_t) - C_t^V(q_t)\} \tag{2.15}$$

in which R_t^V is the revenue from producing q_t units of the final good and equals:

$$R_t^V(q_t) = A_t^{1-\rho} q_t^{\rho} \tag{2.16}$$

and $C_t^V(q_t)$ is the cost function that can be derived based on q_t from below problem:

$$\begin{aligned} &\min_{L,K,H} \; \{C_t^V(h_t, L_{t-T_q^V}, K_{t-T_q^V}) = \\ &p_t^h h_t + (1+\delta T_q^V)(w_{t-T_q^V} L_{t-T_q^V} + r_{t-T_q^V} K_{t-T_q^V})\} \\ \text{s.t.} \quad &\theta_H(\frac{(1-\alpha_i)}{\tau}\theta_m^V[L_{t-T_q^V}^{\alpha} + K_{t-T_q^V}^{\alpha}]^{\frac{1}{\alpha}})^{\beta} h_t^{1-\beta} \geq q_t \end{aligned} \tag{2.17}$$

After some algebra, we can get the cost function as:

$$C_t^V(q_t) = \frac{\tau^{\beta}[1+\delta T_q^V]^{\beta}(p_t^h)^{1-\beta}(w_{t-T_q^V}^{1-\varepsilon} + r_{t-T_q^V}^{1-\varepsilon})^{\frac{\beta}{1-\varepsilon}}}{\beta^{\beta}(1-\beta)^{1-\beta}\theta_H\theta_m^{\beta}}\, q_t$$

or

$$C_t^V(q_t) = \frac{\tau^{\beta}[1+\delta T_q^V]^{\beta}(p_t^h)^{1-\beta}(\overline{p}_{t-T_q^V}^{mV})^{\beta}}{\beta^{\beta}(1-\beta)^{1-\beta}\theta_H}\, q_t \tag{2.18}$$

where

$$\overline{p}_{t-T_q^V}^{mV} = \frac{(w_{t-T_q^V}^{1-\varepsilon} + r_{t-T_q^V}^{1-\varepsilon})^{\frac{1}{1-\varepsilon}}}{\theta_m} \tag{2.19}$$

is shadow price of m at time $t - T_q^V$.

Substituting equation (2.18) and equation (2.16) into equation (2.15) and solving the problem, we obtain the optimal value of q_t^V:

$$q_t^{V*} = E_{t-T_q^V}[A_t \rho^{\frac{1}{1-\rho}}[\frac{\beta^{\beta}(1-\beta)^{1-\beta}\theta_H}{\tau^{\beta}[1+\delta T_q^V]^{\beta}(p_t^h)^{1-\beta}(\overline{p}_{t-T_q^V}^{mV})^{\beta}}]^{\frac{1}{1-\rho}}]$$

The time of reaching to stability in queues is very small comparing to the reaction time of prices to the shocks, thus we can assume [4] that:

$$p_t^h = p^h \quad , \quad \overline{p}_{t-T_q^V}^{mV} = \overline{p}^{mV} \quad \textit{and} \quad p_{t-T_q^j+T_{q_1}^j}^{mj} = p^{mj} \tag{2.20}$$

[4] This assumption is just for simplifying calculations and does not affect theoretical implications

So we can write:

$$q_t^{V*} = \rho^{\frac{1}{1-\rho}} [\frac{\beta^\beta (1-\beta)^{1-\beta} \theta_H}{\tau^\beta [1+\delta T_q^V]^\beta (p^h)^{1-\beta} (\overline{p}^{mV})^\beta}]^{\frac{1}{1-\rho}} E_{t-T_q^V}[A_t] \tag{2.21}$$

The amount of intrafirm trade for this MNE would be:

$$m_t^{V*} = \frac{\rho^{\frac{1}{1-\rho}} \theta_H^{\frac{\rho}{1-\rho}} \beta^{1+\frac{\beta\rho}{1-\rho}} (1-\beta)^{\frac{\rho(1-\beta)}{1-\rho}}}{\tau^{\frac{\rho\beta}{1-\rho}} (1+\delta T_q^V)^{1+\frac{\beta\rho}{1-\rho}} (\overline{p}^{mV})^{1+\frac{\beta\rho}{1-\rho}}} . \frac{1}{(p^h)^{\frac{\rho(1-\beta)}{1-\rho}}} E_{t-T_q^V}[A_t] \tag{2.22}$$

which yields below profit:

$$\pi_t^{V*} = \theta_H^{\frac{\rho}{1-\rho}} (\frac{\beta^\beta (1-\beta)^{1-\beta}}{(p^h)^{1-\beta}})^{\frac{\rho}{1-\rho}} (\frac{1}{\tau [1+\delta T_q^V] \overline{p}^{mV}})^{\frac{\beta\rho}{1-\rho}} (\rho^{\frac{\rho}{1-\rho}} A_t^{1-\rho} E_{t-T_q^V}[A_t]^\rho - \rho^{\frac{1}{1-\rho}} E_{t-T_q^V}[A_t]) \tag{2.23}$$

If the procurement method is not vertical FDI, the problem of the headquarter is:

$$\max_{q_t} \quad E_{t-T_q^j} \{\pi_t^j(q_t) = R_t^j(q_t) - C_t^j(q_t)\} \qquad j \in \{O, M\} \tag{2.24}$$

in which the cost function could be defined as following:

$$\begin{aligned} \min_{h_t, m_{t-T_q^j+T_{q_1}^j}} \quad & \{C_t^j(h_t, m_{t-T_q^j+T_{q_1}^j}) = p_t^h h_t + \widetilde{T}_j p^{mj}_{t-T_q^j+T_{q_1}^j} m_{t-T_q^j+T_{q_1}^j}\} \\ \text{s.t.} \quad & \theta_H [\frac{\theta_m}{\tau} m_{t-T_q^j+T_{q_1}^j} (1-\alpha_j)]^\beta h_t^{1-\beta} \geq q_t \end{aligned} \tag{2.25}$$

where we have used below notation in the cost formulation:

$$\widetilde{T}_j = \begin{cases} 1 + s_O \delta T_{q_1}^O + \delta T_{q_2}^O & \text{if} \quad j = O \\ 1 + \delta T_q^M & \text{if} \quad j = M \end{cases}$$

Regarding equation (2.20), solution of this problem becomes:

$$C_t^j(q) = \frac{\tau^\beta [\widetilde{T}_j p^{mj}]^\beta (p^h)^{1-\beta}}{\beta^\beta (1-\beta)^{1-\beta} \theta_H (1-\alpha_j)^\beta} q_t \tag{2.26}$$

Inserting the cost function in equation (2.24) and solving it gives the optimal level of final good and the optimal profit of the headquarter:

$$q_t^{j*} = \rho^{\frac{1}{1-\rho}} [\frac{\beta^\beta (1-\beta)^{1-\beta} \theta_H (1-\alpha_j)^\beta}{\tau^\beta [\widetilde{T}_j p^{mj}]^\beta (p^h)^{1-\beta}}]^{\frac{1}{1-\rho}} E_{t-T_q^j}[A_t] \tag{2.27}$$

$$\pi_t^{j*} = \theta_H^{\frac{\rho}{1-\rho}} (\frac{\beta^\beta (1-\beta)^{1-\beta}}{(p^h)^{1-\beta}})^{\frac{\rho}{1-\rho}} (\frac{1-\alpha_j}{\tau \widetilde{T}_j p^{mj}})^{\frac{\beta\rho}{1-\rho}} (\rho^{\frac{\rho}{1-\rho}} A_t^{1-\rho} E_{t-T_q^j}[A_t]^\rho - \rho^{\frac{1}{1-\rho}} E_{t-T_q^j}[A_t]) \tag{2.28}$$

Regarding our assumption for A_t, we can write:

$$E_{t-T_q^j}[A_t] = E_{t-T_q^V}[A_t] = A$$

And finally, substituting $\widetilde{\alpha}_j = 1 - \alpha_j$ and $\widetilde{T}_V = 1 + \delta T_q^V$ in the above results, we can derive:

$$\Pi_t^{Vj} = \frac{\pi_t^{V*}}{\pi_t^{j*}} = [\frac{\widetilde{T}_j p^{mj}}{\widetilde{T}_V \overline{p}^{mV} \widetilde{\alpha}_j}]^{\frac{\beta\rho}{1-\rho}} \tag{2.29}$$

So, the MNE decides on the type of organizational structure based on the time terms, the degree of component contractibility and the prices of intermediate good. We treated the time terms as given in this part. The next part uses queueing theory to calculate them.

2.2.4 Deriving the time terms

One of the important features of a GVC is the flow of information among different linkages. In our setting (i.e. the simplest from of a GVC), we assume that the information flows according to what is shown in figure (2.4).

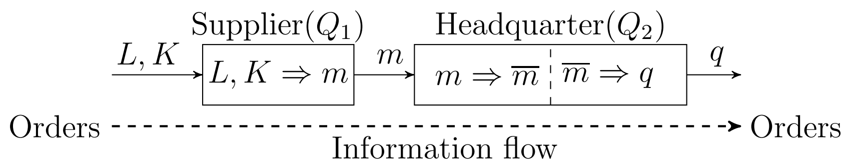

Figure 2.4: The information evolves in parallel to the production of q

Here, we assume that each order for m is immediately made after the production of the final good and in parallel to the production of m and q, a specific type of information that contains product characteristics is developed and moves between the two linkages of the GVC. In fact, this information is embodied in the intermediate component and evolves with any change in it. Regarding these assumptions, we can consider the information flow across the linkages as a two-stage tandem network of queues (figure 2.5). The first queue corresponds to the production of m and the second one stands for transforming m to $\overline{m}$. Q_1 is an approximation for the information flow in production of m. The arrival rate of information orders is λ_S and the service rate on processing this information (that evolves with production operations) is μ_S. Q_2 represents the process of obtaining $\overline{m}$.

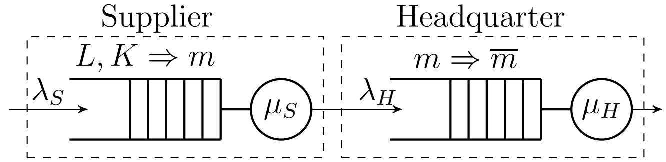

Figure 2.5: Information flow as a tandem network of queues

Figure 2.5 varies across three different types of organizational structures. The more relevant explanation for each of them is as following.

Vertical FDI: As mentioned before, in the case of vertical integration, since the intermediate input produced by the subsidiary is completely specific to the production of the final good, it does not need to the further processing and orders are immediately made after its production. So, in this case Q_2 does not exist and figure 2.5 boils down to the below figure:

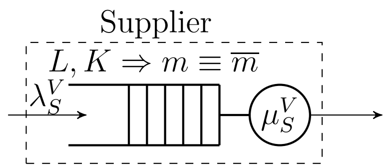

Figure 2.6: Information flow in the case of vertical FDI

Here, λ_S^V is the average arrival rate of the orders and μ_S^V is the service rate assumed to be:

$$\mu_S^V = \mu_S^V(\theta_m^V, I_c) \quad , \quad \frac{\partial \mu_S^V}{\partial \theta_m^V} > 0\,, \frac{\partial \mu_S^V}{\partial I_c} \geq 0 \tag{2.30}$$

where, θ_m^V is the productivity of the subsidiary and I_c is the level of the institutional quality of the host country. This assumption states that the average service rate received by information at the subsidiary level is a function of the productivity of the subsidiary and the host country 's institutional quality. The logic behind the former is the fact that information evolves in parallel to the production operation. We know that higher productivity leads to the sooner operations on the factors for a unit of output. So, higher productivity results in higher rates of information processing. The intuition for the latter is that the higher level of institutional quality increase the efficiency of codifying information and documenting it. Consequently, the service rate of information processing rises.

Outsourcing: In this type of organizational structure, Q_1 corresponds to the production of m and yields $T_{q_1}^O$.

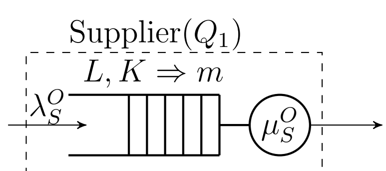

Figure 2.7: Information flow for the production stage of outsourcing

The same explanation as vertical FDI method goes to λ_S^O and μ_S^O. We can write for the service rate:

$$\mu_S^O = \mu_S^O(\theta_m^O, I_c) \quad , \quad \frac{\partial \mu_S^O}{\partial \theta_m^O} > 0 \, , \, \frac{\partial \mu_S^O}{\partial I_c} \geq 0 \tag{2.31}$$

Q_2 relates to the purifying stage and yields $T_{q_2}^O$. We make below assumption for μ_H^O:

$$\mu_H^O = \mu_H^O(\widetilde{\alpha}_O, I_c) \quad , \quad \frac{\partial \mu_H^O}{\partial I_c} \geq 0 \, , \, \frac{\partial \mu_H^O}{\partial \widetilde{\alpha}_O} > 0 \tag{2.32}$$

where $\widetilde{\alpha}_O = 1 - \alpha_O$ captures the degree of contractibility for m produced by outsourcing. This assumption says that any increase in the degree of input contractibility will raise the average service rate of information processing in the refining stage. The intuition is clear: an increase in $\widetilde{\alpha}_O$ leads to the decrease in the degree of informational asymmetries. Consequently, less effort is needed to purify m. Thus, the time needed to process each unit of intermediate input falls. In other words, the average service rate of information processing is reduced.

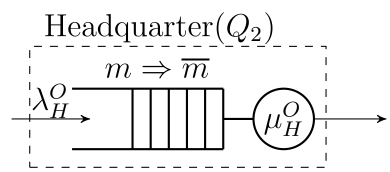

Figure 2.8: Information flow for the purifying stage of outsourcing

Market-based procuring: in this case Q_1 formalizes the information flow for the search stage and Q_2 is similar to that of outsourcing. Figure (2.9) depicts these queues. Here, λ_M and λ_H^M are average arrival rates for the search stage and refining stage, respectively. μ_M and μ_H^M are the average service rates. We assume below relations for these service rates:

$$\mu_M = \mu_M(MS, I_c) \quad , \quad \frac{\partial \mu_M}{\partial I_c} \geq 0 \tag{2.33}$$

$$\mu_H^M = \mu_H^M(\widetilde{\alpha}_M, I_c) \quad , \quad \frac{\partial \mu_H^M}{\partial I_c} \geq 0, \frac{\partial \mu_H^M}{\partial \widetilde{\alpha}_M} > 0 \tag{2.34}$$

Assumption (2.33) says that average service rate of the search activity depends on the market structure (MS) and the host country's level of institutional quality. Furthermore, it has a positive relation with I_c: we expect that under better country-level institutions (e.g. market regulation, contract enforcement, rule of low, good governance, ...), it is easier to find intermediate good in the market. Assumption (2.34) corresponds to the assumption (2.32) with similar intuitions.

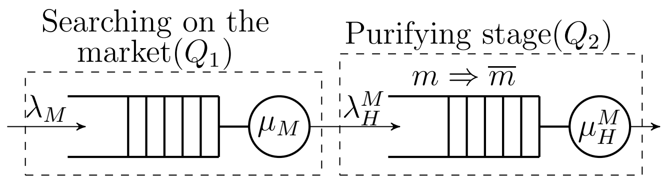

Figure 2.9: Information flow for market-based procuring

We can further go ahead and expect the service rates to satisfy additional equations. Indeed, we can characterize the three different types of organizational structure as follows. In the vertical FDI method, we have the Lowest efficiency level in production of m due to shadow prices and incentives problems (Hart and Moore [1990] and Williamson [1979]). Prices are not observable, so performance pay does not work. In addition, the subsidiary does not own the intermediate good or does not have any bargaining power over the production revenues, so the headquarter can not motivate him/her to produce productively. On the other hand, potential informational asymmetries associated with the input are absent because of complete relationship-specific investments (Williamson [1979]) and this results in the highest quality level (this is the logic behind the assumption $\alpha_V = 0$). Outsourcing provides higher efficiency level in production of m compared to vertical integration. This is attributed to the higher incentives of the supplier (due to reputation effects and the presence of outside-option). Thus, we can write:

$$\mu_S^O > \mu_S^V \tag{2.35}$$

For the case of market-based procuring, it is normally accepted that buying from market is a rather fast activity. So, we can write:

$$\mu_M > \mu_S^O \tag{2.36}$$

The highest level of informational asymmetries embodied in the input are present in this method. This is due to the fact that buyer cannot observe quality ex-ante and it is not possible to alleviate this problem by contract design. Thus, the service rate of purifying stage is bigger for outsourcing.

$$\mu_H^O > \mu_H^M \tag{2.37}$$

It is noteworthy to mention that $\widetilde{\alpha}_j$, $j \in \{O, M\}$ and I_c are exogenous to the firms and they vary during time and across countries. Now, we can use queueing theory to obtain the time of information flow (or equivalently, the total service time) for the three situations. As depicted in figures 2.6-2.9, deriving T_q^V,$T_{q_1}^O$ and $T_{q_2}^O$ needs solving a single queue. Following the literature on queueing theory, we make below assumptions for each of these single queues.

i. Arrival process has a Poisson distribution.

ii. Service times are i.i.d. and have exponential distribution .

iii. There is a single server in each queue.

iv. The capacity of the waiting room is infinite.

v. Service times are independent of the arrival processes.

vi. Inter-arrival times and service times are birth-death processes.

So, according to the queueing literature, each queue is an $M\backslash M\backslash 1$ queue. The stability condition for queues requires that $\mu_i < \lambda_i$. For this class of queues, the average number of customers in each queue is:

$$N_i = \frac{\lambda_i}{\mu_i - \lambda_i} = \frac{\rho_i}{1-\rho_i} \quad , \quad \rho_i = \frac{\lambda_i}{\mu_i} \tag{2.38}$$

Applying Little's theorem, we can derive the average time during which each customer (unit of information, e.g. each order) receive the relevant service:

$$T_i = \frac{N_i}{\lambda_i} = \frac{1}{\mu_i - \lambda_i} \tag{2.39}$$

So, the time terms for the two cases of vertical FDI and outsourcing would be:

$$T_q^V = \frac{1}{\mu_S^V - \lambda_V} \tag{2.40}$$

$$\begin{aligned} T_{q_1}^O &= \frac{1}{\mu_S^O - \lambda_S^O} \\ T_{q_2}^O &= \frac{1}{\mu_H^O - \lambda_H^O} \end{aligned} \tag{2.41}$$

If the headquarter relies on the market to provide m, we have a two-stage tandem network of queues as shown in figure 2.9. In this case, we add some assumptions to the above assumptions in order to make the problem solvable.

a. Service times for Q_1 and Q_2 are exponentially distributed and mutually independent.

b. Service times are independent of the arrival processes.

From Burke's theorem we know that $\lambda_H = \lambda_M$. After some algebra, one can derive the average number of customers in each queue as:

$$\begin{aligned} N_M &= \frac{\lambda_M}{\mu_M - \lambda_M} = \frac{\rho_M}{1-\rho_M} \quad , \quad \rho_M = \frac{\lambda_M}{\mu_M} \\ N_H^M &= \frac{\lambda_H^M}{\mu_H^M - \lambda_H^M} = \frac{\rho_H^M}{1-\rho_H^M} \quad , \quad \rho_H^M = \frac{\lambda_H^M}{\mu_H^M} \end{aligned} \tag{2.42}$$

Again by Little's theorem:

$$T_q^M = \frac{1}{\mu_M - \lambda_M} + \frac{1}{\mu_H^M - \lambda_H^M} \tag{2.43}$$

Since we want to compare the performance of all organizational structures for the same headquarter, we can consider the same average arrival rates for all of them:

$$\lambda_S^O = \lambda_S^V = \lambda_M$$

Moreover, we apply Burke's theorem to extend this equation:

$$\lambda_S^O \underbrace{=}_{Burke's\, theorem} \lambda_H^O = \lambda_S^V = \lambda_M \underbrace{=}_{Burke's\, theorem} \lambda_M^H = \lambda \tag{2.44}$$

The average arrival rate, λ, depends on the size and distribution of orders and thus is a function of economic conditions, Bullwhip effect, working traffic, ...

Now, we are ready to state the main implications of the model in the next part.

2.2.5 Theoretical implications

In this part, we extract some implications of our model that can justify the suddenness of the recent trade collapse and the presence of north-north vertical FDI. The first proposition relates the suddenness feature to the long-run change in the institutional quality of host countries. The second proposition states its relationship with the change in the degree of contractibility of intermediate component. Finally, the last proposition explain the situations under which within industry vertical FDI (north-north vertical FDI) emerges.

Proposition 1: Any increase in the level of institutional quality of the host country will induce a non-positive change in the time of procuring the full-specific input provided that it does not alter organizational type from vertical FDI to arm's length trade or the magnitude of institutional improvement is high enough. Furthermore, if the productivity of procuring the full-specific intermediate good is positively related to the level of institutional quality (regardless of organizational type), then this change is negative.

Proposition 2: Any improvement in the degree of component-contractibility results in a non-increasing change in the time of providing the full-specific input if it does not alter the method of procurement or the magnitude of improvement is high enough. In addition, if this improvement pushes the new degree of contractibility above a threshold, then this time change is negative.

These propositions show that the degree of the input contractibility ($\widetilde{\alpha}_j$) and institutional quality of the host country are good candidates to address the suddenness of the recent trade collapse. Indeed, if time trends of these parameters are upward, then we would overall expect a downward trend for the reaction time of the headquarter to any shocks. The next proposition explains the motivation for within-industry vertical FDI. Before moving to the details, we make below assumptions:

Assumption 1: Let I denote the set of all possible levels of countries' institutional qualities. There are $\underline{I}_c$, $\overline{I}_c \in I$ such that $[\underline{I}_c, \overline{I}_c]$ provides an interval on which for all amounts of $\widetilde{\alpha}_j > 0$ the service rates are well-defined and greater than λ.

This assumption states that there is a domain of host-country's institutional qualities that has the following properties. First, the service rates of information processing for any degree of product contractibility except $\widetilde{\alpha}_j = 0$ are well-defined. Second, queues are stable in this interval and the time of procuring activity is finite.

Assumption 2:

$$\mu_H^j(\widetilde{\alpha}_j = 0, I_c) = \lambda \quad \forall\, I_c \in I \quad (\widetilde{\alpha}_j \to 0^+ \Rightarrow \widetilde{T}_j \to +\infty)$$

In other words, when the degree of input contractibility is zero, refining m to obtain $\overline{m}$ is not possible and it takes infinite units of time! In fact, when $\widetilde{\alpha}_j$ moves toward 0, the time of information processing for the case of j-organizational structure increases dramatically.

Assumption 3:

$$\Pi_{Vj}(\widetilde{\alpha}_j = 1, I_c) < 1 \quad \forall I_c \in [\underline{I}_c, \overline{I}_c]$$

This assumption says that When the input is fully contractible, if the host country is enough attractive ($I_c \in [\underline{I}_c, \overline{I}_c]$), it would be better for the headquarter to do not rely on vertical FDI. This is completely compatible with the rationality of the headquarter due to the higher productivity of the supplier in producing m.

Proposition 3: Under assumptions 1-3, if the degree of input contractibility is not high enough, then the best way of getting the component from the foreign country is vertical FDI.

According to this proposition, even though the institutional quality of the host country is high, $I_c = \overline{I}_c$, it is probable that the headquarter establishes a subsidiary for procuring the intermediate input. In other words, when the degree of the product contractibility is low enough, the inefficiencies caused by informational asymmetries and the increase in the time of purifying the intermediate component make buying the input suboptimal in compare with making it. For these cases, although the host country is north (possesses high institutional quality), the nature of FDI is vertical and within industry. So, our model can justify the presence of north-north vertical FDI.

2.3 Some stylized facts on the US trade during the recent trade collapse

2.3.1 Dataset description

The dataset covers monthly bilateral trade data between US and 25 countries that have the largest bilateral trade shares with US (based on 2008 trade flows). These countries undertake more than 80 percent of US total trade and include the top 10 partners engaged in related-party trade during 2008. Table (2.1) presents these countries. The time period for the data covers Jan 2007 (=1) until Dec 2010 (=48). The data for each country is available at the 6-digit NAICS level.

Country	**Bilateral trade with US (1000$)**	**Share in total trade**
THAILND	31887706810	0.009780593
ISRAEL	32502146601	0.009969054
RUSSIA	35657709353	0.010936928
SWITZLD	37960396500	0.011643207
IRELAND	39378269069	0.012078097
SINGAPR	41373945783	0.012690211
AUSTRAL	41506074474	0.012730737
MALAWI	42225315513	0.012951343
NIGERIA	42316338132	0.012979261
BELGIUM	43147182288	0.013234098
INDIA	43205510173	0.013251988
ITALY	49911589770	0.015308876
NETHLDS	58178704524	0.017844564
BRAZIL	59088106792	0.018123496
TAIWAN	59831653998	0.018351556
VENEZ	62110505387	0.019050525
S ARAB	66128628989	0.020282964
FRANCE	70119835059	0.021507146
KOR REP	79761693535	0.024464495
U KING	1.0748E+11	0.032966238
FR GERM	1.45978E+11	0.044774481
JAPAN	2.00548E+11	0.061511904
MEXICO	3.47836E+11	0.106688147
CHINA	4.0467E+11	0.124120352
CANADA	5.57264E+11	0.17092392
Sum	3.2603E+12	**0.82816418**

Table 2.1: List of countries that are the top 25 partners of US trade

2.3.2 Data characteristics

Table (2.2) shows the summary statistics of the main variables. First, we investigate the behavior of these variables during the specified period. Then, we use them to construct year-on-year monthly mid-point-growth rates and analyze the behavior of these rates during trade collapse. We run these stages for different categories of goods: intermediate goods, capital goods, consumption goods (durables and nondurables) and the pool of all categories. Due to the fact that the NAICS system distinguishes the data just by industry, the data for these categories are constructed by using other classification systems. This task is done in three steps. First, we apply the MIG (Main Industrial Groupings) system and find its correspondence in the NACE REV.2 system. Then, we adapt ISIC REV.4 to NACE REV.2 and finally we extract the data for different good categories from the NAICS by fitting ISIC REV.4 to 2007 NAICS. In each category (also in the pool of all categories), we consider four groups of industries by Dividing based on four levels (quartiles) that partition the interval of related-party trade shares into four equal slices. The first group of industries (the first quartile) have the lowest related party trade shares (GLq). The second quartile includes industries with the related-party trade shares above the first level and below the second level (GMLq). The third group consists of industries with the shares above the second level and below the third level (GMHq) and finally, the last group covers industries with the highest shares (GHq).

Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**	**variable label**
NAICS	506339	-	-	1	455	Industry codes
time	506339	-	-	1	48	Jan 2007(=1) until Dec 2010(=48)
id	506339	-	-	1	25	Country id
imp	505757	12274.71	108597.5	0	1.11e+07	General imports-customs Value Basic
exp	505860	7501.892	37818.68	0	2497632	Exports
im_re_share	506339	.353383	.2204704	0	.9510981	The share of related-party imports in total imports
ex_re_share	505357	.2319741	.1455318	0	.8144016	The share of related-party exports in total exports

Table 2.2: Data summaries

The suddenness of the trade collapse necessitates the use of monthly data. For example, in US, the collapse started about July 2008 and stopped around June 2009 and yearly data does not disclose the important features of the data. However, in the monthly data, seasonality may hide the real effects of the negative shock. To fix this problem, we use the so-called mid-point-growth rates of imports and exports (Davis and Haltiwanger [1992] and Bricongne et al. [2012]). This index is computed as following. If the imports/exports value of industry i (at 6-digit NAICS level) from/to country c at month t is x_{ict}, the mid-point-growth rate would be:

$$g_{ict} = \frac{x_{ict} - x_{ic(t-12)}}{\frac{1}{2}(x_{ict} + x_{ic(t-12)})}$$

In order to control for the different share of industries in the total trade, the weight of each flow g_{ict} is calculated as:

$$w_{ict} = \frac{x_{ict} - x_{ic(t-12)}}{\Sigma_c \Sigma_i x_{ict} + \Sigma_c \Sigma_i x_{ic(t-12)}}$$

and finally we can derive the year-on-year growth rate of the total imports/exports by summing the weighted flows:

$$G_t = \Sigma_c \Sigma_i w_{ict} * g_{ict}$$

Figure (2.10) compares the monthly mid-point growth rates of all categories. It shows that:

- The highest magnitude of collapse in both imports and exports belongs to intermediate goods and the lowest one is a feature of consumption goods.

- All categories react to the shock in the same time except the imports of capital goods and the imports of intermediate goods. They have a 2-months delay.

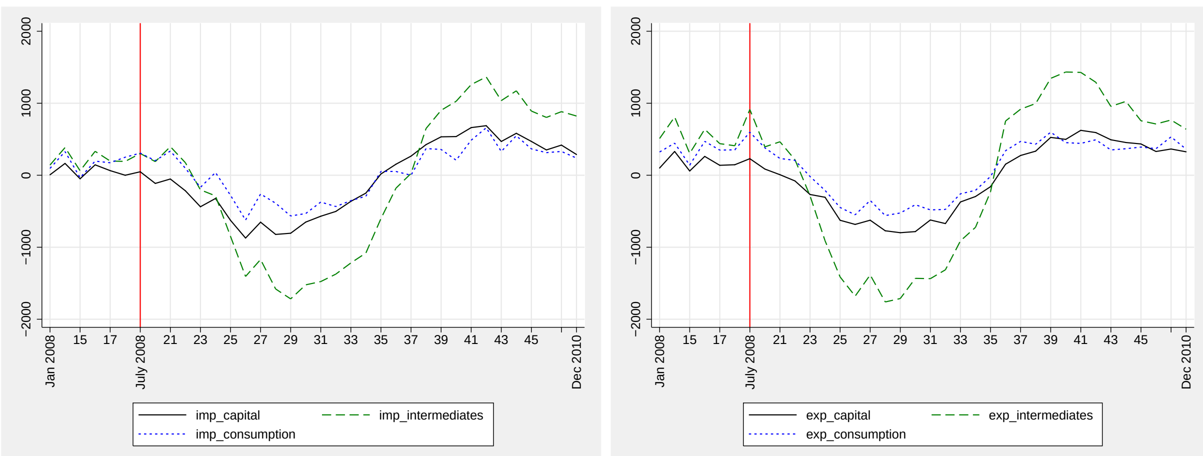

Figure 2.10: Comparing mid-point growth rates of different good categories

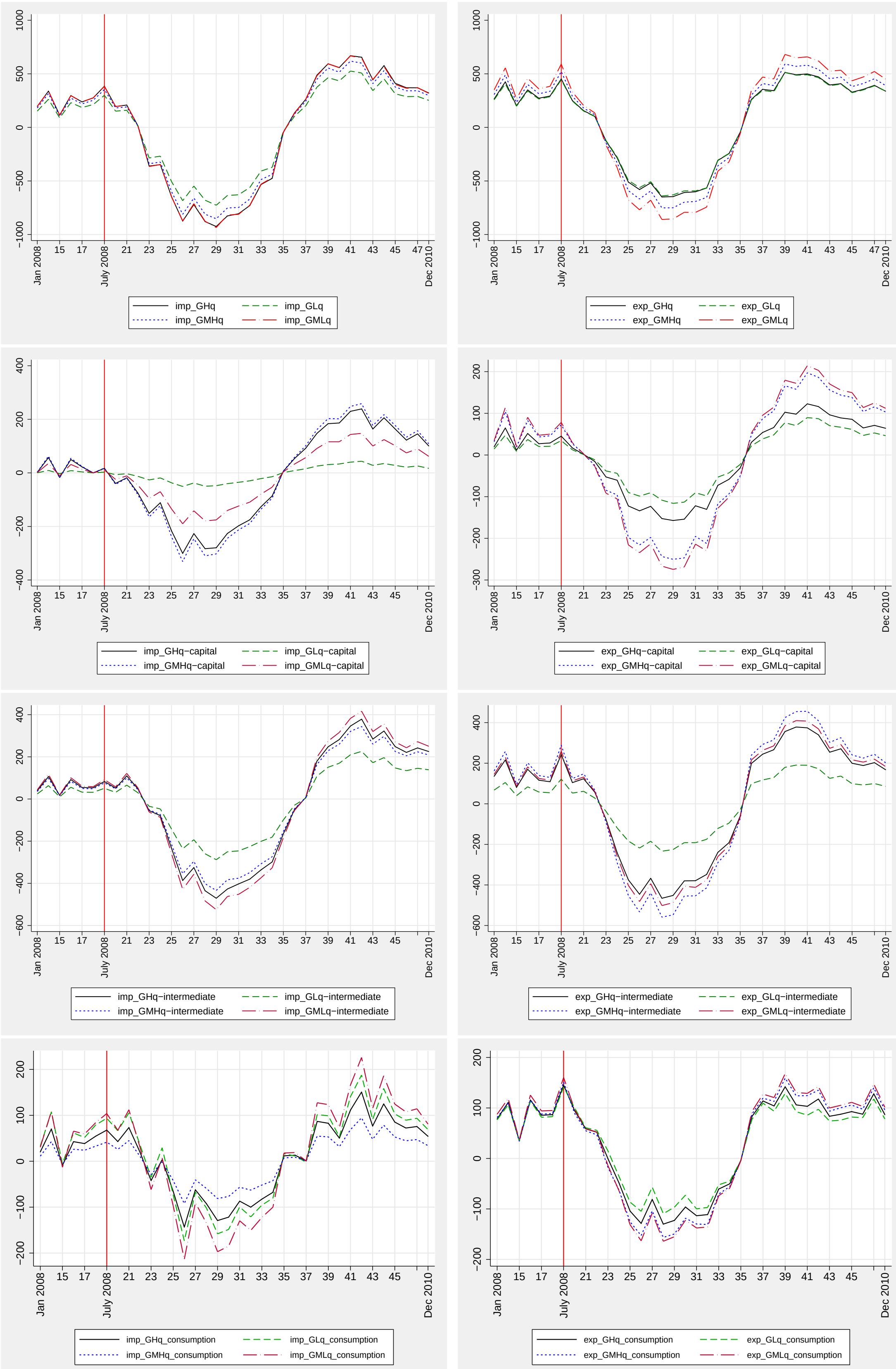

Figure 2.11: Mid-point growth rates for all categories of goods

Figure (2.11) presents the behavior of year-on-year growth rates for the different good categories. We extract the following facts from these figures:

- Across all categories, there is not any significant difference among different industry groups in responding to the negative shock.

- Almost all groups of industries fell in recession on July 2008 except imports of consumption goods and imports of intermediate goods, with 2 months lag.

- Intermediate goods category has the most similarity to the pool of all categories in terms of functional form and magnitude of collapse.

- There is a symmetric behavior in the growth rates during the collapse and recovery periods (V/U-shape behavior)

Next section simulates the model to see whether the model has the capability of generating these features or not.

2.4 Simulation

In this section, we want to see whether our model has the capability to produce the main properties of the data or not. By choosing suitable parameter values and using Matlab software, we obtain qualitatively similar results to the real world data. The simulation is done by only considering the negative demand shock to the final good. The reason for this goes back to the recent research by Eaton et al. [2011] on the recent trade collapse. They show that a major part of the recent trade shock can be accounted for as a result of demand shock (figure (2.12) by Eaton et al. [2011]. We use a U-shape change in the demand as depicted in figure (2.13) for a proxy of demand collapse. This change is created by the relevant changes in the fixed component of demand coefficient (A) during recession. This figure also shows the relevant trade reactions for the two different types of trade: related-party trade (intra-firm trade) and non-related party trade. The former corresponds to the GHq group of industries and the latter to the GLq group of them.

Figure (2.14) presents simulation results and compares them with the real world data. The parameter values for this result is reported in table (2.3).

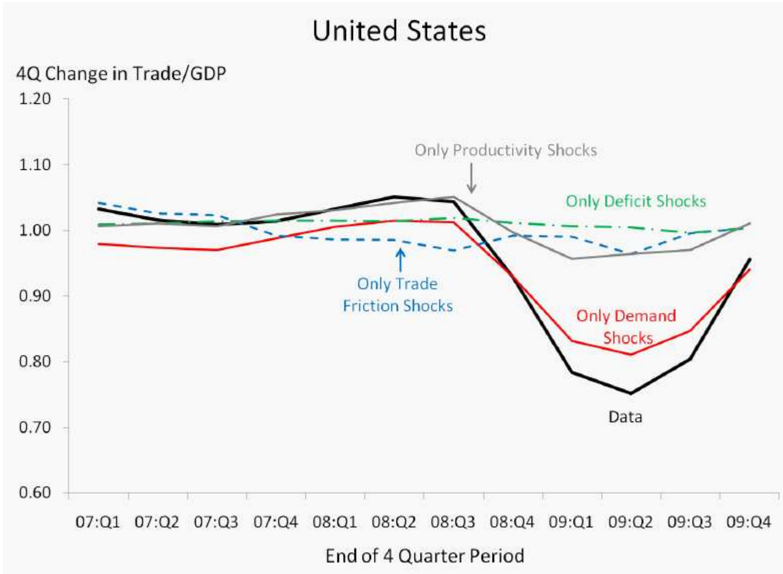

Figure 2.12: Country trade/GDP across many four-quarter periods in data and counterfactuals created by different shocks (source: Eaton et al., 2011)

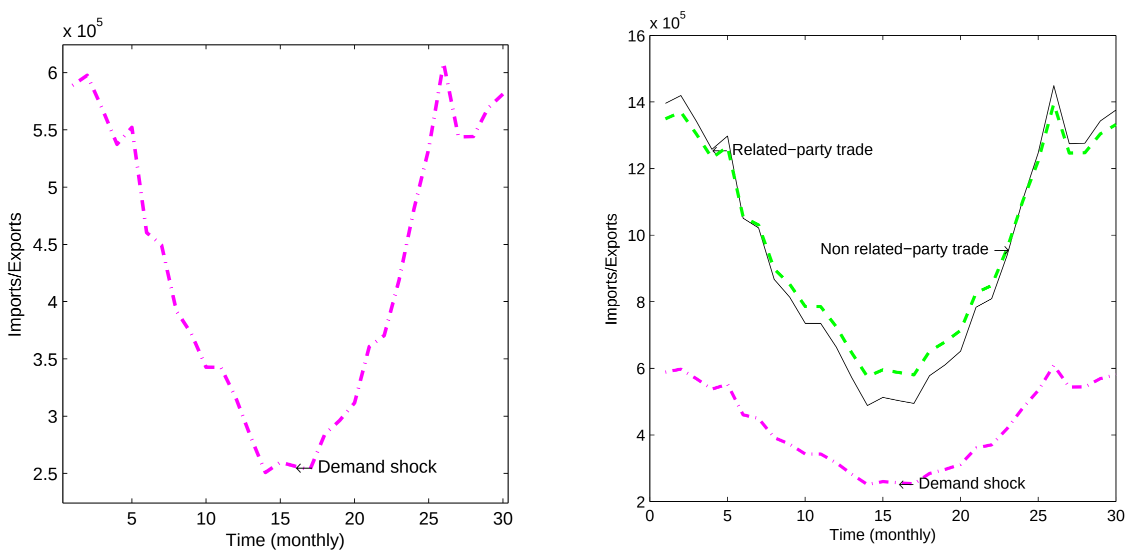

Figure 2.13: Simulated demand shock and the relevant simulation for trade reaction

Par.	Definition	Imp.	Exp.
β	The share of intermediate input in the production of final good	0.35	0.5
δ	Intertemporal depreciation rate of the input (including the inventory costs)	0.05	0.05
θ_H	Productivity of the headquarter in the production of final good	8	8
θ_m^V	Productivity of the headquarter in the production of input	$[1, 8]$	$[1, 8]$
θ_m^O	Productivity of input production for the outsourcing case	10	10
θ_m^M	Productivity of input production in the market-base procuring	12	12
ε	Elasticity of substitution in the CES production function for input	0.65	0.65
τ	The inverse of the rate of iceberg trade costs	0.95	0.95
I_c	The level of institutional quality for the host country	$[0.6, 1]$	$[0.6, 1]$
$\widetilde{\alpha}_M$	The degree of input contractibility in the market	$[0.5, 0.8]$	$[0.46, 0.8]$
$\widetilde{\alpha}_O$	The degree of input contractibility in the outsourcing contracts	$\widetilde{\alpha}_M + 0.1$	$\widetilde{\alpha}_M + 0.1$
s_{HO}	The headqurter share on the input investing in the outsourcing	0.2	0.2
λ	Average arrival rate	0.6	0.6
ω	The normalized wage of workers in the production of intermediate	1	1
r	The interest rate of capital	0.04	0.04
p_H	The price of final good	20	20
ρ	The power coefficient of the CES demand function	0.7	0.7

Table 2.3: Parameter values for simulation

Moreover, we make below assumptions for the service rates.

$$\mu_H^M = \lambda + \widetilde{\alpha}_M I_c$$

$$\mu_S^O = \lambda + 2I_c$$

$$\mu_H^O = \lambda + \widetilde{\alpha}_O I_c$$

$$\mu_S^V = \lambda + \frac{\theta_m^V}{\theta_m^O} I_c$$

These relations satisfy our assumptions on efficiency ($\mu_S^V < \mu_S^O$) and the degree of informational asymmetries ($\mu_H^M < \mu_H^O$). It is evident from this figure that the simulation results capture the V/U shape reaction of trade to the negative demand collapse. Moreover, as the real world data, for imports this reaction's magnitude is bigger for intrafirm trade than arm's length trade during the collapse whereas for exports there is not a significant difference between them.

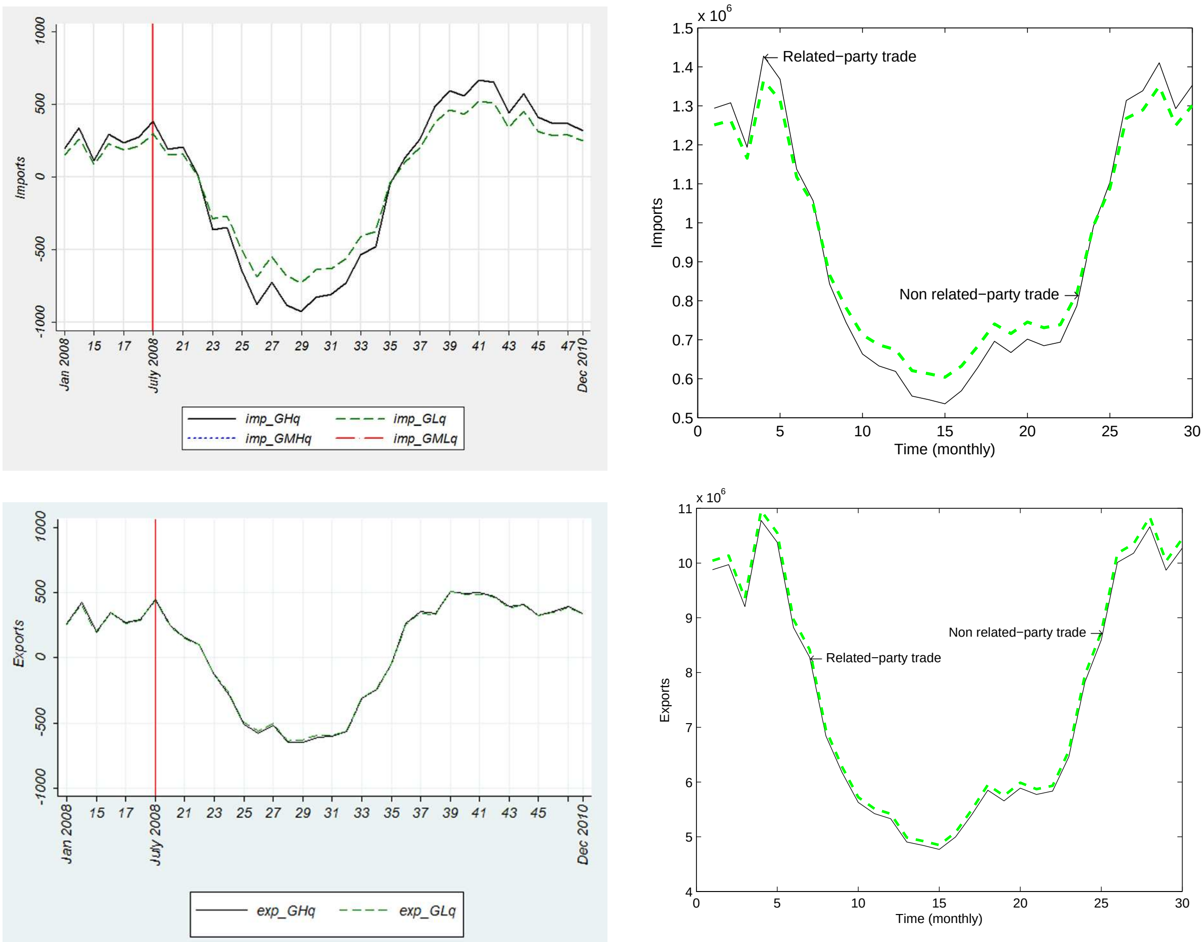

Figure 2.14: The model simulation captures the main qualitative features of the data on both imports and exports

2.5 Conclusion

This paper tries to address the suddenness feature of the recent trade collapse. For this aim, it incorporates the "time costs" of input procuring in the internalization decision of MNEs. These time costs associated with the time lasts from ordering an intermediate good by the headquarter to availability of that good for using in the production of the final good. There are three organizational structures to obtain intermediate component from the foreign country: vertical FDI, outsourcing and buying from the foreign market. We use queueing theory to endogenize the "time terms" in each of these cases. Using the results of this model, the paper argues that the suddenness feature of the recent trade collapse may be a result of the change in the institutional quality of the host country or increasing in the contractibility of the input during recent decades.

A side product of the model is addressing the presence of north-north vertical FDI. In fact, when the degree of the product contractibility is not high enough, the inefficiencies arising from informational asymmetries of the input characteristics and the increase in the time of purifying it make outsourcing unattractive for the headquarter.

On the Empirical part, we extract the main features of the data on US monthly bilateral trade. Applying suitable values for parameters and considering a demand shock, the model generates results that are qualitatively compatible with the real world data and captures the main stylized facts obtained by using them.

2.6 appendix

Proof of Proposition 1. We can say from previous assumptions that:

$$\begin{cases} \frac{\partial \widetilde{T}_V}{\partial I_c} = (1-\delta)(\frac{-1}{(\mu_S^V-\lambda)^2})\,(\overbrace{\frac{\partial \mu_S^V}{\partial I_c}}^{>0}) \leq 0 \\ \frac{\partial \widetilde{T}_O}{\partial I_c} = (1-\delta)\,\underbrace{(\frac{-s_H}{(\mu_S^O-\lambda)^2}\underbrace{\frac{\partial \mu_S^O}{\partial I_c}}_{\geq 0} - \frac{1}{(\mu_H^O-\lambda)^2}\underbrace{\frac{\partial \mu_H^O}{\partial I_c}}_{\geq 0})}_{\leq 0} \leq 0 \\ \frac{\partial \widetilde{T}_M}{\partial I_c} = (1-\delta)\,\underbrace{(\frac{-1}{(\mu_M-\lambda)^2}\underbrace{\frac{\partial \mu_M}{\partial I_c}}_{\geq 0} - \frac{1}{(\mu_H^M-\lambda)^2}\underbrace{\frac{\partial \mu_H^M}{\partial I_c}}_{\geq 0})}_{\leq 0} \leq 0 \end{cases} \tag{2.45}$$

So, if organizational structure remains unchanged, then $\Delta T^* \leq 0$. For defining the effect of I_c on Π_{vj} we can write

$$\begin{aligned} \frac{\partial \Pi_{Vj}}{\partial I_c} &= \frac{\beta\rho}{1-\rho}[\frac{\widetilde{T}_j p_m^j}{\widetilde{T}_V \overline{p}_m^V \widetilde{\alpha}_j}]^{\frac{\beta\rho}{1-\rho}-1}\frac{p_m^j}{\overline{p}_m^V}[\frac{1}{\widetilde{T}_V\widetilde{\alpha}_j}\frac{\partial \widetilde{T}_j}{\partial I_c} + \frac{\widetilde{T}_j}{\widetilde{\alpha}_j}\frac{-1}{\widetilde{T}_V^2}\frac{\partial \widetilde{T}_V}{\partial I_c} + \frac{\widetilde{T}_j}{\widetilde{T}_V}\frac{-1}{\widetilde{\alpha}_j^2}\frac{\partial \widetilde{\alpha}_j}{\partial I_c}] \\ &= \frac{\beta\rho}{1-\rho}\Pi_{vj}[\frac{1}{\widetilde{T}_j}\frac{\partial \widetilde{T}_j}{\partial I_c} - \frac{1}{\widetilde{T}_V}\frac{\partial \widetilde{T}_V}{\partial I_c} - \frac{1}{\widetilde{\alpha}_j}\frac{\partial \widetilde{\alpha}_j}{\partial I_c}] \\ &= \frac{\beta\rho}{1-\rho}\Pi_{vj}[\epsilon_{\widetilde{T}_V,I_c} + \epsilon_{\widetilde{\alpha}_j,I_c} - \epsilon_{\widetilde{T}_j,I_c}] \end{aligned}$$

So, the sign of $\frac{\partial \Pi_{Vj}}{\partial I_c}$ depends on the elasticities $\epsilon_{\widetilde{T}_V,I_c}$, $\epsilon_{\widetilde{\alpha}_j,I_c}$ and $\epsilon_{\widetilde{T}_j,I_c}$ as following:

$$\begin{cases} \frac{\partial \Pi_{vj}}{\partial I_c} = 0 \quad if\, \epsilon_{\widetilde{T}_V,I_c} + \epsilon_{\widetilde{\alpha}_j,I_c} = \epsilon_{\widetilde{T}_j,I_c} \\ \frac{\partial \Pi_{vj}}{\partial I_c} > 0 \quad if\, \epsilon_{\widetilde{T}_V,I_c} + \epsilon_{\widetilde{\alpha}_j,I_c} > \epsilon_{\widetilde{T}_j,I_c} \\ \frac{\partial \Pi_{vj}}{\partial I_c} < 0 \quad if\, \epsilon_{\widetilde{T}_V,I_c} + \epsilon_{\widetilde{\alpha}_j,I_c} < \epsilon_{\widetilde{T}_j,I_c} \end{cases} \tag{2.46}$$

Define $\widetilde{\alpha}_1$ and $\widetilde{\alpha}_2$ such that:

$$\begin{cases} \Pi_{vj}(\underline{I}_c, \widetilde{\alpha}_j) = 1 & if \quad \widetilde{\alpha}_j = \widetilde{\alpha}_1 \\ \Pi_{vj}(\underline{I}_c, \widetilde{\alpha}_j) > 1 & if \quad \widetilde{\alpha}_j < \widetilde{\alpha}_1 \\ \Pi_{vj}(\underline{I}_c, \widetilde{\alpha}_j) < 1 & if \quad \widetilde{\alpha}_j > \widetilde{\alpha}_1 \end{cases} \quad and \quad \begin{cases} \Pi_{vj}(\overline{I}_c, \widetilde{\alpha}_j) = 1 & if \quad \widetilde{\alpha}_j = \widetilde{\alpha}_2 \\ \Pi_{vj}(\overline{I}_c, \widetilde{\alpha}_j) > 1 & if \quad \widetilde{\alpha}_j < \widetilde{\alpha}_2 \\ \Pi_{vj}(\overline{I}_c, \widetilde{\alpha}_j) < 1 & if \quad \widetilde{\alpha}_j > \widetilde{\alpha}_2 \end{cases} \tag{2.47}$$

Depending on the sign of $\frac{\partial \Pi_{vj}}{\partial I_c}$, $\widetilde{\alpha}_1$ and $\widetilde{\alpha}_2$ can have three different relations:

$$\begin{cases} \widetilde{\alpha}_1 = \widetilde{\alpha}_2 & if \quad \frac{\partial \Pi_{vj}}{\partial I_c} = 0 \\ \widetilde{\alpha}_1 > \widetilde{\alpha}_2 & if \quad \frac{\partial \Pi_{vj}}{\partial I_c} > 0 \\ \widetilde{\alpha}_1 < \widetilde{\alpha}_2 & if \quad \frac{\partial \Pi_{vj}}{\partial I_c} < 0 \end{cases}$$

Now, we investigate each of these cases separately. The first relation brings us to the situation in which the organizational structure does not change and thus $\Delta T^* \leq 0$. When $\widetilde{\alpha}_1 > \widetilde{\alpha}_2$ ($\frac{\partial \Pi_{vj}}{\partial I_c} > 0$) the organizational structure does not shift and we goes back to $\Delta T^* \leq 0$. The reason is that with a rise in I_c, in the same time the two conditions of $\frac{\partial \Pi_{vj}}{\partial I_c} > 0$ and $\frac{\partial \widetilde{\alpha}_j}{\partial I_c} \geq 0$ should be satisfied. By the first condition, the only feasible option is moving from j-structure to vertical FDI. But, as depicted in figure (2.15), this shift is not consistent with the second condition.

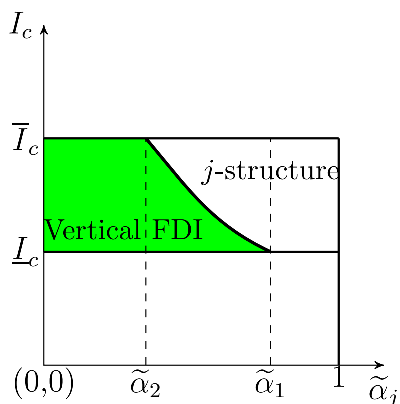

Figure 2.15: The situation in which organizational structure does not change with I_c-rise

Finally, the last situation corresponds to figure (2.16). Let $\widetilde{T}_V^0$, $\widetilde{T}_j^0$, $\widetilde{\alpha}_j^0$ and Π_{vj}^0 denote the amount of variables prior to rise in I_c and $\widetilde{T}_V^1$, $\widetilde{T}_j^1$, $\widetilde{\alpha}_j^1$ and Π_{vj}^1 refer to the same variables after I_c-change. From equation (2.45) and $\frac{\partial \widetilde{\alpha}_j}{\partial I_c} \geq 0$, we know that

$$\widetilde{T}_V^0 > \widetilde{T}_V^1 \,,\, \widetilde{T}_j^0 > \widetilde{T}_j^1 \; and \, \widetilde{\alpha}_j^0 < \widetilde{\alpha}_j^1$$

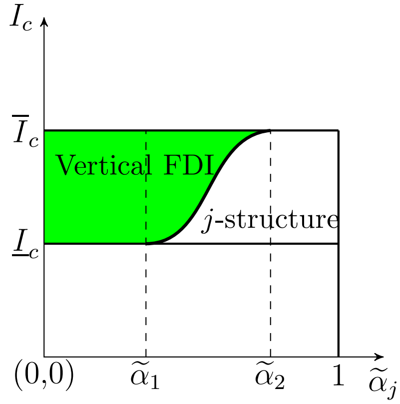

Figure 2.16: Shifting from vertical FDI to j-structure is possible

We can partition the post-change position to two different pieces based on the amount of price (productivity) ratio:

a. $\frac{p_m^j}{\overline{p}_m^v}\frac{1}{\widetilde{\alpha}_j^1} > 1$

We also have $\Pi_{vj}^1 = \frac{\widetilde{T}_j^1}{\widetilde{T}_V^1}\frac{p_m^j}{\overline{p}_m^v}\frac{1}{\widetilde{\alpha}_j^1} < 1$, thus we can write:

$$\frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} < 1 \quad \Rightarrow \quad \widetilde{T}_V^1 > \widetilde{T}_j^1 \underbrace{\Rightarrow}_{\widetilde{T}_V^0 > \widetilde{T}_V^1} \Delta T^* = \widetilde{T}_j^1 - \widetilde{T}_V^0 < 0$$

b. $\frac{p_m^j}{\overline{p}_m^v}\frac{1}{\widetilde{\alpha}_j^1} < 1$

Here, $\frac{\widetilde{T}_j^1}{\widetilde{T}_V^1}$ can be bigger or smaller than one:

$$\Pi_{vj}^1 = \frac{\widetilde{T}_j^1}{\widetilde{T}_V^1}\frac{p_m^j}{\overline{p}_m^v}\frac{1}{\widetilde{\alpha}_j^1} < 1 \Rightarrow \frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} < \widetilde{\alpha}_j^1\frac{\overline{p}_m^v}{p_m^j} \underbrace{\Rightarrow}_{\widetilde{\alpha}_j^1\frac{\overline{p}_m^v}{p_m^j} > 1} \frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} \textit{could be smaller or bigger than one.}$$

If $\frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} < 1$, then again $\Delta T^* = \widetilde{T}_j^1 - \widetilde{T}_V^0 < 0$; otherwise, regarding the fact that $\widetilde{T}_j(\widetilde{\alpha}_j = 1, I_c) < \widetilde{T}_V(I_c)\,\forall\, I_c \in [\underline{I}_c, \overline{I}_c]$ and continuity of $\widetilde{T}_j(\widetilde{\alpha}_j, I_c)$ in $[\widetilde{\alpha}_j^1, 1]$, there is $\widetilde{\alpha}_j^T \in [\widetilde{\alpha}_j^1, 1]$ such that:

$$\frac{\widetilde{T}_j(\widetilde{\alpha}_j^T, I_c)}{\widetilde{T}_V(I_c)} < 1\ \forall I_c \in [\underline{I}_c, \overline{I}_c] \quad \textit{and} \quad \Pi_{vj}(\widetilde{\alpha}_j^T, I_c) < 1\ \forall I_c \in [\underline{I}_c, \overline{I}_c]$$

So, if I_c is raised high enough, it will lead to $\Delta T^* < 0$.

The proof of the last part is straightforward. ■

Proof of proposition 2. Considering our previous assumptions on the service rates, we have:

$$\begin{cases} \frac{\partial \widetilde{T}_j}{\partial \widetilde{\alpha}_j} = (1-\delta)(\frac{-1}{(\mu_H^j-\lambda)^2})\overbrace{(\frac{\partial \mu_H^j}{\partial \widetilde{\alpha}_j})}^{>0} < 0 \\ \frac{\partial \Pi_{Vj}}{\partial \widetilde{\alpha}_j} = \frac{\beta\rho}{1-\rho}(\frac{p_m^j}{\widetilde{T}_V \overline{p}_m^V})^{\frac{\beta\rho}{1-\rho}}(\frac{\widetilde{T}_j}{\widetilde{\alpha}_j})^{\frac{\beta\rho}{1-\rho}-1}\underbrace{[\frac{1}{\widetilde{\alpha}_j}\underbrace{\frac{\partial \widetilde{T}_j}{\partial \widetilde{\alpha}_j}}_{<0} + \widetilde{T}_j(\frac{-1}{\widetilde{\alpha}_j^2})]}_{<0} < 0 \\ \frac{\partial \widetilde{T}_V}{\partial \widetilde{\alpha}_j} = 0 \end{cases} \tag{2.48}$$

Thus, if the rise in $\widetilde{\alpha}_j$ does not alter organizational type, then its effect on T^* depends on the type of current organizational structure. For the vertical FDI, we have $\Delta T^* = 0$ and for the other cases $\Delta T^* < 0$. When organizational structure shifts (to j-structure), the sign of ΔT^* is defined by the price (productivity) ratio and the new degree of product contractibility. Again, Let $\widetilde{T}_V^0$, $\widetilde{T}_j^0$, $\widetilde{\alpha}_j^0$ and Π_{vj}^0 denote the amount of variables prior to rise in $\widetilde{\alpha}_j$ and $\widetilde{T}_V^1$, $\widetilde{T}_j^1$, $\widetilde{\alpha}_j^1$ and Π_{vj}^1 refer to the final amount of these variables.We can write:

$$\begin{cases} \Pi_{vj}^0 = \frac{\widetilde{T}_j^0}{\widetilde{T}_V^0}\frac{p_m^j}{\overline{p}_m^v}\frac{1}{\widetilde{\alpha}_j^0} > 1 \\ \Pi_{vj}^1 = \frac{\widetilde{T}_j^1}{\widetilde{T}_V^1}\frac{p_m^j}{\overline{p}_m^v}\frac{1}{\widetilde{\alpha}_j^1} < 1 \\ \widetilde{T}_V^0 = \widetilde{T}_V^1 \,,\, \widetilde{T}_j^0 > \widetilde{T}_j^1 \; and \, \widetilde{\alpha}_j^0 < \widetilde{\alpha}_j^1 \end{cases} \tag{2.49}$$

Define $\widetilde{\alpha}_B$ and $\widetilde{\alpha}_E$ such that:

$$\frac{\widetilde{T}_j(\widetilde{\alpha}_E)}{\widetilde{T}_V} = 1$$

$$\frac{\widetilde{T}_j(\widetilde{\alpha}_B)}{\widetilde{T}_V}\frac{p_m^j}{\overline{p}_m^v}\frac{1}{\widetilde{\alpha}_B} = 1$$

Three different situations are possible based on the relation between $\widetilde{\alpha}_B$ and $\widetilde{\alpha}_E$:

a. $\widetilde{\alpha}_B = \widetilde{\alpha}_E$

Indeed, $\widetilde{\alpha}_B$ is a threshold for defining organizational structure. If $\widetilde{\alpha}_j > \widetilde{\alpha}_B$ the headquarter relies on j-structure, otherwise it establishes a subsidiary. When $\widetilde{\alpha}_B = \widetilde{\alpha}_E$, the threshold is also $\widetilde{\alpha}_E$. In other words, as figure (2.17) presents, for defining the type of input procuring method, it's enough to just compute $\frac{\widetilde{T}_j(\widetilde{\alpha}_j)}{\widetilde{T}_V}$. Consequently, we can write

$$\Pi_{vj}^1 < 1 \Rightarrow \frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} < 1 \Rightarrow \Delta T^* < 0$$

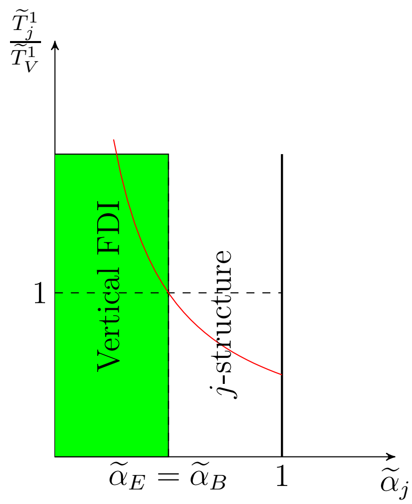

Figure 2.17: Choice of organizational structure when $\widetilde{\alpha}_E = \widetilde{\alpha}_B$

b. $\widetilde{\alpha}_B > \widetilde{\alpha}_E$

As shown in figure (2.18), in this case we have:

$$\frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} < 1 \Rightarrow \widetilde{T}_j^1 < \widetilde{T}_V^1 = \widetilde{T}_V^0 \Rightarrow \Delta T^* = \widetilde{T}_j^1 - \widetilde{T}_V^0 < 0$$

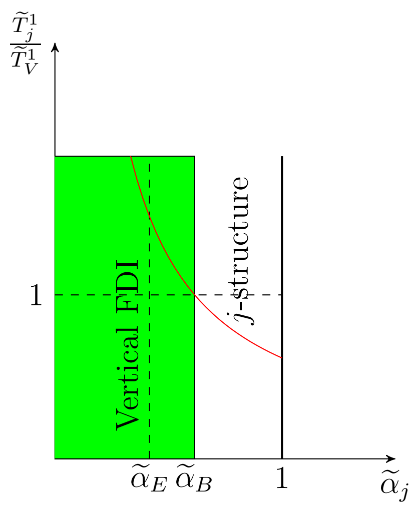

Figure 2.18: Choice of organizational structure when $\widetilde{\alpha}_E < \widetilde{\alpha}_B$

c. $\widetilde{\alpha}_B < \widetilde{\alpha}_E$ Here, depending on the amount of $\widetilde{\alpha}_j^1$, ΔT^* might be positive or negative (as depicted in figure (2.19)).

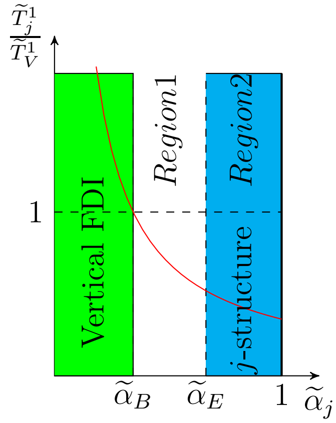

Figure 2.19: Choice of organizational structure when $\widetilde{\alpha}_E > \widetilde{\alpha}_B$

If $\widetilde{\alpha}_j^1 \in \{Region\,1\}$ then we have $\frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} < 1$ which again results in:

$$\frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} < 1 \Rightarrow \widetilde{T}_j^1 < \widetilde{T}_V^1 = \widetilde{T}_V^0 \Rightarrow \Delta T^* = \widetilde{T}_j^1 - \widetilde{T}_V^0 < 0$$

However, If $\widetilde{\alpha}_j^1 \in \{Region\,2\}$ then we get:

$$\frac{\widetilde{T}_j^1}{\widetilde{T}_V^1} > 1 \Rightarrow \widetilde{T}_j^1 > \widetilde{T}_V^1 = \widetilde{T}_V^0 \Rightarrow \Delta T^* = \widetilde{T}_j^1 - \widetilde{T}_V^0 > 0$$

So, we can guarantee $\Delta T^* < 0$ if the increase in $\widetilde{\alpha}_j$ is high enough. ■

Proof of proposition 3. Define $\underline{\Pi}_{Vj}(\widetilde{\alpha}_j)$ and $\overline{\Pi}_{Vj}(\widetilde{\alpha}_j)$ as:

$$\underline{\Pi}_{Vj}(\widetilde{\alpha}_j) = \min_{I_c \in [\underline{I}_c, \overline{I}_c]} \Pi_{Vj}(\widetilde{\alpha}_j, I_c) \quad and \quad \overline{\Pi}_{Vj}(\widetilde{\alpha}_j) = \max_{I_c \in [\underline{I}_c, \overline{I}_c]} \Pi_{Vj}(\widetilde{\alpha}_j, I_c)$$

since $\frac{\partial \widetilde{T}_j}{\partial \widetilde{\alpha}_j} < 0$, $\frac{\partial \widetilde{T}_V}{\partial \widetilde{\alpha}_j} = 0$, $\frac{\partial \overline{p}_m^V}{\partial \widetilde{\alpha}_j} = 0$, $\frac{\partial p_m^j}{\partial \widetilde{\alpha}_j} \geq 0$, we have:

$$\begin{aligned}
\lim_{\widetilde{\alpha}_j \to 0^+} \underline{\Pi}_{Vj}(\widetilde{\alpha}_j) &= \lim_{\widetilde{\alpha}_j \to 0^+} \min_{I_c} \overbrace{\left(\frac{\widetilde{T}_j p_m^j}{\widetilde{T}_V \overline{p}_m^V \widetilde{\alpha}_j}\right)^{\frac{\beta\rho}{1-\rho}}}^{f(\widetilde{\alpha}_j)} \\
&= \min_{I_c} \lim_{\widetilde{\alpha}_j \to 0^+} \left(\frac{\widetilde{T}_j p_m^j}{\widetilde{T}_V \overline{p}_m^V \widetilde{\alpha}_j}\right)^{\frac{\beta\rho}{1-\rho}} \qquad (becuase\, of\, the\, continuity\, of\, f(\widetilde{\alpha}_j)\, in\, \widetilde{\alpha}_j) \\
&= \min_{I_c} +\infty = +\infty
\end{aligned}$$

Considering this result and the efficiency-dominance assumption, by the continuity of $\Pi_{Vj}(\widetilde{\alpha}_j)$ on $(0, 1]$, we can write:

$$\exists\, \widetilde{\alpha}_{tj} \in (0, 1) \quad such\, that \quad \Pi_{Vj}(\widetilde{\alpha}_j, I_c) > 1 \quad \forall\, \widetilde{\alpha}_j < \widetilde{\alpha}_{tj} \quad , \quad \forall\, I_c \in [\underline{I}_c, \overline{I}_c]. \quad ■$$

Chapter 3

Technological Changes and Global Value Chains

3.1 Introduction

There has been a growing trend in the ratio of trade happening within Global Value Chains (hereafter, GVCs) out of the total world trade. Johnson and Noguera [2012] argue that production fragmentation across countries has been rising during last four decades and in particular after 1990. Hummels et al. [2001] focuse on 10 OECD and four emerging market countries and show that vertical specialization accounts for 21% of these countries' exports, and grew almost 30% between 1970 and 1990. Miroudot et al. [2009] analyze trade flows in intermediate goods and services among OECD countries and their partners for the period 1995-2005. They discuss that trade in intermediate inputs takes place mostly among developed countries and represents 56% and 73% of overall trade flows in goods and services, respectively. In spite of these facts, there is a sparse theoretical literature on GVCs and specially on the pattern of task and income distribution within a GVC. An important piece of this literature is a study by Costinot, Vogel and Wang (2013)(hereafter, CVW) that rationalizes the pattern of vertical specialization within a GVC. Focusing on the productivity of countries, they provide a theoretical framework to explain the interdependence of countries and income distribution within a production chain. They show that a unique outcome in the free trade equilibrium emerges in which countries specialize vertically and position of each country in the chain is defined based on its productivity level. In their setting, the labor input is homogenous, so the model is silent about the observations related to the heterogeneity of the labor market. In particular, their model tells nothing about the observations on the trend of skill premia inside countries. As we will see in the next section, regardless of the level of development, the skill premia has been rising in some countries, falling in some others and almost constant in the rest.

There is a huge literature including traditional (HO) theories and the new research to address the relationship between trade and inequality trend within countries. Traditional theories predict that trade will lead to an increasing skill premia in North and a decreasing one in South. So, these theories cannot justify this observation. Some parts of the new research (e.g. skill-biased technological change (Acemoglu [2003]) and Trade in tasks (Feenstra and Hanson) predicts an increasing skill premia both in North and south and some others (e.g. Search frictions and unemployment (Davidson and Matusz [2009] and Trade and innovation (Dinopoulos and Segerstrom [1999])) can generate a wide range of effects on labor-market outcomes. Although, some theories can potentially explain the different trends of skill premia across (both south and north) countries, there is not a study that rationalizes the pattern of vertical specialization within GVCs and at the same time justifies these kind of observations on skill premia. So, we need a new framework in which a sequential production is done by multiple countries and labor factors are heterogeneous.

This paper develops the CVW's model by allowing for two types of labor and two types of production stages. CVW's framework consists of a world with an arbitrary number of countries, one type of labor, a continuum of intermediate goods and one final good produced sequentially in a multistage production. Each stage of production is subject to a mistake rate which is different across countries. This mistake rate has actually an inverse relation with total productivity of the country. They found that such a framework yields a unique free trade equilibrium in which there is full employment across countries and countries with lower mistake rates at all stages specialize in later stages. In other words, there is a vertical specialization based on the mistake rates of countries in the unique equilibrium.

To extend their model, we consider two different types of labor and two different types of stages. Each labor force is either skilled or unskilled and each stage is either high-tech or low-tech. High-tech stages need a production technology that is a Leontief function of the intermediate input from previous stage and a Cobb-Douglas combination of both labor types. Whereas, low-tech stages use a production technology that is a Leontief function of the intermediate good from previous stage and unskilled labor. These modifications enable us to represent technological changes in a wider domain. In this setting, the vertical specialization is preserved, but these modifications result in some new results about the position of countries in the chain and the effect of technological changes on the skill premia within countries. Now, the position of countries depends not only on mistake rates, but also on the endowment of skilled and unskilled labor. Moreover, the contribution level of each country to both type of stages is a function of these two factors. The lower is the mistake rate of a country, the more downstream is the position of that country and the higher is the skill ratio of a country, the bigger is the share of high-tech stages that it produces. In turn, the wage of labor factors and skill premium are defined by the position of the country in the chain, the share of high-tech stages produced by the country and the productivity ratio of skilled labor over unskilled labor in high-tech stages.

This paper contributes to a growing theoretical literature on GVCs. A number of papers try to analyze theoretically different aspects of GVCs. Fujita and Thisse [2006] focus on the trade costs of goods, communication costs between headquarters and production facilities and wage differentials across regions to analyze the location decision of plants. Baldwin and Venables [2010] model the interaction between international cost differences and benefits of co-location of related stages. This interaction determines the fragmentation level of production stages. Antràs and Chor [2013], take as given a GVC, try to rationalize the optimal way of organizing production (FDI vs outsourcing) along each linkage of a GVC.

Our paper is closely related to several studies on trade and skill premia. Traditional HO models predict a rising effect of trade on the relative demand for low-skilled workers in south and a rising effect on the relative demand for high-skilled workers in north. Consequently, we have a decreasing effect on the skill premium of south and an increasing effect on the skill premium of north. However, some studies (e.g. Hanson and Harrison [1995] and Robbins [1996]) show that this effect on developing countries is not symmetric. In fact, Some developing countries experienced a decline in the skill premium. Some papers (e.g. Feenstra and Hanson, Zhu [2004], and Zhu and Trefler [2005]) address this puzzle by resorting to outsourcing and technology transfer. These two phenomena shift a portion of input production from the North to the South, which is the most skilled-intensive in the South, and the most unskilled-intensive in the North. Some other studies (e.g. Acemoglu [2002, 2003], Thoenig and Verdier [2003], Dinopoulos and Segerstrom [1999]) focus on the role of skill biased technological changes. They argue that trade creates a tendency for the relative price of skilled-intensive goods to increase. So, the development of technologies used in the production of these goods is more profitable. This induces further skill biased technological change, which contributes to the increase in wage inequality.

The rest of the paper is organized as follows. Section II explains stylized facts. Section III describe the model setup and derives the main results relevant to any free trade equilibrium. Section IV analyzes the effects of technological changes on the patterns of vertical specialization and inequality across and within countries including simulation results. Finally section V states some concluding remarks.

3.2 Stylized Facts

We use WIOD[1] database to derive the trend of skill premia for different countries. WIOD database covers 40 countries[2] and contains annual data on wages and employment by skill type (low-, medium- and high-skilled) of 35 industries for the period 1995-2009. This includes data on hours worked and compensation for three labor types. Skills in this database are defined based on educational attainment levels. We calculate hourly wage for each skill category and then calculate skill premia of medium-skilled and low-skilled (wage ratio of medium-skilled (M) over low-skilled (L)) and skill premia of high-skilled and low-skilled. We find that both types of skill premia have similar trend for almost all 40 countries. Regardless of short time cyclical variation, we can categorize countries based on their trend in skill premia to 5 groups: 37.5 percent of them experienced a rising

[1] World Input-Output Database

[2] These countries are:

Australia, Austria, Belgium, Brazil, Bulgaria, Canada, China, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Russia, Slovak Republic, Slovenia, South Korea, Spain, Sweden, Taiwan, Turkey, United Kingdom and United States trend, 30 percent witnessed a falling trend, 22.5 percent have a constant trend, 7.5 percent experienced a rising and then a falling trend and finally 2.5 percent witnessed a falling and then a rising trend. Putting aside the last two groups (due to their small sizes), each group contains both developed and developing countries.

Figures (3.1)-(3.3) depict three examples related to the first three groups. For better capturing of trends, we have normalized the skill premium of the starting year (1995) to 1. The solid line is the trend of normalized value of skill premium between high skilled and low skilled and the dashed line is the trend of normalized value of skill premium between medium skilled and low skilled.

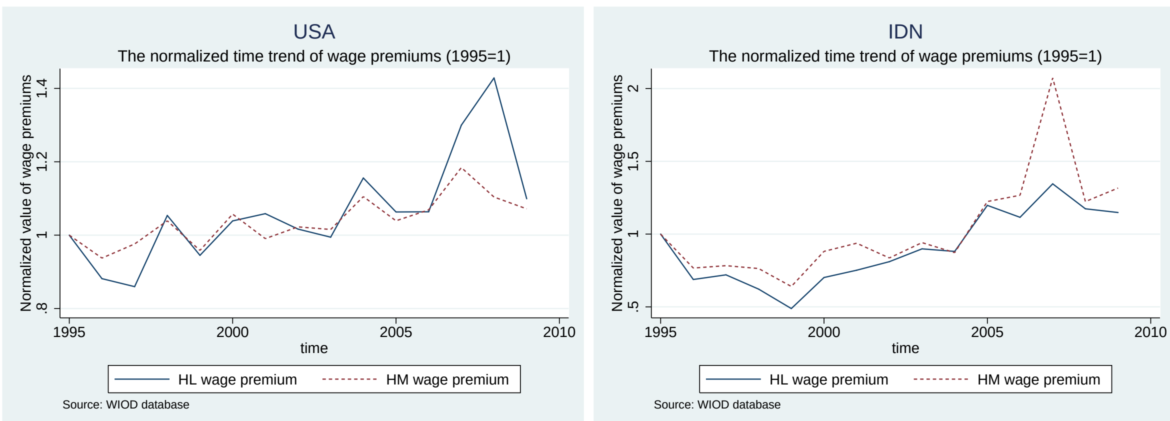

Figure 3.1: Example of countries with rising trend of wage premium

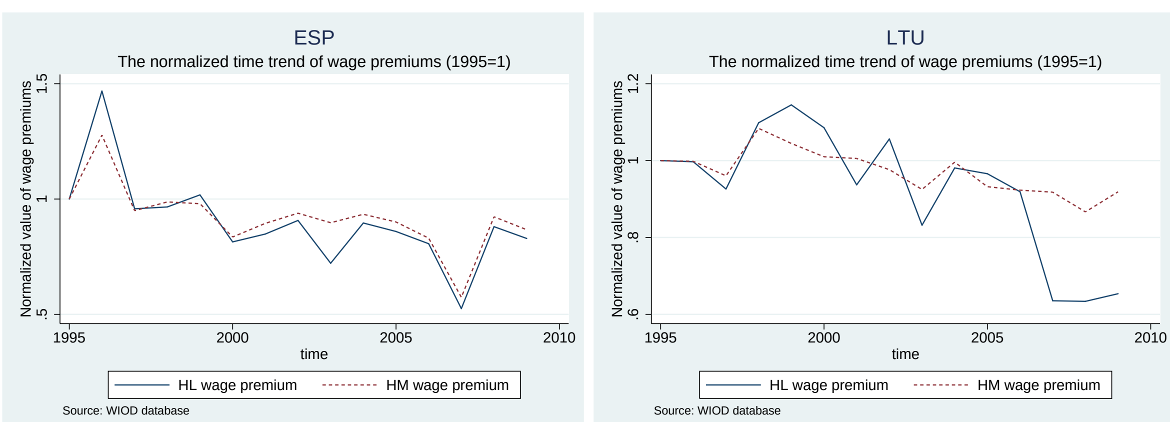

Figure 3.2: Example of countries with declining trend of wage premium

It can be seen from these figures that countries are heterogenous in terms of the time trend of skill premia within them. In addition, the time trend of the skill premium between high skilled and low skilled is very similar to the time trend of skill premium between medium skilled and low skilled. So, without loss of generality, we can theoretically focus on the case with only two types of labor. It is also evident for the figures that the time behavior of skill premia does not depend on the level of development. All kinds of trends could be found in both developed and developing countries. Finally, we can see that there is a sharp change in the trend of either type of skill premia during 2007-2009. It might be due to the recent crisis. In the rest of the paper, we will try to rationalize these heterogeneities in skill premia trends both for developed and developing countries.

Figure 3.3: Example of countries with constant trend of skill premia

3.3 The model

3.3.1 Setup

Consider a world with Multiple countries $c \in \mathcal{C} \equiv \{1, ..., C\}$ that are producing a final good q. To produce the final good, a continuum of stages $s \in \mathcal{S} \equiv (0, S]$ must be performed in a sequential way. Production at any stage is subject to a country-specific mistake rate. Mistakes occur at a exogenous constant Poisson rate, $\lambda_c > 0$. When a unit of intermediate good meets a mistake, at any stage, it is entirely lost. Following CVW, we order countries in the way that λ_c is strictly decreasing in c. In other words, more productive countries are bigger in label. Unlike to CVW, the stages of production are not homogenous here. There are two types of production stages: low-tech stages and high-tech stages. Low-tech stages need two factors of production: unskilled labor L

and intermediate good from previous stage. High-tech stages use three factors: skilled labor H, unskilled labor L and the intermediate good. Each type of labor is inelastically supplied and immobile across countries. Let L_c and H_c denote the endowment of unskilled and skilled labor in country c, respectively. Similarly, w_c^L and w_c^H represent the wage of unskilled and skilled labor in country c, respectively.

For the sake of simplicity, and without loss of generality, we assume that $\mathcal{S}$ is composed of finite subintervals of each stage type, as shown in figure (3.4). Here σ_i^z ($i \in \{1, 2, ..., n\}$ and $z \in \{l, h\}$) is the i^{th} subinterval of type z, $\mathcal{S}_h$ is the set of all high-tech subintervals and $\mathcal{S}_l$ is the set of all low-tech subintervals:

$$\mathcal{S}_l = \sigma_1^l \cup \sigma_2^l \cup ... \cup \sigma_n^l \quad , \quad \mathcal{S}_h = \sigma_1^h \cup \sigma_2^h \cup ... \cup \sigma_n^h$$

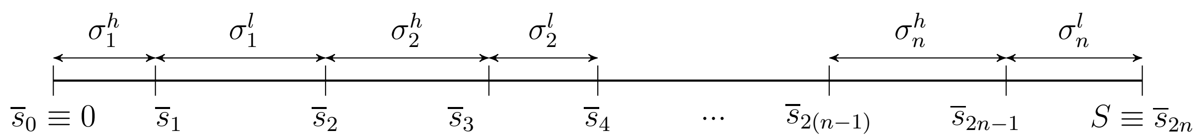

Figure 3.4: The continuum of total stages is partitioned by subintervals of high-tech and low-tech subintervals

Consider two consecutive stages, s and $s + ds$, with ds infinitesimal. The production function for a firm from country c that is undertaking a high-tech stage $s + ds$ is:

$$q(s + ds) = (1 - \lambda_c ds) Min\{q(s), H^\alpha L^{1-\alpha}\} \quad (0 < \alpha < 1) \tag{3.1}$$

where q_s is the intermediate input from stage s and α is an exogenous coefficient that represents the productivity of high-skilled labor in the labor content of the production technology. Similarly, the production function in a low-tech stage is:

$$q(s + ds) = (1 - \lambda_c ds) Min\{q(s), L\} \tag{3.2}$$

There is no trade cost and all markets are perfectly competitive. The world price of intermediate good $q(s)$ is $p(s)$. As CVW, we assume that $q(0)$ is in infinite supply and thus $p(0) = 0$. Moreover, $q(S)$ corresponds to q and is considered as numeraire, $p(S) = 1$. Furthermore, we also assume that: if a firm produces intermediate good $s + ds$, then it necessarily produces a measure $\Delta > 0$ of intermediate goods around that stage. Formally, for any intermediate good $s + ds$, we assume the existence of $s_\Delta < s + ds \leq s_\Delta + \Delta$ such that if $q(s + ds) > 0$, then $q(s') > 0$ for all $s' \in (s_\Delta, s_\Delta + \Delta]$. As CVW point out, this assumption implies that each unit of q is produced by a finite number of firms.

3.3.2 Free Trade Equilibrium

Free trade equilibrium requires all markets to be cleared and all firms to maximize their profits. Profit maximizing behavior of firms leads to:

$$\begin{cases} p(s+ds) \leq (1+\lambda_c ds)p(s) + w'_{hc}ds & \text{if } s' \in int(\mathcal{S}_h) \\ \\ p(s+ds) \leq (1+\lambda_c ds)p(s) + w_{lc}ds & \text{if } s' \in int(\mathcal{S}_l) \end{cases} \tag{3.3}$$

$$(\forall s' \in (s, s+ds], \text{with equality if } Q_c(s') > 0)$$

where

$$w'_{hc} = \frac{(w_c^L)^{1-\alpha}(w_c^H)^\alpha}{\alpha^\alpha(1-\alpha)^{1-\alpha}} \quad \text{and} \quad w_{lc} = w_c^L$$

and $Q_c(s')$ denotes the total output of country c at stage s'. For boundary points, we have these relationships:

$$p(0) = 0 \quad , \quad p(S) = 1 \quad and \quad p(\overline{s}_i) = \overline{p}_i = \lim_{s \to (\overline{s}_i)^-} p(s) \quad \forall i \in \{1, 2, ..., 2n\} \tag{3.4}$$

The last expression guarantees that the price of intermediate goods is continuous in the borders of subintervals. Let call w'_{Hc} the wage profile of country c at high-tech stages. Equation (3.3) says that, regardless of the stage type, the price of intermediate component $s + ds$ could not be larger than its unit cost of production. If some firms of country c are actually producing $s + ds$, then this price is equal to the unit cost. This result arises from the competitiveness of markets. The reasoning is similar to that of CVW with the exception of replacing wage profile by wage in the high-tech stages.

Market clearing for goods implies that:

$$\sum_{c=1}^{C} Q_c(s_2) - \sum_{c=1}^{C} Q_c(s_1) = -\int_{s_1}^{s_2} \sum_{c=1}^{C} \lambda_c Q_c(s) ds \quad \forall s_1 < s_2 \tag{3.5}$$

This equation states that the change in the total supply of intermediate goods between stages s_1 and s_2 is equal to the amount of goods that are lost (because of mistakes) in all countries between these stages.

Labor market clearing for the low-skilled requires that:

$$L_c = (\frac{1-\alpha}{\alpha}\frac{w_c^H}{w_c^L})^{\alpha}\int_{s\in\mathcal{S}_h} Q_c(s)ds + \int_{s\in\mathcal{S}_l} Q_c(s)ds \tag{3.6}$$

and for the high-skilled, it implies that:

$$H_c = (\frac{1-\alpha}{\alpha}\frac{w_c^H}{w_c^L})^{1-\alpha}\int_{s\in\mathcal{S}_h} Q_c(s)ds \tag{3.7}$$

Equation (3.6) states that the total demand for unskilled labor in country c equals its total endowment of that kind of labor. This demand is equal to the sum of what is consumed in high-tech stages and low-tech stages. Similarly, equation (3.7) says that the total demand for skilled workers in country c clears its total endowment of skilled workers. However, the demand for skilled labor originates only from high-tech stages. Now, we can define a free trade equilibrium in the same way as CVW:

Definition 1: A free trade equilibrium corresponds to output levels $Q_c(.) : \mathcal{S} \to \mathcal{R}^+$ for all $c \in \mathcal{C}$, wages $(w_c^L, w_c^H) \in \mathcal{R}_+^2$ for all $c \in \mathcal{C}$, and intermediate good prices $p(.) : S \to \mathcal{R}^+$, such that (3.3)-(3.7) hold.

Before characterizing the pattern of international specialization in a free trade equilibrium, we label the countries undertaking σ_i^z by $c_{i,1}^z, c_{i,2}^z, ...$ and $c_{i,n_{iz}}^{iz}(n_{iz} \geq 1)$ as shown in figure (3.5):

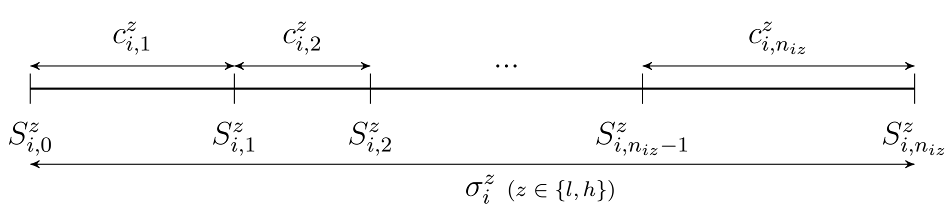

Figure 3.5: Countries that are doing σ_i^z

and label unskilled and skilled labor use of country $c_{i,j}^z$ during the interval σ_i^z by $L_{i,j}^z$ and $H_{i,j}^z$, $(z \in \{l,h\}\ , \ j \in \{1,2,...,n_{iz}\})$, respectively. Since the skilled labor use of low-tech stages is zero, we can set $H_{i,j}^h \equiv H_{i,j}$. These notations help us to explain the following propositions in an easier way.

Proposition 1: In any free trade equilibrium, for every $z \in \{l,h\}$,there exists a sequence of stages $0 < S_1^z \leq S_2^z ... \leq S_C^z$ such that for all $s \in \mathcal{S}_z$ and $c \in \mathcal{C}$, $Q_c(s) > 0$ if and only if $s \in (S_{c-1}^z, S_c^z]$.

This proposition states that in any free trade equilibrium, there is vertical specialization within the set of all high-tech subintervals ($\mathcal{S}_h$) and within the set of all low-tech subintervals ($\mathcal{S}_l$). According to each of these vertical specializations, the countries that are active in the later stages are more productive that the active countries in the early stages. This proposition is similar to the first proposition in CVW, except the fact that here we have two parallel vertical specializations. Actually, the case in which less productive country is active at later stages (but with different stage type) than more productive firm is not impossible here.

Proposition 2: In any free trade equilibrium, for every $\sigma_i^z \in \mathcal{S}$, there exists a sequence of stages $S_{i,0}^z < S_{i,1}^z < S_{i,2}^z ... < S_{i,n_{iz}}^z$ such that for all $s \in \sigma_i^z$ and $c_{i,j}^z \in \{c_{i,1}^z, c_{i,2}^z, ..., c_{i,n_{iz}}^z\}$, $Q_{c_{i,j}^z}(s) > 0$ if and only if $s \in (S_{i,j-1}^z, S_{i,j}^z]$. The first and last terms of this sequence are equal to:

$$(S_{i,0}^z, S_{i,n_{iz}}^z) = \begin{cases} (\overline{s}_{2(i-1)}, \overline{s}_{2i-1}) \quad if \quad z = h \\ \\ (\overline{s}_{2i-1}, \overline{s}_{2i}) \quad if \quad z = l \end{cases}$$

Furthermore, $\forall i < j$ we have $c_{i,n_{iz}}^z \leq c_{j,1}^z$.

Proposition 2 shows that in any free trade equilibrium there is also vertical specialization within each subinterval of sages in which more productive countries produce and export at later stages of production. The intuition behind proposition 1 and proposition 2 is similar to CVW. One possibility is to look at them from the standpoint of the hierarchy literature (e.g. Robert E. Lucas [1978], Rosen [1982] and Garicano [2000]): the efficiency of final good production requires that countries with higher productivity work on larger amount of inputs. Another explanation is that since new intermediate goods require intermediate goods produced in previous stages, skilled labor and unskilled labor, prices must be increasing along the supply chain. So, the non-labor cost share is relatively higher at later stages. Or, equivalently, labor-cost share is relatively lower in countries with higher wages. These countries are those with higher productivity at all stages. However, There is a difference between this proposition and that of CVW. In the CVW framework, productivity differences across countries define their location in the GVC, whereas, there are two defining factors here: productivity differences across countries and the share of skilled labor in the endowments of countries. In fact, the second factor defines the degree of participation in each type of stages.

We call the vector $(S^z_{i,1}, S^z_{i,2}, ..., S^z_{i,n_{iz}})$ the pattern of vertical specialization in interval σ^z_i and the set of all vectors $\{(S^z_{i,1}, S^z_{i,2}, ..., S^z_{i,n_{iz}})\,\forall i \in \{1, 2, ..., n\}$ and $z \in \{l, h\}\}$ the pattern of vertical specialization. We denote by $Q^z_{i,j} \equiv Q_{c^z_{i,j}}(S^z_{i,j})$ the total amount of intermediate good $S^z_{i,j}$ produced by country $c^z_{i,j}$. The total amount of intermediate goods produced and exported by country c is equal to:

$$Q_c = \sum_z \sum_i \sum_{j=1}^{n_{iz}} 1_{(c=c^z_{i,j})} Q^z_{i,j}$$

where $1_{(c=c^z_{i,j})}$ is an indicator function. Finally, let $\lambda^z_{i,j}$ represents the mistake rate of j^{th} country which is active in subinterval σ^z_i (i.e. $\lambda_{c^z_{i,j}}$). Using these notations, we can state lemma 1.

Lemma 1: The pattern of vertical specialization within i^{th} high-tech subinterval (σ^h_i) satisfies [3]:

$$S^h_{i,j} = S^h_{i,j-1} - (\frac{1}{\lambda^h_{i,j}})Ln(1 - \frac{\lambda^h_{i,j} H_{i,j}}{\widetilde{Q}^h_{i,j-1}}) \quad \forall j \in \{1, 2, ..., n_{ih}\} \tag{3.8}$$

and for the low-tech subinterval σ^l_i, we have:

$$S^l_{i,j} = S^l_{i,j-1} - (\frac{1}{\lambda^l_{i,j}})Ln(1 - \frac{\lambda^l_{i,j} L^l_{i,j}}{Q^l_{i,j-1}}) \quad \forall j \in \{1, 2, ..., n_{il}\} \tag{3.9}$$

Moreover, the pattern of export levels satisfies:

$$Q^z_{i,j} = e^{-\lambda^z_{i,j}(S^z_{i,j} - S^z_{i,j-1})} Q^z_{i,j-1} \quad \forall z \in \{l, h\}\,,\; j \in \{1, 2, ..., n_{iz}\} \tag{3.10}$$

Lemma 1 is derived from market clearing Conditions for goods and labors. According to this lemma, labor use of countries producing in σ^z_i depends on their mistake rates and their level of production. Equation (3.10) is a result of the fact that intermediate goods would be destroyed at a constant rate at each stage when produced in country $c^z_{i,j}$.

[3] Here, we use below notation to avoid unnecessary complications:

$$\widetilde{Q}^h_{i,j-1} \equiv (\frac{1-\alpha}{\alpha} \frac{w^H_c}{w^L_c})^{1-\alpha} Q^h_{i,j-1}$$

Let $w^{'}_{i,j}$ denote the wage profile of j^{th} country producing in subinterval σ^h_i (i.e. $w^{'}_{Hc^h_{i,j}}$), $w^l_{i,j}$ proxy the wage of j^{th} country producing in subinterval σ^l_i (i.e. $w_{Lc^l_{i,j}}$), $p^z_{i,j}$ represents $p_{c^z_{i,j}}$ and $N^z_{i,j} = S^z_{i,j} - S^z_{i,j-1}$ denote the measure of stages performed by country $c^z_{i,j}$ within the interval σ^z_i. Lemma 2 explains the relationships between world income distribution and export prices.

Lemma 2: The world income distribution and export prices satisfy these conditions:

a. For the high-tech subintervals, the wage profiles follow the equation below:

$$w^{'}_{i,j+1} = w^{'}_{i,j} + (\lambda^h_{i,j} - \lambda^h_{i,j+1})p^h_{i,j}, \quad \forall c^h_{i,j} < c^h_{i,n_{ih}} \quad (\forall i \text{ and } \forall \sigma^h_i) \tag{3.11}$$

and prices of intermediate goods are:

$$p^h_{i,j} = e^{\lambda^h_{i,j} N^h_{i,j}} p^h_{i,j-1} + (e^{\lambda^h_{i,j} N^h_{i,j}} - 1)(\frac{w^{'}_{i,j}}{\lambda^h_{i,j}}), \quad \forall c^h_{i,j} \in \{c^h_{i,1}, ..., c^h_{i,n_{ih}}\} \quad (\forall i \text{ and } \forall \sigma^h_i) \tag{3.12}$$

b. For the low-tech subintervals, the wages of unskilled labor satisfy:

$$w^l_{i,j+1} = w^l_{i,j} + (\lambda^l_{i,j} - \lambda^l_{i,j+1})p^l_{i,j}, \quad \forall c^l_{i,j} < c^l_{i,n_{il}} \quad (\forall i \text{ and } \forall \sigma^l_i) \tag{3.13}$$

and the export prices will behave as follow:

$$p^l_{i,j} = e^{\lambda^l_{i,j} N^l_{i,j}} p^l_{i,j-1} + (e^{\lambda^l_{i,j} N^l_{i,j}} - 1)(\frac{w^l_{i,j}}{\lambda^l_{i,j}}), \quad \forall c^l_{i,j} \in \{c^l_{i,1}, ..., c^l_{i,n_{il}}\} \quad (\forall i \text{ and } \forall \sigma^l_i) \tag{3.14}$$

c. With the boundary conditions:

$$\begin{cases} p^z_{i,0} = \overline{p}_i \, , \, p^z_{i,n_{iz}} = \overline{p}_{i+1} \quad if \quad z = l \\ \\ p^z_{i,0} = \overline{p}_{i-1} \, , \, p^z_{i,n_{iz}} = \overline{p}_i \quad if \quad z = h \\ \\ p^l_{n,n_{nl}} = p_C = 1 \, , \, p^h_{1,0} = 0 \end{cases}$$

Equation (3.11) states that the wage profile $w^{'}_{i,j+1}$ in country $c^h_{i,j+1}$ is greater than the wage profile $w^{'}_{i,j}$ in country $c^h_{i,j}$ because the mistake rate of country $c^h_{i,j+1}$ is smaller. Indeed this equation is a result of the fact that the unit cost of producing the "cutoff good" $S^h_{i,j}$ in country $c^h_{i,j}$ $((1+\lambda^h_{i,j})ds + w^{'}_{i,j}ds)$ is equal to that of country $c^h_{i,j+1}$ $((1+\lambda^h_{i,j+1})ds + w^{'}_{i,j+1}ds)$. Regarding that the wage profile is a combination of skilled and unskilled wages, we can use this equation to justify the heterogeneous behavior of skill premia across countries.

Equation (3.13) has the same intuition as equation (3.11) except the fact that in the low-tech subintervals the unit cost of producing the intermediate goods is only a function of unskilled wage and not wage profile.

Equation (3.12) shows that the price of the high-tech cutoff good produced by country $c_{i,j}^h$ depends on the price of the intermediate good imported from country $c_{i,j-1}^h$ plus the total labor cost in country $c_{i,j}^h$. Total labor cost consists of both skilled and unskilled labor cost. So, we have the wage profile in the right hand side of this equation. The same intuition applies for equation (3.14).

Using proposition 1, proposition 2, lemma 1 and lemma 2, proposition 3 shows existence and uniqueness of the free trade equilibrium.

Proposition 3: There exists a unique free trade equilibrium. In this equilibrium, the pattern of vertical specialization and export levels are defined by proposition 1, proposition 2 and lemma 1 and the pattern of world income distribution and export prices are illustrated by lemma 2.

3.4 Technological changes

Before starting to analyze the effect of technological changes on GVCs, we define an important index for value chains based on the share of high-tech stages in the interval of all stages.

Definition 2: The degree of high-tech intensity of a chain could be defined as:

$$\gamma = \frac{\mid \mathcal{S}_h \mid}{\mid \mathcal{S} \mid} = \frac{S - \sum_{i=1}^{n}(\overline{s}_{2i} - \overline{s}_{2i-1})}{S}$$

Introduction of this index yields more possibilities to represent technological changes in our framework. CVW has two proxies for modeling global technological changes: increasing in complexity (increase in S) and standardization (decreasing in the mistake rate of all countries). However, we can consider other possibilities as well. For instance, increase in complexity, depending on the amount and direction of γ change, could be analyzed in many different cases. Or, technological innovation may change γ without any variation in complexity and mistake rates. To be more precise, we represent global technological innovations by below options:

1. Increasing in complexity that not only induces an increase to S, but also causes γ to change across spectrum

2. Increasing in the level of skilled labor productivity (increase in α)

3. Decreasing in the degree of high-tech intensity of a chain without any change in the complexity and mistake rates

For the sake of simplicity, we focus on the case in which there are just one subinterval of each type (figure (3.6)). Moreover, we skip innovations that lead to a chain with more than two subintervals. As we will see, this simple case also provides main results including rationale for our observation about the heterogeneity of skill premia trends across countries.

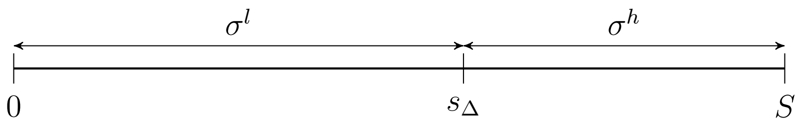

Figure 3.6: An example with $C = 5$ and $n = 2$

Before analyzing the effect of technological changes on the patterns of vertical specialization and wages, it is useful to introduce some other formal definitions.

Definition 3: Let $(S^{'}_{h1}, S^{'}_{h2}, ..., S^{'}_{hC})$ denote the initial pattern of vertical specialization in the set of all high-tech subintervals $(\mathcal{S}_h)$ and $(S_{h1}, S_{h2}, ..., S_{hC})$ represent the new pattern. A country c is moving up (down) the high-tech part of the value chain if $S_{hc} \geq S^{'}_{hc}$ and $S_{hc-1} \geq S^{'}_{hc-1}$ ($S_{hc} \leq S^{'}_{hc}$ and $S_{hc-1} \leq S^{'}_{hc-1}$). The same definition applies to the low-tech part of the chain.

Definition 4: A country is a high-tech (low-tech) producer, if it produces only high-tech (low-tech) intermediate goods. It is bi-tech producer, if it is active in both types of stages.

Definition 5: Inequality in the wage of type z labor between countries c_1 and c_2 ($c_1 > c_2$) is increasing (decreasing) if $(w^z_{c_1})'/(w^z_{c_2})' > w^z_{c_1}/w^z_{c_2}$ $((w^z_{c_1})'/(w^z_{c_2})' < w^z_{c_1}/w^z_{c_2})$.

3.4.1 Increase in complexity

As CVW mentioned, in some cases, technological innovations lead to an increase in the number of operations required for the production of the final good. In this part, we analyze the consequences of an increase in the measure of production stages. It is assumed that the utility gain from this increase in complexity is zero. This assumption does not affect on our results about the pattern of task allocation, inequality changes across countries and skill premia within countries. However, it's easy to see that allowing for utility gains will affect real wages. Since it is rarely the case that technological changes lead to the transformation of low-tech stages to high-tech stages, we confine our attention to the cases where $\Delta s_\Delta \geq 0$.

Proposition 4: Provided that the number of subintervals remains fixed and the new measure of high-tech stages is high enough, any increase in complexity will cause all countries to move up the high-tech part of the chain. Reaction of countries in the low-tech part depends on the direction and size of change in γ.

Proposition 5: Provided that the number of subintervals remains fixed, any increase in complexity may lead to a rise or fall in inequality of type z labor income between each pair of countries. Moreover, the skill premia within a country depends on the direction and size of γ change, as well.

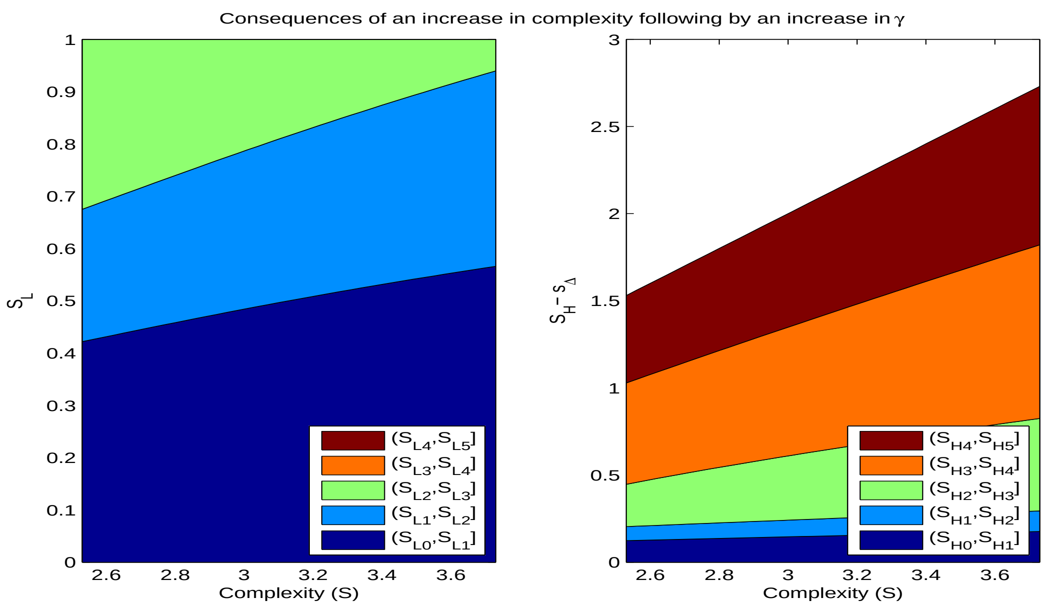

Figure 3.7: Changes in the pattern of vertical specialization

To be more intuitive, Consider a simple example with 5 countries and two subintervals. Figure (3.7) depicts the effects of increasing in complexity following by an increase in γ. Here, we assume that $\alpha = 0.7$. It's also assumed below values for mistake rates and labor endowments:

$$\begin{cases} (\lambda_1, L_1, H_1) = (0.7802, 0.9500, 0.2000) \\ (\lambda_2, L_2, H_2) = (0.6256, 0.4563, 0.1200) \\ (\lambda_3, L_3, H_3) = (0.3685, 0.6447, 0.3000) \\ (\lambda_4, L_4, H_4) = (0.1835, 0.9890, 0.4500) \\ (\lambda_5, L_5, H_5) = (0.0811, 0.5268, 0.4300) \end{cases}$$

As shown in the figure (3.7), an increase in S from 2.5 to 3.8 when s_Δ remains constant would cause all countries to move up in the high-tech part of the chain. In the low-tech part, countries 4 and 5 do not produce and countries 1-3 move up the chain. The overall intuition behind these changes is simple. An increase in complexity will decrease the total output at all high-tech stages of production. Since the production technology is Leontief, the labor component of the production in each high-tech stage also decreases. Moreover, labor market clearing needs skilled labor supply to be equal to skilled labor demand. So, the measure of stages performed by each country in the high-tech subinterval increases. Thus, all countries in the high-tech part will move p the chain. On the other hand, the unskilled labor demand of bi-producers in the high-tech part decreases due to the decrease in the total output of each high-tech stage. So, they will use more unskilled labor in the low-tech part and move up the chain.

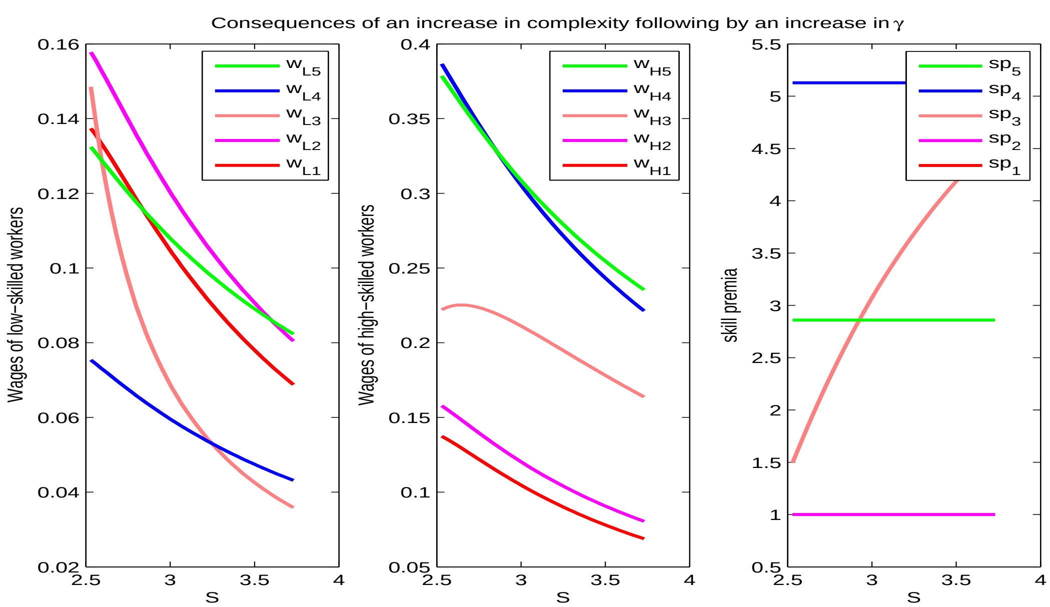

Figure 3.8: Changes in wages and skill premia

Figure (3.8) depicts the relevant changes in wages and skill premia. An obvious observation is that countries react heterogeneously to any increase in complexity. Moreover, the wage of both types of labor in all countries decreases. As noted before, this is a direct result of the assumption that increasing the complexity does not affect the utility. Finally, the skill premia of country 4 increases as a result of a decrease in its contribution to the low-tech part. Indeed, the unskilled labor use of country 4 in the high-tech part increases and since the supply of skilled labor is fixed, the wage ratio of skilled labor over unskilled labor increases.

The other cases related to increasing in complexity and decreasing in the high-tech intensity of the chain are explained in the appendix.

3.4.2 Increase in α

Another possibility for technological change is increasing in the productivity level of skilled labor in the Cob-Douglas combination of high-tech stages' production function. This type of innovation affects the chain in the following way:

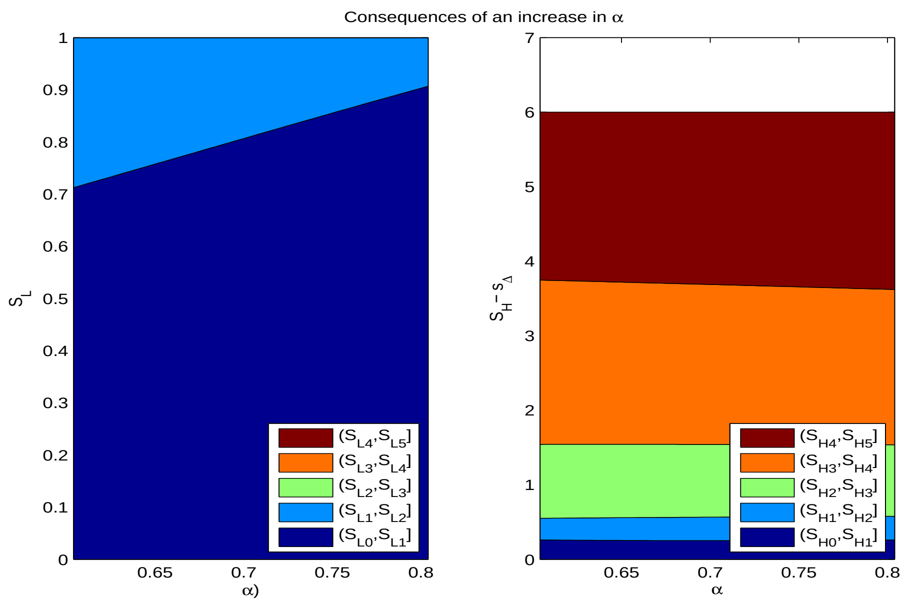

Figure 3.9: Changes in the pattern of vertical specialization

Proposition 6: Depending on the relationship between mistake rates and the skill ratio of the endowments, increasing in α would have different effects on the pattern of task allocation within the high-tech part. In particular, if the mistake rate of every country is a negative function of the skill ratio of its endowments, then any increase in the level of α leads all high-tech producers with the skill ratio above 0.5 to move down in the high-tech part of the chain. In the low-tech part, if the unskilled labor use of the most productive bi-producer increases high enough, then all bi-producers move down in the low-tech part. If it decreases or the increase is smaller than the increase in other bi-producers, then all bi-producers move up in the low-tech part.

Proposition 7: Any increase in the level of α has an heterogenous effect on the wage inequality of type z between pairs of countries. The effect on skill premia is to raise in some countries and zero effect in the others.

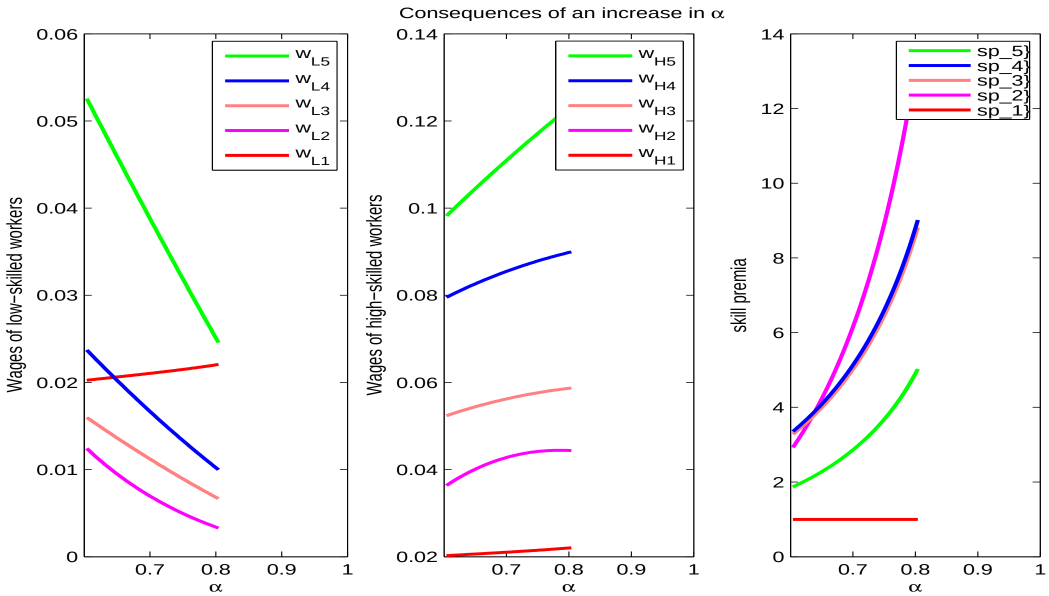

Figure 3.10: Changes in wages and skill premia

Figures (3.9) and (3.10) show an example on the effect of this kind of technological change on the pattern of task allocation and wages within a GVC.

3.4.3 Increase in α accompanied by decrease in γ

As we explained in the introduction section, the observation about the trend of skill premia for some countries reveals that it is rising for some countries, falling for some others and constant for the remaind ones. However, we saw in previous parts that there is not any single technological change that generates a rising trend of skill premia in some countries and a falling trend in some others. To rationalize this fact, we can consider cases where more than one type of technological innovations happen at the same time. For instance, figures (3.11) and (3.12) show the change in the pattern of vertical specialization, wages and skill premia produced by an increase in the productivity level of the skilled labor in the Cobb-Douglas combination and a decrease in the high-tech intensity of the chain. We can see that these two types of innovations can generate all types of trends in skill premia.

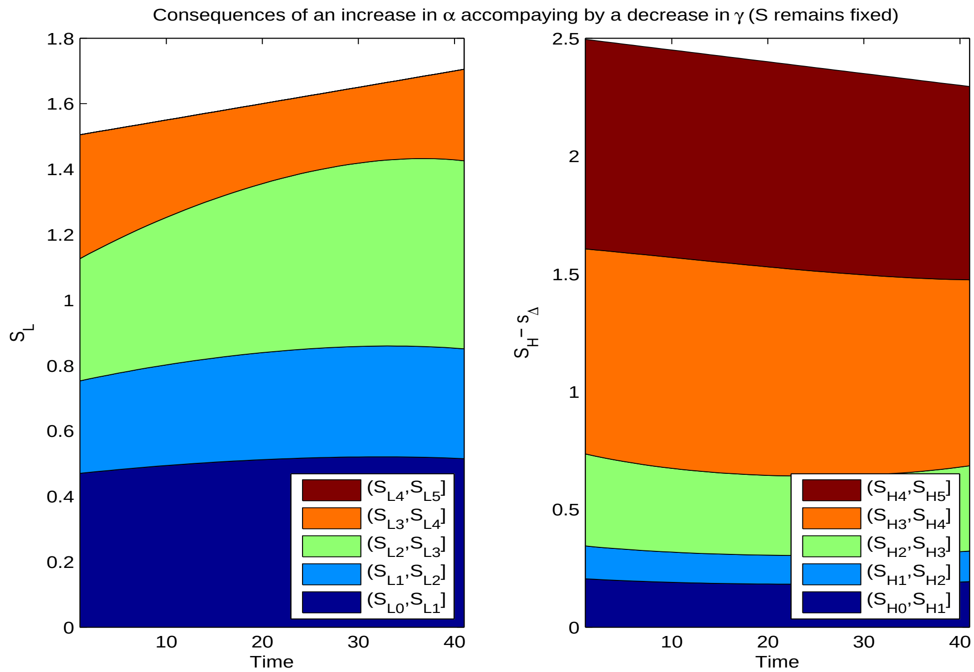

Figure 3.11: Changes in the pattern of vertical specialization

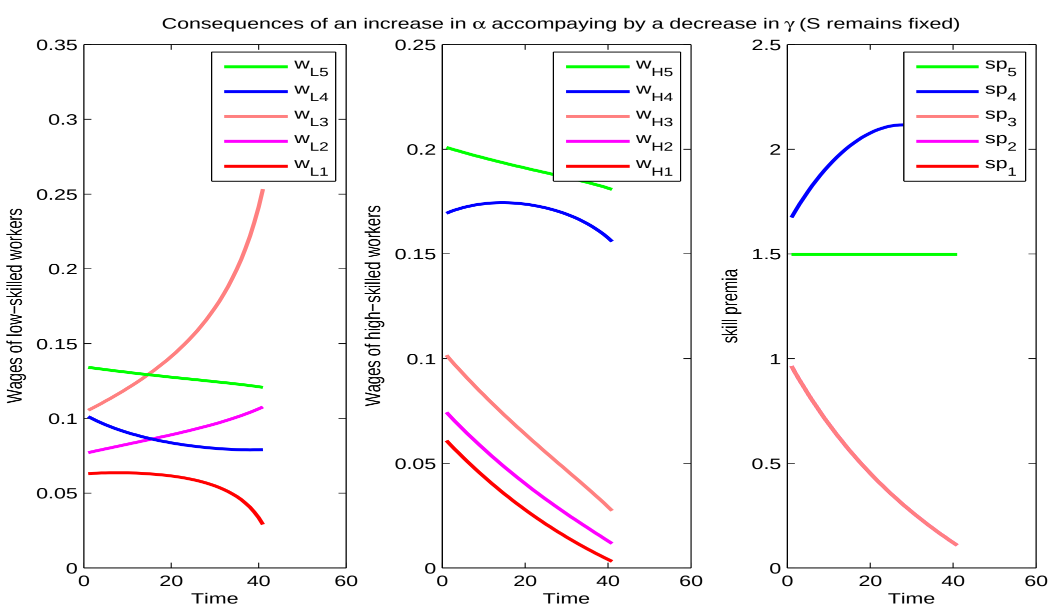

Figure 3.12: Changes in wages and skill premia

3.5 Conclusions

In this paper, we have developed a rudimentary framework to rationalize the pattern of task and income distribution within a global value chain and at the same time address the heterogeneity of countries in their trends of skill premia. The model is based on the Costinot et al. [2013]'s setting and focuses on an international sequential production that is subject to mistake. However, we adopt some heterogeneity assumptions on labor and production stages.

In the new setting, the unique vertical specialization of countries is preserved but with some different results from Costinot et al. [2013] findings. First, the vertical specialization happens in both types of stages. Second, beside the absolute productivity differences, the skill ratios of endowments are also a source of comparative advantage among countries. In fact, these ratios are defining in the level of contribution of each country to the each type of stages. Finally, the assumptions on the heterogeneity of labor and stages enable us to address the stylized facts on the trends of skill premia across countries derived from the WIOD database. Indeed, the effects of technological innovations on different types of labor and different types of stages are not symmetric. This is one source of different behavior of both developed and developing countries on some variables including skill premium.

This paper assumes that trade costs are zero and all firms inside a country are similar. Another limiting aspect of the paper is the strong assumption that the mistake rate of countries is constant over all stages. There is space for future research to relax each of these assumption and study more features of global value chains.

3.6 appendix

3.6.1 Simulations

Increasing in complexity

Figure (3.13) shows the changes in the pattern of vertical specialization for the situation in which Complexity increases but γ decreases. Here, the same values for mistake rates and labor endowments are assumed and the productivity coefficient of the skilled labor in the Cob-Douglas combination is set to $\alpha = 0.8$. The complexity increases from 4 to 5.8 and s_Δ grows from 1 to 2.86 in a rate slightly greater than the growth rate of complexity. It can be seen that all countries move up the high-tech part of the chain and the number of countries active in the low-tech part increases when S increases and γ decreases.

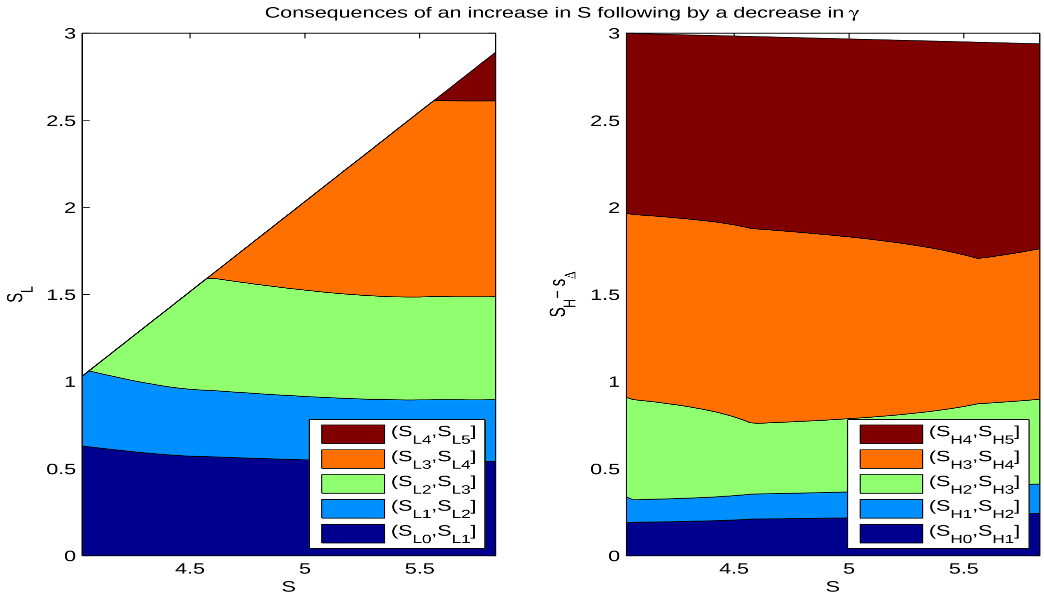

Figure 3.13: Changes in the pattern of vertical specialization

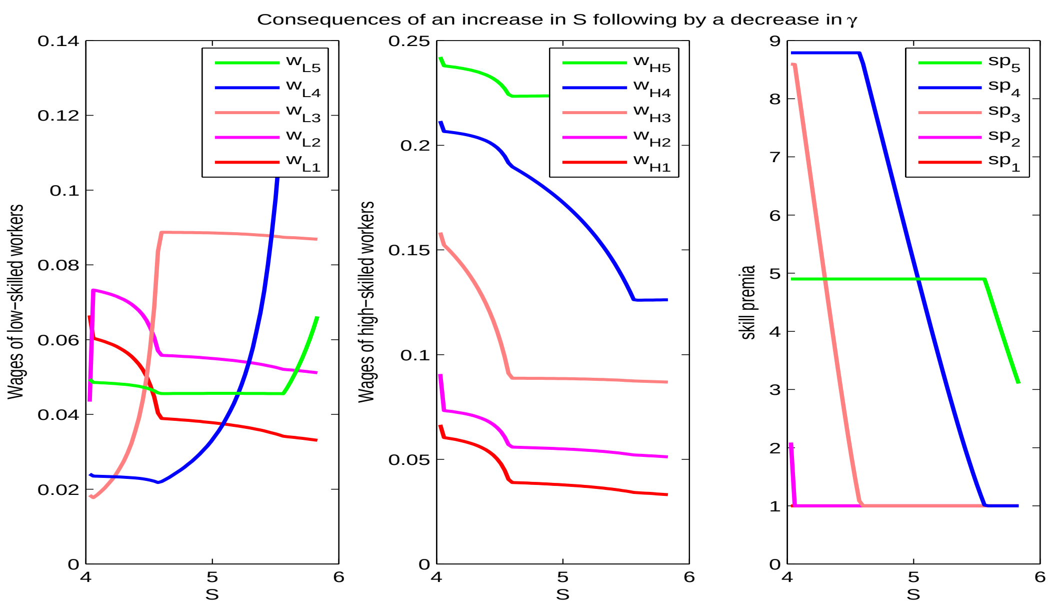

Figure 3.14: Changes in wages and skill premia

The reaction of skilled and unskilled labor wages and the skill premia are depicted in figure (3.14). We can see that the wage of unskilled labor in countries (3)-(5) increases and in countries (1) and (2) decreases. The reason is that the demand for unskilled labor in countries (3)-(5) increases as a result of producing in the low-tech part of the chain. Moreover, as noted before, countries (1) and (2) move down the low-tech part of the chain and so the demand for unskilled labor decreases. The wage of skilled labor decreases in all countries. This is due to the fact that the high-tech intensity of the chain decreases and there is not any utility gain of increasing in complexity, as well. The right column in the figure shows changes in skill-premia that is compatible with the changes in the wage of skilled and unskilled labor.

Decrease in the high-tech intensity of the chain

Technological innovation could be the transforation of some high-tech stages to low-tech stages. We can represent this case by a decrease in the level of the high-tech intensity of the chain. As figure (3.15) shows any decrease in the level of high-tech intensity leads all countries to move up in the high-tech part. In the low-tech part, the impact is heterogenous across countries. Some countries may move down the chain and some of them transfer from a high-tech producer to a bi-producer country.

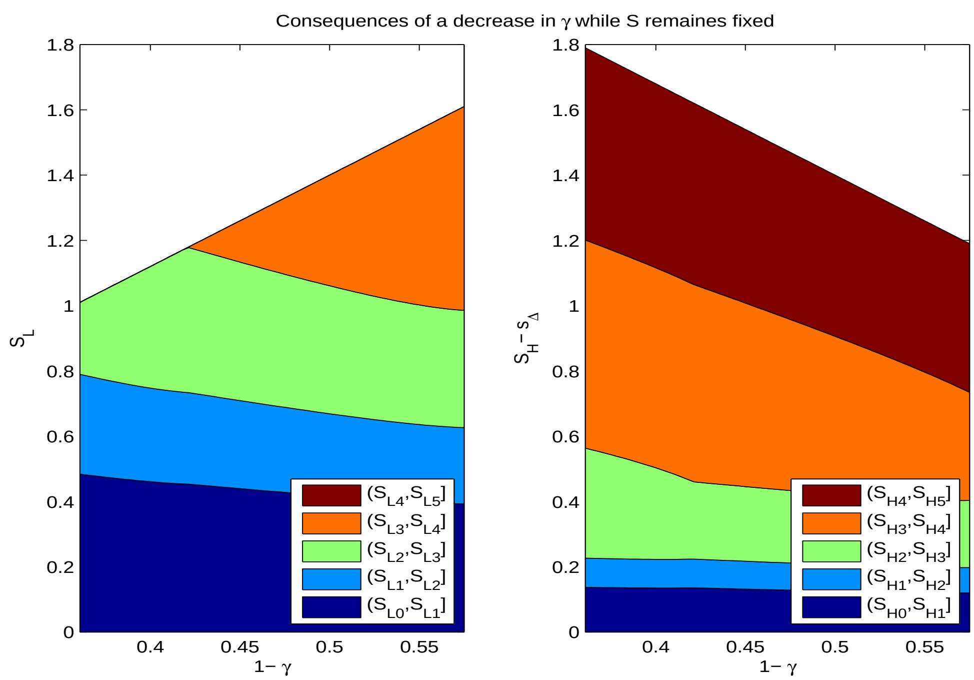

Figure 3.15: Changes in the pattern of vertical specialization

Figure (3.16) depicts the example on the effects of this technological innovation on pattern of wages and skill premia. Any decrease in the level of high-tech intensity results in a decrease in the skill premia of some countries and a constant skill premia for the others. The impact on the wage inequality of type z between any pair of countries varies based on the chain and technology parameters.

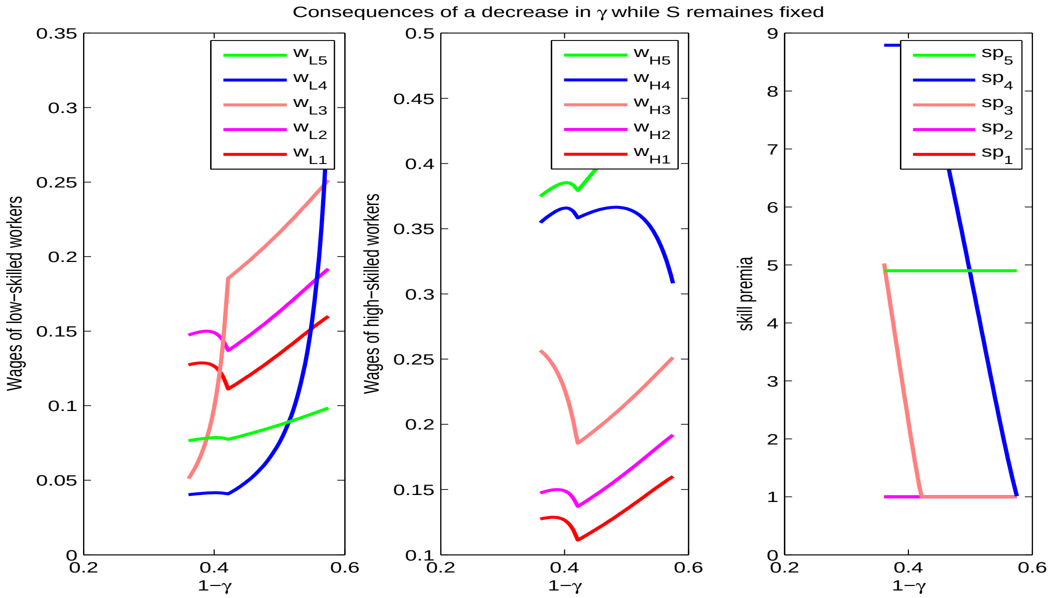

Figure 3.16: Changes in wages and skill premia

3.6.2 Proofs

Proof of Proposition 1

As we note before, for technical reason, we assume that if a firm produces intermediate good $s + ds$, then it necessarily produces a measure $\Delta > 0$ of intermediate goods around that stage. Formally, for any intermediate good $s + ds$, we assume the existence of $s_\Delta < s + ds \leq s_\Delta + \Delta$ such that if $q(s + ds) > 0$, then $q(s') > 0$ for all $s' \in (s_\Delta, s_\Delta + \Delta]$. The proof of this proposition is similar to the proof of the proposition 1 in CVW. We define $\Delta(s) \equiv (s_\Delta, s_\Delta + \Delta)$ for some s_Δ satisfying previous conditions. The proof, however, does not depend on which exact s_Δ we pick up. Like CVW, we provide the proof in four steps:

Step 1: $p(.)$ is continuous.

For each subinterval σ_i^z, we can easily use the result of the first step in the proof of proposition 1 of CVW and show that $p(.)$ is continuous within each subinterval. For the boundary points, we assumed:

$$p(\overline{s}_i) = \overline{p}_i = \lim_{s \to (\overline{s}_i)^-} p(s) \quad \forall i \in \{1, 2, ..., 2n\}$$

so, there is not a jump in price when moving from a subinterval to its neighbors.

Step 2: If $s_1 > s_2$ then $p(s_2) > p(s_1)$.

By step 1, we know that $p(.)$ is continuous and for each σ_i^z, $p'(s) > 0\,\forall s \in \sigma_i^z$. These two facts indicate that $p(.)$ is strictly increasing.

Step 3: If $c_2 > c_1$ then $w'_{hc_2} > w'_{hc_1}$ and $w^l_{c_2} > w^l_{c_1}$.

Factor market clearing implies that country c_1 produces at least one intermediate good in a high-tech stage (s_1) and one in a low-tech stage (s_2). By assumption, this requires $Q_{c_1}(s) > 0$ for all $s \in \Delta(s_1)$ and $s \in \Delta(s_2)$. Equation (3.3) indicates that:

$$\begin{cases} p(s_1) = (1 + \lambda_{c_1} ds)p(s_1 - ds) + w'_{hc_1} ds \\ \\ p(s_1) \leq (1 + \lambda_{c_2} ds)p(s_1 - ds) + w'_{hc_2} ds \end{cases} \qquad (1)'$$

and

$$\begin{cases} p(s_2) = (1 + \lambda_{c_1} ds)p(s_2 - ds) + w^l_{c_1} ds \\ \\ p(s_2) \leq (1 + \lambda_{c_2} ds)p(s_2 - ds) + w^l_{c_2} ds \end{cases} \qquad (2)'$$

Equations (1)' and (2)' plus $\lambda_{c_2} < \lambda_{c_1}$ yield $w'_{hc_2} > w'_{hc_1}$ and $w^l_{c_2} > w^l_{c_1}$.

Step 4: If $c_2 > c_1$ and $Q_{c_1}(s_1) > 0 (s_1 \in \mathcal{S}_z)$, then $Q_{c_2}(s) = 0\,\forall s \in \mathcal{S}_z, s < s_2$.

[The same proof as CVW]

To finish the proof of proposition 1, define $S_c^Z \equiv Sup\{s \in \mathcal{S}_z | Q_c(s) > 0\}\,\forall c \in \mathcal{C}$. Regarding step 4, we must have $S_0^h \equiv 0 < S_1^h < ... < S_C^h = \overline{s}_{2n-1}$ and $S_0^l \equiv \overline{s}_1 < S_1^l < ... < S_C^l = S$, such that for all $s \in \mathcal{S}$ and $c \in \mathcal{C}$, $Q_c^z(s) > 0$ if $S_{c-1}^z < s < S_c^z$ and $Q_c^z(s) = 0$ if $s < S_{c-1}^z$ or $s > S_c^z$. Moreover, since $Q_c^z(s) > 0$ requires $Q_c^z(s') > 0$ for all $s' \in (s - ds, s]$, we must also have $Q_c^z(S_c) > 0$ and $Q_c^z(S_{c-1}) = 0$ for all $c \in \mathcal{C}$. So, $Q_c^z(s) > 0$ if and only if $s \in (S_{c-1}^z, S_c^z]$. Lastly, the good market clearing condition implies that $S_C^h = \overline{s}_{2n-1}$ and $S_C^l = S$. ■

Proof of Proposition 2

Consider an arbitrary σ_i^z that is undertook by countries $c_{i,1}^z, c_{i,2}^z, ...$ and $c_{i,n_{iz}}^z$. Applying proposition 1 of CVW, it is straightforward to obtain this proposition. ■

Proof of Lemma 1

The proof of this lemma is very similar to the proof of lemma 1 in CVW. It's easier to first prove the equation (3.10) and then equations (3.8) and (3.9). Proposition 2 and equation (3.5) yield:

$$Q^z_{i,j}(s_2) - Q^z_{i,j}(s_1) = -\lambda^z_{i,j} \int_{s_1}^{s_2} Q^z_{i,j}(s)ds, \text{ for all } s_2 \in (S^z_{i,j-1}, S^z_{i,j}] \tag{3.15}$$

Taking the derivative of this expression with respect to s_2 gives us:

$$\frac{dQ^z_{i,j}(s)}{ds} = -\lambda^z_{i,j} Q^z_{i,j}(s), \text{ for all } s \in (S^z_{i,j-1}, S^z_{i,j}]$$

The solution of this equation would satisfy:

$$Q^z_{i,j}(S^z_{i,j}) = e^{-\lambda^z_{i,j}(S^z_{i,j} - S^z_{i,j-1})} \lim_{s \to (S^z_{i,j-1})^+} Q^z_{i,j}(s) \tag{3.16}$$

Proposition 2 and equation (3.5) would also imply:

$$Q^z_{i,j}(S^z_{i,j-1}+ds) - Q^z_{i,j-1}(S^z_{i,j-1}-ds) = -[\lambda^z_{i,j} \lim_{s \to (S^z_{i,j-1})^+} Q^z_{i,j}(s) + \lambda^z_{i,j-1} Q^z_{i,j-1}(S^z_{i,j-1}-ds)]ds$$

ds is infinitesimal, so this imply:

$$\lim_{s \to (S^z_{i,j-1})^+} Q^z_{i,j}(s) = \lim_{s \to (S^z_{i,j-1})^-} Q^z_{i,j-1}(s) = Q^z_{i,j-1}(S^z_{i,j-1}) \tag{3.17}$$

Regarding this equation, equation (3.16) and the definition of $Q^z_{i,j} \equiv Q^z_{i,j}(S^z_{i,j})$, we can obtain equation (3.10).

To derive equations (3.8) and (3.9), we can use proposition 2 and equations (3.7) and (3.6). We only derive equation (3.8). Equation (3.9) could be obtained in the same way. By proposition 1 and equation (3.7), we can write:

$$(\frac{1-\alpha}{\alpha} \frac{w^H_c}{w^L_c})^{1-\alpha} \int_{S^z_{i,j-1}}^{S^z_{i,j}} Q^z_{i,j}(s)ds = H^z_{i,j} \tag{3.18}$$

Regarding equations (3.16) and (3.17) we can also get:

$$\int_{S^z_{i,j-1}}^{S^z_{i,j}} Q^z_{i,j}(s)ds = \frac{1}{\lambda^z_{i,j}} [Q^z_{i,j-1}(S^z_{i,j-1}) - Q^z_{i,j}(S^z_{i,j})] \tag{3.19}$$

Equations (3.18) and (3.19) imply:

$$H^z_{i,j} = (\frac{1-\alpha}{\alpha} \frac{w^H_c}{w^L_c})^{1-\alpha} \frac{1}{\lambda^z_{i,j}} [Q^z_{i,j-1}(S^z_{i,j-1}) - Q^z_{i,j}(S^z_{i,j})] \tag{3.20}$$

Equation (3.8) is obtained from equations (3.10) and (3.20) and the definition of $Q^z_{i,j} \equiv Q^z_{i,j}(S^z_{i,j})$. ■

Proof of Lemma 2

We only prove part (a) of this lemma. Proof of part (b) is similar. We first consider equation (3.11). Proposition 2 and condition (3.3) yield:

$$p(S^z_{i,j}+ds)-(1+\lambda^z_{i,j+1}ds)p(S^z_{i,j})-w^z_{i,j+1}ds \geq p(S^z_{i,j}+ds)-(1+\lambda^z_{i,j}ds)p(S^z_{i,j})-w^z_{i,j}ds$$

$$p(S^z_{i,j})-(1+\lambda^z_{i,j}ds)p(S^z_{i,j}-ds)-w^z_{i,j}ds \geq p(S^z_{i,j})-(1+\lambda^z_{i,j+1}ds)p(S^z_{i,j}-ds)-w^z_{i,j+1}ds$$

for any σ^z_i and any $c^z_{i,j} \in \{c^z_{i,1}, c^z_{i,2}, ..., c^z_{i,n_{iz}}\}$. After some algebra, we can get:

$$(\lambda^z_{i,j}-\lambda^z_{i,j+1})p(S^z_{i,j}) \geq w^z_{i,j+1}-w^z_{i,j} \geq (\lambda^z_{i,j}-\lambda^z_{i,j+1})p(S^z_{i,j}-ds)$$

Considering that $p(.)$ is continuous and ds is infinitesimal, we can write:

$$w^z_{i,j+1}-w^z_{i,j}=(\lambda^z_{i,j}-\lambda^z_{i,j+1})p(S^z_{i,j}),\ \text{for all } c^z_{i,j} \in \{c^z_{i,1}, c^z_{i,2}, ..., c^z_{i,n_{iz}}\}$$

This equation is equivalent to equation (3.11) in which $p^z_{i,j} \equiv p(S^z_{i,j})$.

To show equation (3.12), consider proposition 2 and condition (3.3). We can derive:

$$p(s+ds)=(1+\lambda^z_{i,j}ds)p(s)+w^z_{i,j}ds,\ \text{for all } s \in (S^z_{i,j-1}, S^z_{i,j}]$$

Dividing by ds, we gain:

$$\frac{dp(s)}{ds}=\lambda^z_{i,j}p(s)+w^z_{i,j}$$

The solution of this differential equation must satisfy:

$$p(S^z_{i,j})=e^{\lambda^z_{i,j}(S^z_{i,j}-S^z_{i,j-1})}\lim_{s\to(S^z_{i,j-1})^+}p(s)+[e^{\lambda^z_{i,j}(S^z_{i,j}-S^z_{i,j-1})}-1](\frac{w^z_{i,j}}{\lambda^z_{i,j}})$$

Since $p(.)$ is continuous and regarding $N^z_{i,j} \equiv S^z_{i,j}-S^z_{i,j-1}$ and $p^z_{i,j} \equiv p(S^z_{i,j})$, this equation is equivalent to equation (3.12). ■

Proof of Proposition 3

We provide the proof in four steps. Before going through these steps, we use a new labeling for the cutoff stages and border points of subintervals. Let m, m_h and m_l denote the total number of subintervals, the total number of high-tech subintervals and total number of low-tech subintervals produced by border points and cutoff stages, respectively. $\mathcal{I}=\{1,2,...,m\}$ is the set of all these m subintervals as shown in figure (3.17).

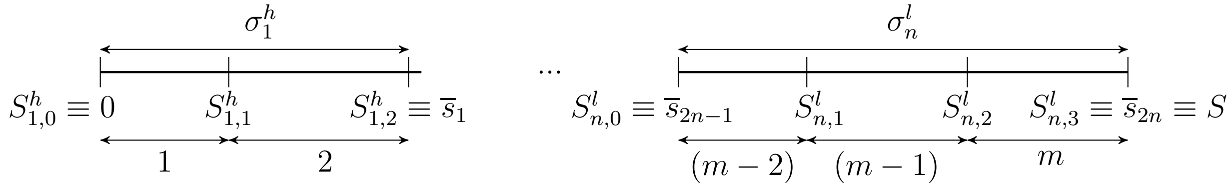

Figure 3.17: An example of new labeling

In addition, we define $(S'_0, S'_1, ..., S'_m)$ and $(Q'_0, Q'_1, ..., Q'_m)$ as:

$$(S'_0, S'_1, ..., S'_m) = (S^h_{1,0}, S^h_{1,1}, ..., S^l_{n,n_{nl}})$$

$$(Q'_0, Q'_1, ..., Q'_m) = (Q(S'_0), Q(S'_1), ..., Q(S'_m))$$

Step 1: $(S^z_{i,0}, ..., S^z_{i,n_{iz}})$ and $(Q^z_{i,0}, ..., Q^z_{i,n_{iz}})$ satisfy equations (3.8)-(3.10) $(\forall \sigma^z_i)$ if and only if $(S'_0, S'_1, ..., S'_m)$ and $(Q'_0, Q'_1, ..., Q'_m)$ satisfy

$$S'_i = S'_0 + \sum_{j=1}^{i} (\frac{1}{\lambda_j}) ln[\frac{Q'_0 - \sum_{k=1}^{j-1} \lambda_k \widetilde{L}_k}{Q'_0 - \sum_{k=1}^{j} \lambda_k \widetilde{L}_k}], \text{ for all } i \in \mathcal{I} \tag{3.21}$$

$$Q'_i = Q'_0 - \sum_{j=1}^{i} \lambda_j \widetilde{L}_j, \text{ for all } i \in \mathcal{I} \tag{3.22}$$

To prove this step, notice that $(S^z_{i,0}, ..., S^z_{i,n_{iz}})$ and $(Q^z_{i,0}, ..., Q^z_{i,n_{iz}})$ satisfy equations (3.8)-(3.10) if and only if $(S'_0, S'_1, ..., S'_m)$ and $(Q'_0, Q'_1, ..., Q'_m)$ satisfy following equations:

$$S'_i = S'_{i-1} - (\frac{1}{\lambda_i}) Ln(1 - \frac{\lambda_i \widetilde{L}_i}{Q'_{i-1}}) \,, \, for\, all\, i \in \mathcal{I} \tag{3.23}$$

$$Q'_i = e^{-\lambda_i (S'_i - S'_{i-1})} Q'_{i-1} \,, \, for\, all\, i \in \mathcal{I} \tag{3.24}$$

Regarding our labeling, this one-to-one correspondence is straightforward. So, we must show that $(S'_0, S'_1, ..., S'_m)$ and $(Q'_0, Q'_1, ..., Q'_m)$ satisfy equations (3.23) and (3.24) if and only if they satisfy equations (3.21) and (3.22). By equations (3.23) and (3.24), we have:

$$Q'_i = Q'_{i-1} - \lambda_i \widetilde{L}_i$$

and by iteration, we get:

$$Q'_i = Q'_0 - \sum_{j=1}^{i} \lambda_j \widetilde{L}_j, \text{ for all } i \in \mathcal{I}$$

which is equation (3.22). Now, regarding equations (3.23), again we can iterate and obtain:

$$S'_i = S'_0 - \sum_{j=1}^{i} (\frac{1}{\lambda_j}) ln[1 - \frac{\lambda_j \widetilde{L}_j}{Q'_{j-1}}], \text{ for all } i \in \mathcal{I}$$

Substituting equation (3.22) in this expression, we can derive equation (3.21). It's a simple algebra to show that if $(S'_0, S'_1, ..., S'_m)$ and $(Q'_0, Q'_1, ..., Q'_m)$ satisfy equations (3.21) and (3.22), then they will satisfy equations (3.23) and (3.24).

Step 2: There exists a unique set of vectors $(S^z_{i,0}, ..., S^z_{i,n_{iz}})$ and $(Q^z_{i,0}, ..., Q^z_{i,n_{iz}})$ $(\forall \sigma^z_i)$ that satisfy equations (3.8)-(3.10) and boundary conditions

$$\begin{cases} (S^z_{i,0}, S^z_{i,n_{iz}}) = (\overline{s}_{2(i-1)}, \overline{s}_{2i-1}) & \text{if } z = h \\ \\ (S^z_{i,0}, S^z_{i,n_{iz}}) = (\overline{s}_{2i-1}, \overline{s}_{2i}) & \text{if } z = l \end{cases}$$

Again, it is straightforward from our labeling that this statement is equivalent to show that there exists a unique pair of vectors $(S'_0, S'_1, ..., S'_m)$ and $(Q'_0, Q'_1, ..., Q'_m)$ that satisfy equations (3.23) and (3.24) and the boundary conditions: $S'_0 = 0$ and $S'_I = S$. To prove the latter, define $\widetilde{Q'}_0 = \sum_{i=1}^{I} \lambda_i L_i$. Considering step 1, it's obvious that there does not exist a pair of vectors $(S'_0, S'_1, ..., S'_m)$ and $(\widetilde{Q'}_0, Q'_1, ..., Q'_m)$ that satisfy equations (3.21) and (3.22). Thus, there does not exist such a pair of vectors that satisfy (3.23) and (3.24). So, we focus on $Q'_0 > \widetilde{Q'}_0$. Considering equation (3.21), we can see that $\partial S'_I / \partial Q'_0 < 0$ for all $Q'_0 > \widetilde{Q'}_0$. In addition, it is easy to check that:

$$\lim_{Q'_0 \to \widetilde{Q'}_0^+} S'_I = +\infty \quad \text{and} \quad \lim_{Q'_0 \to +\infty} S'_I = S'_0$$

So, conditional on setting $S'_0 = 0$, there exists a unique $Q'_0 > \widetilde{Q'}_0$ such that vectors $(S'_0, S'_1, ..., S'_m)$ and $(Q'_0, Q'_1, ..., Q'_m)$ satisfy equation (3.21) and (3.22) and $S'_I = S$.

Step 3: Within each high-tech subinterval, for any vector $(N^h_{i,1}, ..., N^h_{i,n_{ih}})$ there exists a unique pair of vectors $(w'_{i,1}, ..., w'_{i,n_{ih}})$ and $(p^h_{i,0}, ..., p^h_{i,n_{ih}})$ satisfying equations (3.11) and (3.12) and the boundary conditions $p^h_{i,0} = \overline{p}_{i-1}$ and $p^h_{i,n_{ih}} = \overline{p}_i$.

The proof of this step is exactly the same as the proof of proposition 2 of CVW (step 3).

Step 4: Within each low-tech subinterval, for any vector $(N^l_{i,1}, ..., N^l_{i,n_{il}})$ there exists a unique pair of vectors $(w^l_{i,1}, ..., w^l_{i,n_{il}})$ and $(p^l_{i,0}, ..., p^l_{i,n_{il}})$ satisfying equations (3.13) and (3.14) and the boundary conditions $p^l_{i,0} = \overline{p}_i$ and $p^l_{i,n_{il}} = \overline{p}_{i+1}$.

The proof of this step is also exactly the same as the proof of proposition 2 of CVW (step 3).

Steps (1)-(4) indicate the existence and uniqueness of $(\{(S^z_{i,0},...,S^z_{i,n_{iz}}),(Q^z_{i,0},...,Q^z_{i,n_{iz}})\}\,\forall\sigma^z_i)$, $(\{(w'_{i,1},...,w'_{i,n_{ih}}),(p^h_{i,0},...,p^h_{i,n_{ih}})\}\forall\sigma^h_i)$ and $(\{(w^l_{i,1},...,w^l_{i,n_{il}}),(p^l_{i,0},...,p^l_{i,n_{il}})\}\forall\sigma^l_i)$ that satisfy equations (3.8)-(3.14) with boundary conditions:

$$\begin{cases} (S^z_{i,0},S^z_{i,n_{iz}})=(\overline{s}_{2(i-1)},\overline{s}_{2i-1}) & \text{if } z=h \\ \\ (S^z_{i,0},S^z_{i,n_{iz}})=(\overline{s}_{2i-1},\overline{s}_{2i}) & \text{if } z=l \end{cases}$$

$$\begin{cases} p^z_{i,0}=\overline{p}_i\,,\ p^z_{i,n_{iz}}=\overline{p}_{i+1} & \text{if } z=l \\ \\ p^z_{i,0}=\overline{p}_{i-1}\,,\ p^z_{i,n_{iz}}=\overline{p}_i & \text{if } z=h \\ \\ p^l_{n,n_{nl}}=p_C=1\,,\ p^h_{1,0}=0 \end{cases}$$

If we consider these output levels ($\forall z\in\{l,h\}\,,\ j\in\{1,2,...,n_{iz}\}$):

$$Q^z_{i,j}(s)=e^{-\lambda^z_{i,j}(s-S^z_{i,j-1})}Q^z_{i,j-1},\quad \forall s\in(S^z_{i,j-1},S^z_{i,j}]$$

and these intermediate good prices:

$$p^h_{i,j}(s)=e^{\lambda^h_{i,j}(s-S^h_{i,j-1})}p^h_{i,j-1}+(e^{\lambda^h_{i,j}(s-S^z_{i,j-1})}-1)(\frac{w'_{i,j}}{\lambda^h_{i,j}}),\quad \forall s\in(S^h_{i,j-1},S^h_{i,j}]\text{ and }\forall\sigma^h_i$$

$$p^l_{i,j}(s)=e^{\lambda^l_{i,j}(s-S^l_{i,j-1})}p^l_{i,j-1}+(e^{\lambda^l_{i,j}(s-S^l_{i,j-1})}-1)(\frac{w^l_{i,j}}{\lambda^l_{i,j}}),\quad \forall s\in(S^l_{i,j-1},S^l_{i,j}]\text{ and }\forall\sigma^l_i$$

By construction, these output levels, input prices and the relevant wages satisfy conditions (3.3)-(3.6). So, a free trade equilibrium exists. Moreover, $(\{(S^z_{i,0},...,S^z_{i,n_{iz}}),(Q^z_{i,0},...,Q^z_{i,n_{iz}})\}\,\forall\sigma^z_i)$, $(\{(w'_{i,1},...,w'_{i,n_{ih}}),(p^h_{i,0},...,p^h_{i,n_{ih}})\}\forall\sigma^h_i)$ and $(\{(w^l_{i,1},...,w^l_{i,n_{il}}),(p^l_{i,0},...,p^l_{i,n_{il}})\}\forall\sigma^l_i)$ are unique and regarding propositions 1 and 2 and Lemmas 1 and 2, the free trade equilibrium is unique as well. ■

Proof of Proposition 4

Before going through the proof, it is useful to note that since $w^H_c\geq w^L_c$, the Cobb-Douglas combination of labors in the high-tech stages and the overall production structure result in the partitioning of countries to three categories: a group with only one country (c_0) that is a bi-producer and $w^H_{c_0}>w^L_{c_0}$, the group of bi-producers that have mistake rates bigger than λ_{c_0} in which the skill premium is equal to one and the group of countries more productive than c_0 and are only active in high-tech stages. Let call c_0, the "border country". Furthermore, let Q_0 and $\widehat{Q}_0$ represent the input at stages 0 and s_Δ respectively.

Denote the number of countries producing at low-tech stages by n_1. We know that skilled labor market clearing entails the number of countries that are active in high-tech part to be equal to n. Let $(l_1, l_2, ..., l_{n_1})$ and $(\widetilde{L}_1, ..., \widetilde{L}_n)$ represent respectively the unskilled labor use of countries $\{1, ..., n_1\}$ in the low-tech part and the labor content that countries use in the high-tech part, where:

$$\widetilde{L}_c = H_c^\alpha (L_c - l_c)^{1-\alpha}$$

It is evident from this equation that $\widetilde{L}_c$ has a reverse relationship with l_c. By lemma 1, we know that the amount of H_c and l_c depend on α and cutoff stages (S_j^h). For the proof of the first part, we consider the high-tech part as a CVW type supply chain with $(L_1, ...L_2)$ replaced by $(\widetilde{L}_1, ..., \widetilde{L}_n)$ and for the proof of the second part, we consider the low-tech part as a CVW type supply chain with $(L_1, ...L_2)$ replaced by $(l_1, ..., l_n)$. Regarding the border country (c_{n_1}), increasing in complexity leads to one of these cases: increasing n_1, decreasing n_1 and changing the contribution of n_1 in each type of stages while n_1 remains fixed. First, we analyze the third case. Two options for the change in the contribution of n_1 in each type of stages could be imagined:

a. If the share of unskilled labor that n_1 devotes to low-tech production decreases $(l_{c_{n_1}} \downarrow)$, then $\widetilde{L}_{c_{n_1}} \uparrow$. Moreover, since $\Delta s_\Delta \geq 0$ then $Q_0 \downarrow$ and $\widehat{Q}_0 \downarrow$. Thus, considering propositions 3 and 5 of CVW and the fact that $\widetilde{L}_c$ does not change for other countries, we can conclude that all countries in the high-tech part will move up the chain. In this case, it is easy to check that all countries in the low-tech also move up the chain.

b. If the share of unskilled labor that n_1 devotes to low-tech production decreases $(l_{c_{n_1}} \uparrow)$, then $\widetilde{L}_{c_{n_1}} \downarrow$. Moreover, since $\Delta s_\Delta \geq 0$ then either $Q_0 \downarrow$ or $Q_0 \uparrow$. In the former case, the same reasoning as part (a) applies. The latter case could be followed by two different situations: either $\widehat{Q}_0 \downarrow$ or $\widehat{Q}_0 \uparrow$. Again, in the first situation, all countries move up the high-tech part and non border countries in the low-tech part also move up the chain. In the second situation, depending on the size of the drop in $\widetilde{L}_{c_{n_1}}$, which is a negative function of the measure of high-tech stages, we will have different results. If the drop is low enough (or the measure of high-tech stage is high enough), then all countries in the high-tech part will move up the chain.Here, non border countries in the low-tech part move down the chain.

If n_1 decreases, we can follow the same reasoning as part (a) for all countries that would be a border country at some point. If n_1 increases, the same reasoning as part (b) applies. ■

Proof of Proposition 5

Following the proof of proposition 4 and regarding the proposition 5 of CVW, it is straightforward to get this proposition. ■

Proof of Proposition 6

Define "border country", $\widetilde{L}_c$ and l_c as proof of proposition 4. Consider the high-tech part as a CVW type supply chain with $(L_1, ...L_2)$ replaced by $(\widetilde{L}_1, ..., \widetilde{L}_n)$ and the low-tech part as a CVW type supply chain with $(L_1, ...L_2)$ replaced by $(l_1, ..., l_n)$.

For the proof of the first part, consider country c with the skill ration of greater than 0.5 that only produce in high-tech part. Since $\frac{H_c}{L_c} > 1$, $\widetilde{L}_c$ is an increasing function of α. On the other hand, if λ_c is a decreasing function of $\frac{H_c}{L_c}$, the most productive countries experience an increase in $\widetilde{L}_c$ when α increases. Moreover, we can get below relationship for each non border bi-producer:

$$\widetilde{L}_c = (\frac{1-\alpha}{\alpha})^{1-\alpha} H_c$$

which is a declining function of α. Thus, any increase in α causes the labor content of high-tech stages to decrease for all non border bi-producers. Consequently, since the measure of high-tech stages remains fixed, the high-tech producers with $\frac{H_c}{L_c} > 1$ must move down the high-tech part to satisfy the conditions for skilled and unskilled labor market clearing.

In order to prove the second part, note that for every non border bi-producer we have:

$$\frac{w_c^H}{w_c^L} = \frac{\alpha}{1-\alpha} . \frac{L_c^H}{H_c} = 1$$

So, any increase in α will decrease $\frac{L_c^H}{H_c}$ and since H_c is fixed, this is equivalent to decline in $L_c^H \equiv (L_c - l_c)$ and a rise in l_c. Thus, if the increase in the unskilled labor use of the border bi-producer in the low-tech part is too high, the unskilled labor market clearing induces bi-producers to move down the low-tech part. On the other hand, if the increase is below the increase in other bi-producers or it decreases, then unskilled labor market clearing condition requires all bi-producers to move up the low-tech part. ■

Proof of Proposition 7

The first part is derived directly from the previous proposition, lemma 1 and lemma 2. The proof of the second part is straightforward. Note that if a country is non border bi-producer (refer to the proof of proposition 4 for the definition of this) then the skill premia always remains constant because the optimality condition requires it to put the most possible labor on the low-tech part. Otherwise, from the Cobb-Douglas combination of the labor content of high-tech stages, we can derive:

$$\frac{w_c^H}{w_c^L} = \frac{\alpha}{1-\alpha}.\frac{L_c^H}{H_c}$$

that is an increasing function of α. ■

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