

# A COASIAN MODEL OF INTERNATIONAL PRODUCTION CHAINS

Thibault Fally and Russell Hillberry  
UC-Berkeley ARE and World Bank\*

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## Abstract

International supply chains require coordination of numerous activities across multiple countries and firms. We develop a theoretical model in which the optimal organization of a supply chain involves a series of linked decisions that equate, at the margin, (domestic or international) transaction costs and the costs of coordinating more tasks within the firm. The parameters that govern the two types of costs explain variation in supply chain length as well as cross-country variation in gross output-to-value added ratios. Comparative advantage within chains depends solely on the coordination cost parameter. Conditional on participation in a chain, countries with lower coordination costs locate downstream. Within a chain, domestic transaction costs only affect countries' absolute advantage, but a country with large transaction costs tends to specialize in those chains for which its coordination costs are especially low. We provide an analytical treatment of trade and welfare responses to trade cost change in a simple two-country model. To explore the model's implications in a richer setting we calibrate the model to match key observables in East Asia, and evaluate implications of changes in model parameters for trade, welfare, the length of supply chains and countries' relative position within them.

**Keywords:** Fragmentation of production, Transaction costs, Trade in intermediate goods, Boundary of the firm

**JEL Classification:** F10, L23

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# 1 Introduction

The nature of international trade changed dramatically in recent decades, as vertically integrated production processes spread across international borders, increasing trade in parts and components along the way.<sup>1</sup> This phenomenon has raised a number of important questions for economic policy: How large are the gains from international fragmentation, and how are they distributed across countries? How do changes in trade costs affect trade flows and the distribution of value added across countries? How has China's entry into the world trading system affected the international fragmentation of production? Answers to these questions require quantitative models that can represent the complexities of international production chains in a tractable form.

Recent evidence has documented substantial variation in supply chain length.<sup>2</sup> Even within chains, firms vary in their contribution to value added.<sup>3</sup> The length of supply chains and the degree to which they are internationalized are difficult to separate from decisions that determine firm scope. The Ford Model T, for example, was produced in a single plant, while the production of modern day automobiles can involve a myriad of heterogeneous suppliers scattered across multiple countries. International fragmentation is limited, ultimately, by the extent of fragmentation at the firm level. Yet the literature lacks a unified treatment that can explain endogenous firm boundaries within chains, formalize endogenous chain lengths, and determine comparative advantage within and across chains.

We offer a framework that accomplishes these goals. In the model, an optimal allocation of tasks determines jointly the scope of sequentially-arranged firms of varying size, the length of chains and the sequence of countries in production.<sup>4</sup> We calibrate the model using key moments from input-output tables on East Asia and the United States. Such tables have been used to quantify the extent of fragmentation and the allocation of value across countries.<sup>5</sup> Our focus on East Asia reflects the importance of international fragmentation in that region. Based on our calibration, we are able to quantify the impact on intermediate and final goods trade, and on welfare, of changes in: 1) international trade costs, 2) productivity in China and 3) transaction costs in China.

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<sup>1</sup>Baldwin (2012) surveys these developments and provides insights into how they should affect our thinking about the economics of international trade and trade policy.

<sup>2</sup>See Antràs et al. (2012), Fally (2012).

<sup>3</sup>See Kraemer et al. (2011), who illustrate the distribution of value added for Apple iPhones and iPads.

<sup>4</sup>Our framework is perfectly competitive and therefore silent about the distinction between firms and plants. We shall use the term 'firms' throughout, but one could reinterpret everything in terms of 'plants' without affecting the results.

<sup>5</sup>Johnson (2014) surveys a series of papers that use such tables to calculate value added trade. Koopman et al. (2010) use Chinese tables to calculate the domestic content of China's exports. Antràs et al. (2012) derive indices of supply chain length from input-output tables.

A central theoretical contribution is the development of a tractable framework in which supply chain length is endogenous. Supply chains vary in the number of firms involved because of endogenous differences in firm scope. Following Coase (1937), firm scope is determined by a marginal tradeoff between the cost of coordinating activities inside the firm and the costs of conducting market transactions. Going further, we formalize the marginal tradeoffs facing a chain of firms in an endogenous market for tasks rather than focusing on the boundaries of a single firm.<sup>6</sup> Within countries, outcomes are driven by two key parameters: one that governs coordination costs within the firm and one that summarizes domestic transaction costs. Our continuous representation of a chain allows us to derive strong and transparent links between structural parameters and observables in the data. Specifically, the gross-output-to-value-added ratio at any point in the chain is equal to the ratio of the Coasian parameters that govern coordination costs and transaction costs, respectively.

We allow the Coasian parameters to vary across countries and develop implications for international trade. Vertical specialization in our model is tightly related to firm scope. In equilibrium, firm scope decreases as we move upstream along the chain. In turn, this pattern affects the sorting of countries along the chain. Within a given chain, the most upstream countries are those in which it is most difficult to coordinate multiple tasks within the firm. Transaction costs affect absolute, not comparative, advantage within the chain, but transaction costs have an indirect effect on countries' average position in chains. Countries with high transaction costs are more likely to participate in chains for which the country has low coordination costs, which means that such countries tend to be positioned downstream.

We examine the effect of trade costs on trade and fragmentation in this setting. As expected, we find that opening to trade tends to increase the extent of fragmentation along several dimensions and facilitates production sharing across countries. The channels, however, are not trivial. Trade affects fragmentation at all stages and decreases firm scope even for firms that do not directly offshore production but are related to firms that do. The reduction in firm scope along the chain is associated with a decrease in average costs, especially downstream, and contributes to the reduction in final goods prices. We derive analytical results that reveal transparent links between the impact of fragmentation on firm scope, final goods prices and a shadow cost of tasks that governs firm scope along the chain.

As trade costs decrease, countries tend to move downstream along chains and to enter new chains. We illustrate our finding in a partial-equilibrium setting, holding the set of participating countries and their labor cost constant, and in a two-country general equilibrium setting. In

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<sup>6</sup>Our framework builds on that of Kikuchi et al. (2014) who model a Coasian supply chain in a 1-country partial equilibrium, assuming discrete firms. We develop a continuous firm treatment that facilitates tractable analytical solutions and calibration and extend it to a multi-country general equilibrium setting.

the latter, we also use our framework to examine the response of trade flows to trade costs, both in gross flows and value added content, and the welfare gains from trade. We compare our results to a single-stage Eaton and Kortum (2002) model: the gains from trade are relatively larger in countries that tend to specialize downstream and smaller in countries that tend to specialize upstream.

In order to explore the quantitative implications of our framework, we calibrate a numerical version of our model to match key features of input-output relationships in East Asia. This exercise relies on international input-output tables produced by IDE-JETRO. The data cover the US and nine Asian countries: Japan, China, Taiwan, Korea, Thailand, Malaysia, Singapore, Indonesia and the Philippines. This region is interesting because production fragmentation there has grown quickly and is highly prevalent. The importance of international production in the region is a primary reason for the existence of the detailed cross-country input-output data. The IDE-JETRO data are unique in that they track flows in four dimensions: from the making industry in the origin country to the using industry in the destination country.<sup>7</sup> To illustrate our findings, we adapt recently developed quantitative measures of firm position (i.e. upstreamness) so that they track the average number of international borders crossed, rather than plant boundaries as in the original. Our calculations indicate increasing international fragmentation over time, especially in key industries like electronics.

While the model has rich implications for trade and the fragmentation of production, its relative parsimony is useful for the purpose of calibration. We calibrate our model by targeting key moments such as GDP per capita, value added, countries' average position in international supply chains and gross-output-to-value-added ratios. All these moments imply large cross-country differences in productivity, transaction costs and coordination costs. We use the calibrated model to conduct counterfactual exercises regarding changes in key structural parameters. We first examine what happens when cross-border trade costs decrease by 10%. In this counter-factual simulation, we find larger gains from trade than predicted by Arkolakis, Costinot and Rodrigues-Clare (2012)'s formula (based on imported final goods), especially in downstream countries. We also examine the response in terms of the VAX ratio (the value-added content of exports) as defined by Johnson and Noguera (2012). We find that a decrease in trade costs leads to a decrease in the VAX ratio for most countries, which can be interpreted as an increase in cross-border fragmentation. In other counterfactual exercises, we simulate a 10% increase in productivity in China and a 10% decrease in Chinese transaction costs. Both shocks produce similar changes in Chinese welfare, but the shocks have different implications for other countries and for the organization of international production. The productivity shock

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<sup>7</sup>Other data that report such figures, like the World Input-Output Database (WIOD), impute these values assuming proportional treatments.

produces rather small (positive) effects on other countries' welfare. China's relative position in supply chains changes, as it moves downstream while the rest of the world moves upstream. The reduction in Chinese transaction costs has a substantially larger effect on other countries' welfare. In terms of relative position, China moves upstream, but the more important outcome appears to be a substantial lengthening of international supply chains. This is entirely consistent with the model's predictions, but the calibration teaches us that the shock to Chinese transaction costs implies relatively larger welfare gains for countries outside of China than does the Chinese productivity shock.

**Relation to the literature:** The paper contributes to the literature in two broad ways: 1) we develop a model that formalizes a role for firms (distinct from tasks) in a sequential, multi-country general equilibrium with endogenous chain length, 2) we calibrate our model and provide quantitative implications using input-output tables for East-Asian production. We discuss the literature surrounding each of these contributions in turn.

**1. Models of production chains.** An important question in the literature surrounding international production chains is the spatial organization of production across countries. Costinot et al (2012) derive an explicitly sequential multi-country model in which mistakes can occur with given probability and these mistakes destroy all accumulated value. They show that countries with relatively high probabilities of mistakes are situated upstream. The intuition for this result broadly follows Kremer (1993), that higher rates of mistakes do less damage if they occur upstream. The Costinot et al (2012) framework has no implications for the extent of fragmentation across firms and the allocation of tasks across firms.

Instead, we formalize the firm's internalization decision and endogenize the range of firms involved in the chain. The motivation for this follows Coase (1937), and our mathematical framework is inspired by Kikuchi et al (2014), who show how Coase's insights can be applied to production chains. Kikuchi et al (2014) solve their model in a sequential partial equilibrium setting, and employ discrete firms. We adapt their framework to a continuum of firms in a multi-country setting where countries differ in key parameters governing transaction costs and diseconomies of scope. As in Costinot et al (2012), we examine how countries specialize along the chain but the patterns of specialization are now driven by interactions between firm scope, transaction costs and ad-valorem trade costs affecting cross-border transactions. The Coasian structural parameters in our model offer explicit links to data objects that can be taken from input-output tables. These links make calibration of the model relatively straightforward compared to other models in the literature.

In contrast to the endogenous allocation of stages across tasks, another set of models fixes the number of production stages (Krugman and Venables 1996, Hillberry and Hummels 2002,

Yi 2003, 2010, Johnson and Moxnes 2013). The focus of this literature is often the geographic location of each production stage, relative to the other(s), and so a finite and countable number of stages is useful for analytical purposes.<sup>8</sup> Relative to our work, and others, these models avoid the question of the allocation of activities or tasks across stages, and focus on the extensive margin of completing a specific stage in a certain location. These models are also silent about why some countries specialize upstream while others are downstream.

In Yi (2010) and in Johnson and Moxnes (2013), for example, the specialization of countries along the chain is driven by exogenous productivity shocks and trade costs. Our model also contains these forces, but we introduce intra-firm coordination costs and inter-firm transaction costs as additional sources of cross-country heterogeneity. The length of production chains in our framework is also endogenous - e.g. reductions in inter-firm trade costs can expand the number of firms involved in the chain. The literature makes important insights about non-linear responses of trade to trade costs and differences between gross and VA trade. One goal of our paper is to understand the robustness of these insights to the richer theoretical structure we offer.

We adapt the Kikuchi et al. framework to a continuum of firms in a multi-country general equilibrium setting where countries differ in key parameters governing transaction costs and diseconomies of scope. As in Costinot et al. (2011), we examine how countries specialize along the chain but the patterns of specialization are now driven by interactions between firm scope, transaction costs and ad-valorem trade costs affecting cross-border transactions. It is also easier to calibrate our model. We show how input-output tables can be used to recover key parameters that govern the vertical specialization of countries and the extent of fragmentation.

**2. Quantitative implications.** A number of recent papers exploit information in input-output tables to calculate industries’ relative position in production chains, and the length of production chains. Under the assumption that the IO tables effectively summarize plant-to-plant movements for a representative firm in each industry, matrix algebra can be used to calculate, for each industry in the table, two numerical values: 1) a measure of the industries’ “distance” from final demand (where distance is a count of the number of plant boundaries that will be crossed prior to final consumption) and 2) the average number of stages embodied in an industries production. The first of these, described as “distance to final demand” in Fally (2012) and “upstreamness” in Antras et al (2012). The second was developed in Fally (2012) and computed using the BEA input-output tables for the US. Using the highly disaggregated US table, Fally (2012) finds that the two indicators are not correlated, and that the indicators do

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<sup>8</sup>Antràs and Chor (2013) offer a different perspective by taking the location and length of production chains as exogenous but examining the optimal allocation of ownership along the chain.

not appear to be especially sensitive to aggregation concerns. As yet these indicators remain relatively unconnected from the theory. One of the contributions of this paper is to derive theory that will map structural parameters onto these indicators in equilibrium.<sup>9</sup>

These mappings are useful when we calibrate the model to data on interregional input-output relationships in East Asia. A key purpose of this exercise is to offer a model comparison vis a vis other papers in the literature. A prominent literature has emphasized that intermediate goods trade magnifies the effect of trade costs on trade. Yi (2010) and Johnson and Moxnes (2013) focus on the response of trade to trade cost shocks, whereas Krugman and Venables (1996), Hillberry and Hummels (2002), Yi (2010) and Johnson and Noguera (2014) link the spatial clustering of activities to trade costs in the presence of intermediate goods trade.<sup>10</sup> Clustering occurs in our model, with sequential activities locating so as to avoid trade costs. Our calibrated model can be used to investigate the response of trade to trade cost shocks, as in Johnson and Moxnes (2013) or Yi (2010).

Our paper contributes to the quantitative literature by exploiting input-output matrices in a new way. Input-output matrices and direct requirement coefficients are traditionally taken as an exogenous recipe essentially determined by technology. Instead, we argue that input-output matrices reflect transactions in intermediate goods between firms of that are themselves endogenous economic outcomes. The tables can be informative about the position of firms within supply chains that link firms both within national borders and across them. Unlike any of the papers mentioned above, our theory also determines the allocation of tasks across firms and the length of production chains endogenously, and can thus shed some light on equilibrium input-output relationships when fragmentation is endogenous.

We also contribute to the recent literature on the welfare implications of trade cost change. Arkolakis, Costinot and Rodriguez-Clare (2012) show that a broad class of models imply the same response of welfare to trade costs, provided that the models are calibrated to generate the same trade response to trade cost change. Costinot and Rodriguez-Clare (2014) and Melitz and Redding (2014) show that welfare effects are magnified when intermediate goods trade is involved. Like other papers in the literature, the Armington framework presumes an explicit input-output relationship that governs supply chain length, in contrast to the endogenous length in our model. The Armington framework also precludes movement along the extensive margin (in terms of countries involved in supply chains), while our theory allows this. Our calibrated

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<sup>9</sup>Another contribution of the paper is to extend the indicators to describe countries' relative positions in international supply chains.

<sup>10</sup>More recently, Kee and Tang (2013), Bernard et al. (2014) and Antràs et al. (2014) have used firm-level data to examine both intensive and extensive margins in import decisions. Firm-level data, however, do not allow a full consideration of supply chains over several countries. Multi-country input-output tables are more suitable for exercises like ours.

model implies larger gains than in standard trade as described by Arkolakis et al (2012), but smaller gains than Costinot and Rodriguez-Clare (2014) or Melitz and Redding (2014).

## 2 Model setup

We develop a model where the production of each variety of final good requires a continuum of tasks and firms organized across countries. We describe, in turn, consumers' preferences in final goods, tasks and firms involved in the production of each good, the forces shaping firm scope and firm entry along the chain, the differences between varieties and the labor market.

**Preferences:** Consumers have identical Cobb-Douglas preferences over varieties of final goods indexed by  $\omega$ :

$$U = \int_{\omega} \log q^F(\omega) d\omega \quad (1)$$

where  $q^F(\omega)$  denotes quantities of final goods. All countries have access to the same set of product varieties  $\omega$  but at different prices.

**Tasks and firms along the chain:** In order to produce the final good of variety  $\omega$ , a range  $[0, 1]$  of tasks has to be performed sequentially. These tasks may be performed across different firms and different countries.

Firms are involved sequentially along the chain to produce each good  $\omega$ . A chain is specific to each variety  $\omega$  of the final good and the location of final consumers. On each chain, we assume that there is a continuum of firms indexed by  $f$ . Firms may be located in different countries. For each chain, we rank countries along the chain and index by  $i(n, \omega)$  the  $n^{th}$  country,  $i(1, \omega)$  being the most downstream country and  $i(N, \omega)$  being the most upstream country along the chain.

We denote by  $F_n(\omega)$  the range of firms involved in the chain in the  $n^{th}$  country  $i(n)$ . An elementary firm  $df$  performs a range  $s_{nf}(\omega)$  of tasks. Both the range of firms  $F_n(\omega)$  and firm scope  $s_{nf}(\omega)$  are endogenous, but the range of tasks performed across all firms must sum up to one to obtain a final good:

$$\sum_i \int_{f=0}^{F_n(\omega)} s_{nf}(\omega) df = 1 \quad (2)$$

Denoting  $S_n(\omega) = \int_{f=0}^{F_n(\omega)} s_{nf}(\omega) df$  the total range of tasks to be performed in country  $n$ , the last constraint can be rewritten:

$$\sum_n S_n(\omega) = 1$$

for all chains  $\omega$ .

**Coordination costs:** There are costs and benefits to fragmenting production across firms and countries. Fragmentation across firms reduces total costs because of diseconomies of scope. As firms need to manage employees across different tasks and perform tasks that are away from their core competencies, unit costs increase with the scope of the firm. We will refer to these costs as “coordination costs” that occur within the firm and increase with firm scope.

Formally, we assume that an elementary firm  $df$  in country  $i$  requires one unit of intermediate goods and  $c_i(s, \omega)df$  units of labor which is a function of firm scope  $s$ . The cost of labor is  $w_i$  in country  $i$  and labor is the only production input besides intermediate goods. We assume that  $c_i$  is convex in firm scope  $s$ , thus generating gains from fragmentation across firms.

In particular, we specifying the following labor requirements:

$$c_i(s, \omega) = a_i(\omega) \int_{t=0}^s t^{\theta_i(\omega)} dt$$

whereby the marginal cost of performing additional tasks within the firm increases with the distance  $t$  from the first task. This follows, for instance, recent work on the division of labor (Chaney and Ossa, 2013) and in this context represents the productivity loss associated with movement away from the firm’s core competencies. After integrating and multiplying by the cost of a unit of labor in country  $i$ , the cost function writes:

$$w_i c_i(s, \omega) = w_i a_i(\omega) \frac{s^{\theta_i(\omega)+1}}{\theta_i(\omega) + 1} \quad (3)$$

where  $a_i(\omega)$  and  $\theta_i(\omega)$  are specific parameters for each country  $i$  for variety  $\omega$ . Note however that  $a_i(\omega)$  and  $\theta_i(\omega)$  are constant along the chain (for a given country). In particular,  $\theta_i(\omega)$  parameterizes “coordination costs” and the convexity of the cost function. The higher is  $\theta_i(\omega)$ , the higher is the increase in costs when firms need to manage a larger range of tasks.<sup>11</sup>

**Transaction costs:** Fragmenting production across firms incurs transaction costs. We model transaction costs like iceberg transport costs in standard trade models. More specifically, a transaction in country  $i$  with an elementary firm  $df$  involves losing a fraction  $\gamma_i df$  of the good.

$$q_{i,f+df}(\omega) = q_{i,f}(\omega) (1 + \gamma_i df) \quad (4)$$

Within each country, quantities thus follow a simple evolution depending on transaction costs  $\gamma_i$  and the position on the chain  $f$ . As we go upstream, quantities increase exponentially

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<sup>11</sup>Note that we assume diseconomies of scope but constant returns to scale in production. This differs from Chaney and Ossa (2013) and more closely follows Kikuchi et al (2014). In keeping with Kikuchi et al (2014), this framework allows us to examine patterns of fragmentation across firms while keeping a perfectly-competitive framework where the competitive allocation of tasks across firms is optimal.

with the number of firms  $f$  to cross along the chain:

$$q_{i,f}(\omega) = e^{\gamma_i f} q_{i,0}(\omega) \quad (5)$$

Since part of the production is lost when transactions occur, upstream firms must produce larger quantities. The necessary increase in quantities is starker when transaction costs are high and when the chain is more fragmented.

In a similar fashion, a *cross-border* transaction between two consecutive countries  $i = i(n)$  and  $j = i(n+1)$  along the chain involves an iceberg trade cost  $\tau > 1$  such that:

$$q_{j,0}(\omega) = \tau q_{i,F}(\omega) \quad (6)$$

where  $q_{j,0}(\omega)$  denotes the quantities produced by the most downstream plant in the upstream country  $j$  and  $q_{i,F}(\omega)$  denotes quantities produced by the next plant, i.e. the most upstream plant in the next country along the chain going downstream. For simplicity, we assume away other geographical elements than borders and impose a common border cost. Here, quantities also increase exponentially as we cross borders along the chain.

**Market structure:** In addition to assuming constant returns to scale in production, we assume perfect competition. In this setup, the market equilibrium and the optimal allocation correspond to the social optimum.<sup>12</sup>

**Prices along the chain:** The price of intermediate goods is thus equal to their unit cost of production. Here, this cost accounts for all transaction costs incurred along the chain (going upstream) and the labor costs incurred by each firm. Within country borders, the price of intermediate goods satisfies the following differential equation which describes its evolution along the chain:

$$p_{fi}(\omega) = w_i c_i(s_{fi}) df + (1 + \gamma_i df) p_{i,f+df}(\omega) \quad (7)$$

where  $c_i(s_{fi})$  denotes the cost of performing a range  $s_{fi}$  of tasks at stage  $f$  in country  $i$  as specified above. This equation is close to Costinot, et al. (2012) and also features increasing intermediate goods prices as we go downstream. A key difference, however, is that the labor share is endogenous since  $s_{nf}$  is endogenous and thus not simply driven by differences in input prices along the chain. In particular, the cost of inputs by unit of labor is no longer necessarily

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<sup>12</sup>While there are decreasing return to scale in terms of firm scope, there are constant returns to scale in production in terms of quantities. The equilibrium under perfect competition corresponds to the social optimum. This insight follows Kikuchi et al (2014) generalized to a multi-country setting with heterogenous costs and a continuum of firms.

larger for downstream firms. Many of the results in Costinot et al (2012) are driven by this feature and thus no longer hold in our framework.

Across borders, the price is simply multiplied by the international trade cost  $\tau$ :

$$p_{j,F}(\omega) = \tau p_{i,0}(\omega) \quad (8)$$

for cross-border transactions from the most downstream plant in  $j$  to the most upstream plant in  $i$ .

**Industry heterogeneity:** While the previous assumptions are sufficient to generate interesting patterns of specialization along a particular chain, we still need to specify how chains vary across varieties. Following Eaton and Kortum (2002), we assume that labor efficiency is a random variable drawn independently across varieties and countries. Specifically, we assume that the labor cost parameter  $a_i(\omega)$  is drawn from a Frechet distribution as in Eaton and Kortum (2002). For each country  $i$ , the cumulative distribution function for  $a_i$  is:

$$Proba(a_i < a) = 1 - e^{-T_i a^\xi} \quad (9)$$

where  $T_i$  parameterizes the country average productivity and where  $\xi$  is inversely related to productivity dispersion.<sup>13</sup> Note that  $a_i(\omega)$  is thus constant along the chain for a specific country and variety  $\omega$ . Unlike Yi (2003, 2010), Rodriguez-Clare (2010) and Johnson and Moxnes (2013), our framework does not require  $a_i(\omega)$  to differ across tasks along the chain to generate trade in intermediate goods.

Another component of the cost function is  $\theta_i(\omega)$ . We will explore different settings. In section 4.1 we simply consider two countries  $U$  and  $D$ : one where  $\theta_U(\omega) = \theta_U$  across all varieties, and another country with  $\theta_D(\omega) = \theta_D < \theta_U$  across all varieties. In sections 4.2 and 5 (calibration exercise), we allow  $\theta_i(\omega)$  to vary across countries and varieties. Specifically, we assume that  $\theta_i(\omega)$  is log-normally distributed with a country-level shifter  $\bar{\theta}_i$  and a common standard deviation.

**Labor supply:** Finally, to close the model, we assume that workers are homogenous and perfectly mobile within each country, with an inelastic supply of labor  $L_i$  in country  $i$ . By Walras' law, trade is balanced.

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<sup>13</sup>Parameter  $\xi$  corresponds to the notation  $\theta$  in Eaton and Kortum (2002).

### 3 Partial equilibrium: optimal organization of chains

In this subsection, we take wages  $w_i$  as given and focus on the optimal fragmentation and location of production for a specific chain corresponding to a final good variety  $\omega$ . For the sake of presentation, we drop the index  $\omega$ . The reader should keep in mind, however, that the optimal fragmentation and allocation of value across firms, as well as costs parameters  $a_i$  and  $\theta_i$ , are all specific to each variety of final good  $\omega$ .

For a given chain, we can formulate the equilibrium as the solution to a social planning problem. Given our assumption of perfect competition and constant returns to scale, prices equal unit costs and the competitive equilibrium corresponds to the social optimum.

Let us denote by  $i(n)$  the ranking of countries along the chain, with  $i(1)$  being the most downstream country and  $i(N)$  the most upstream country, assuming that  $N$  countries are involved in the chain. One should keep in mind that the ranking of countries is an equilibrium outcome that we will characterize subsequently. In partial equilibrium (i.e. for a given variety, taking wages as given), the optimal organization of chains minimizes the price of the final good. Hence equilibrium can be summarized by the following optimization problem:

$$\begin{aligned}
 & \min P_1 \tag{10} \\
 & \text{over: } i(n), s_{nf}, F_n, S_n, P_n \\
 & \text{under the constraints: } P_n = \left[ \int_{f=0}^{F_n} e^{\gamma_{i(n)} f} c_{i(n)}(s_{nf}) df + e^{\gamma_{i(n)} F_n} \tau P_{n+1} \right] \\
 & S_n = \int_{f=0}^{F_n} s_{nf} df \\
 & \sum_{i=1}^N S_n = 1
 \end{aligned}$$

where  $N$  is the optimal number of countries involved in the chain and  $P_n \equiv p_{0,n}$  denotes the price at the most downstream stage in country  $i(n)$  at the  $n^{th}$  position. Recall that exponential terms  $e^{\gamma_{i(n)} f}$  reflect the evolution of quantity requirements along the chain as described in equation (5). The transaction cost parameter  $\gamma_{i(n)}$  and the cost function  $c_{i(n)}(s)$  are indexed by  $i(n)$  because they depend on which country  $i(n)$  is at the  $n^{th}$  position upstream. As an abuse of notation,  $P_{N+1}$  refers to the price of the most upstream good and is set to zero.<sup>14</sup>

Chains are optimized along several dimensions. Choice variables include firm scope  $s_{i,f}$ , the range of firms  $F_i$  in the chain in each country and the range of tasks  $S_i$  to be performed in each country. The ranking of countries along the chain, from most downstream  $i(1)$  to most

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<sup>14</sup>Alternatively, we could set an exogenous price  $P_{N+1} = \bar{p}$  of the most upstream good reflecting the price of primary commodity such as oil and minerals available from an outside economy in exchange of final goods.

upstream  $i(N)$ , is itself an endogenous outcome described below.<sup>15</sup>

### 3.1 Fragmentation of production within countries

Before turning to the cross-border organization of chains, we focus on optimal fragmentation within each country. The optimization problem described in (10) can be formulated as a nested optimization problem. In the inner nest, firms in a specific country  $i$  are organized to minimize the price of goods exported by country  $i$  conditional on the overall range of tasks  $S_i$  to be performed in  $i$  and  $P_i^M$  the price of intermediate goods imported by country  $i$ . The outer nest allocates stages across countries to minimize the cost of producing the final good. Here we focus on the inner nest that optimizes within country  $i$ .

The price  $P_i$  can be expressed as the solution of the following optimization:

$$\tilde{P}_i(S_i, P_i^M) = \min_{s_{fi}, F_i} \left[ \int_{f=0}^{F_i} e^{\gamma_i f} w_i c_i(s_{fi}) df + e^{\gamma_i F_i} P_i^M \right] \quad (11)$$

under the constraint:

$$\int_{f=0}^{F_i} s_{fi} df = S_i \quad (12)$$

To examine the optimal allocation of tasks across firms and the optimal range of firms, it is useful to introduce the Lagrange multiplier  $\lambda_i$  associated with the constraint  $\int_0^{F_i} s_f df = S_i$ .

The first-order conditions of this planning program are:

$$\text{For } s_{fi} : \quad e^{\gamma_i f} w_i c'_i(s_{fi}) = \lambda_i \quad (13)$$

$$\text{For } F_i : \quad e^{\gamma_i F_i} w_i c_i(s_{i, F_i}) + e^{\gamma_i F_i} P_i^M \gamma_i = s_{i, F_i} \lambda_i \quad (14)$$

The first of these conditions is central to an understanding of the role of Coasian behavior in the model. On the left hand side is the marginal cost of increasing firm scope for firm  $f$ . On the right hand side is  $\lambda_i$ , the Lagrange multiplier on the staging constraint (equation 12). At the optimum,  $s_{if}$  is chosen to equalize the cost of the marginal task and the shadow price,  $\lambda_i$ , which reflects the burden associated with accomplishing the marginal task elsewhere. In this formulation, the internalization decision (which is conditional on Coasian transaction and coordination cost parameters) also depends on a variable that summarizes an implicit return to internalization.<sup>16</sup>

<sup>15</sup>We can either interpret this optimization from the point of view of the most downstream country, in which case  $i(1)$  is fixed, or we can optimize from the point of view of the consumer, in which case the final good price needs to be multiplied by trade costs  $\tau$  if the optimum location  $i(1)$  is different from the location of the final consumers.

<sup>16</sup>Our Lagrangian formulation in (3.1) generalizes the condition  $\delta c'(s_{f+1}) = c'(s_f)$  in Kikuchi et al (2014)

Not only does (3.1) help us to address the behavior of a single firm, it also offers key insights into the arrangement of production across multiple firms. The condition defines a shadow market for tasks, with all firms in the chain providing tasks such that their marginal costs of tasks equal the shadow price of a task,  $\lambda_i$ . In this way the Coasian conditions that determine the scope of individual firms also define the allocation of tasks across firms that minimizes the cost of producing a given measure of stages  $S_i$  in country  $i$ .

Moreover, these equilibrium conditions offer further insights about the relationship between firm heterogeneity and relative position along the chain. A move upstream (i.e. towards higher index  $f$ ) increases required quantities  $e^{\gamma_i f}$ , which can only be balanced by a reduction in the marginal cost  $c'_i(s_{if})$  and thus firm scope  $s_{if}$  falls with a move upstream. Hence, in equilibrium, (3.1) shows that more upstream firms have smaller firm scope and provide less value added. We can be more explicit about this using our parameterization:  $c'_i = a_i s_{if}^{\theta_i}$ , which implies that firm scope is log-linear in upstreamness  $f$ :

$$\frac{\partial \log s_{fi}}{\partial f} = -\frac{\gamma_i}{\theta_i} \quad (15)$$

The second of the first order conditions, (14) is not as central to the intuition of the model but nonetheless aids us greatly in the derivation of closed-form solutions of the model. The first-order condition in  $F_i$  relates firm scope for the most upstream firm to the Lagrange multiplier and to the price of intermediate goods purchased from firms in the next upstream country. By manipulating the first-order condition in  $F_i$ , we obtain firm scope for the most upstream firm in  $i$ :

$$s_{i,F_i} = \left[ \frac{(\theta_i + 1)\gamma_i}{\theta_i} \frac{P_i^M}{a_i w_i} \right]^{\frac{1}{\theta_i + 1}} \quad (16)$$

We can also use this expression to obtain  $F_i$  as a function of the Lagrange multiplier.

Finally, the shadow cost of fragmentation (Lagrange multiplier  $\lambda_i$ ) is the solution of the constraint  $\int_0^{F_i} s_{if} df = S_i$  using the solutions (above) for  $s_{if}$  and  $F_i$  as a function of  $\lambda_i$ . We find that the shadow cost of fragmentation is:

$$\lambda_i = w_i a_i \left[ \frac{\gamma_i S_i}{\theta_i} + \left( \frac{(\theta_i + 1)\gamma_i}{\theta_i} \frac{P_i^M}{a_i w_i} \right)^{\frac{1}{\theta_i + 1}} \right]^{\theta_i} \quad (17)$$

It increases with all cost parameters  $a_i$ ,  $\theta_i$ ,  $\gamma_i$  and with the price of intermediate goods  $P_i^M$  as well as the range of tasks to be performed  $S_i$ . Note also that the shadow cost also corresponds

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that links the marginal costs of tasks between (discrete) firms  $f$  that neighbor one another in the chain.

to the derivative of the price  $P_i$  w.r.t. the range of tasks  $S_i$ :

$$\lambda_i = \frac{\partial \tilde{P}_i}{\partial S_i} \quad (18)$$

Having solved for the shadow cost of fragmentation, we can now solve for the price of the last-stage goods  $P_i$ , the extent of fragmentation  $F_i$  in country  $i$  and firm scope  $s_{if}$  across all firms  $f$  within the country. We also examine the (endogenous) intensity in intermediate goods at each stage.

**Firm scope:** Firm  $f$  along the chain has a scope  $s_{if}$  given by:

$$\log s_{if} = -\frac{\gamma_i}{\theta_i} f + \log s_{i,0} \quad (19)$$

where  $s_{i,0}$  is the most downstream firm scope. We find:  $s_{i,0} = \frac{\gamma_i S_i}{\theta_i} + \left( \frac{(\theta_i+1)\gamma_i}{\theta_i} \frac{P_i^M}{a_i w_i} \right)^{\frac{1}{\theta_i+1}}$  while the most upstream firm has a scope  $s_{i,F_i} = \left( \frac{(\theta_i+1)\gamma_i}{\theta_i} \frac{P_i^M}{a_i w_i} \right)^{\frac{1}{\theta_i+1}}$ . Combining these gives a linear relationship between the scope of the most downstream and upstream firms in country  $i$  that is informative about within-country heterogeneity of firm scope:

$$s_{i,0} - s_{i,F} = \frac{\gamma_i}{\theta_i} S_i \quad (20)$$

Heterogeneity of firm scope within a country is rising in  $S_i$  because more tasks produced in country  $i$  implies more firms, and thus more room for heterogeneity, conditional on  $\theta_i$  and  $\gamma_i$ . Larger values of transaction costs  $\gamma_i$  imply more heterogeneity in firm scope because upstream firms must reduce  $s_{if}$  relatively more to satisfy equation (3.1). Larger values of  $\theta_i$  imply that scope remains more uniform across firms.

Of further interest is the relative price of intermediate goods relative to labor costs  $\frac{P_i^M}{a_i w_i}$ . Firm scope of both the most up- and downstream firms are rising in this ratio. The intuition for this is that when the price of intermediates is relatively high, the cost of outsourcing is relatively higher and firms will choose to add more value in-house. Conversely, when labor costs are high, firms will produce relatively few stages before outsourcing to upstream firms.

**Price:** First, we find that the price of the most downstream good in country  $i$ , the solution of the minimization program (11), is:

$$P_i = \tilde{P}_i(S_i, P_i^M) = \left[ \frac{S_i}{\theta_i+1} (A_i w_i)^{\frac{1}{\theta_i+1}} + (P_i^M)^{\frac{1}{\theta_i+1}} \right]^{\theta_i+1} \quad (21)$$

expressed as a function of the synthetic parameter  $A_i$ :

$$A_i = a_i \left( \gamma_i \frac{\theta_i + 1}{\theta_i} \right)^{\theta_i} \quad (22)$$

which depends itself on exogenous country-specific parameters  $\theta_i$  (curvature of cost function),  $a_i$  (direct cost parameter) and  $\gamma_i$  (transaction cost). Parameter  $A_i$  reflects the effective labor productivity in country  $i$ . Note that, conditional on  $A_i$ , prices no longer depend on transaction costs  $\gamma_i$ . The price mimics a CES production function with two inputs: imported intermediate goods and labor, where the weight for labor depends on the range of tasks, productivity, transaction costs and coordination costs. The apparent elasticity of substitution is  $\theta_i + 1$ . When coordination costs  $\theta_i$  are larger, production has to be more fragmented and there is a larger amount of production lost in transaction costs. These costs are larger when the price of intermediate goods  $P_i^M$  is high.

**Labor demand:** Each unit of last-stage good produced in country  $i$  generates the following demand for labor in  $i$ :

$$w_i L_i^D = \frac{S_i}{\theta_i + 1} (A_i w_i)^{\frac{1}{\theta_i + 1}} \left[ \frac{S_i}{\theta_i + 1} (A_i w_i)^{\frac{1}{\theta_i + 1}} + (P_i^M)^{\frac{1}{\theta_i + 1}} \right]^{\theta_i} \quad (23)$$

**Imported intermediate goods demand:** Each unit of last-stage good produced in country  $i$  also generates the following demand for the most upstream intermediate goods:

$$\frac{q_{i,F_i}}{q_{i,0}} = e^{\gamma_i F_i} = \left( \frac{P_i}{P_i^M} \right)^{\frac{\theta_i}{\theta_i + 1}} \quad (24)$$

which depends positively on the price of the produced good  $P_i$  and negatively on the price of imported goods  $P_i^M$ . In terms of value rather than quantities, we obtain that the share of imported inputs in the total cost of production in country  $i$  is:

$$\frac{P_i^M q_{i,F_i}}{P_i q_{i,0}} = \frac{(P_i^M)^{\frac{1}{\theta_i + 1}}}{\frac{S_i}{\theta_i + 1} (A_i w_i)^{\frac{1}{\theta_i + 1}} + (P_i^M)^{\frac{1}{\theta_i + 1}}} \quad (25)$$

Like the price of the produced good, this cost share expression mimics a CES production function. Intuitively, the share of labor (one minus the expression above) depends positively on the range of tasks to be performed as well as the price of intermediate goods. Note that it

is also equal to the elasticity of the price in Equation (21) w.r.t. the price of imported goods:

$$\frac{P_i^M q_{i,F_i}}{P_i q_{i,0}} = \frac{\partial \log \tilde{P}_i}{\partial \log P_i^M} \quad (26)$$

This equality is useful for understanding the first-order conditions of the cross-border optimization problem described in the following section.

**Gross-output-to-value-added ratio:** We define gross output as:  $GO_i = \int_0^{F_i} p_{fi} e^{\gamma_i f} df$  by integrating the value of all transactions along the chain, while total value added by country  $i$  corresponds to:  $VA_i = \int_0^{F_i} c_i(s_{fi}) e^{\gamma_i f} df$ . The ratio of these two variables has a useful empirical counterpart since it is readily available in typical input-output tables provided by statistical agencies. Here, we find that the GO-VA ratio equals:

$$\frac{GO_i}{VA_i} = \frac{\theta_i}{\gamma_i} \quad (27)$$

Strikingly, this result also holds at the firm level. To be more precise, we obtain that the ratio of price to cost at each stage is constant and equal to:

$$\frac{p_{if}}{w_i c_i(s_{fi})} = \frac{\theta_i}{\gamma_i} \quad (28)$$

We can interpret this ratio as an index of fragmentation at the firm level. In particular, this ratio reflects the two key forces present in our model: stronger diseconomies of scope and coordination costs  $\theta_i$  lead to more fragmentation while larger transaction costs  $\gamma_i$  leads to less fragmentation. As seen in equations (19) and (20), this ratio also dictates the difference in scope between upstream and downstream firms.

**Free entry and cost decomposition:** We can also use (28) to better understand the link between our model and perfect competition, as well as the nature of the growth in output prices along the chain. Perfect competition implies that firms' average and marginal costs of producing a stage will be equalized along the chain. If average costs exceed marginal costs firms can reduce costs by expanding their scope. If marginal costs exceed average costs there will be entry and firms will reduce their average scope. Applying (28) and (), we can equate average and marginal cost for firm  $f$ , and link these to the shadow cost (per unit of quantity)

$$\frac{w_i c'_i(s_{i,f}) + \gamma_i p_{fi}}{s_{i,f}} = w_i c'_i(s_{i,f}) = \lambda_i e^{-\gamma_i f}. \quad (29)$$

It is also useful to decompose the sources of costs in the left-hand-side term of (29). Average cost has two components: labor costs associated with producing tasks inside the firm and transaction costs linked to shipments between firms. A decomposition exercise highlights the central role of the coordination cost parameter  $\theta_i$ , and will be useful in a later discussion of comparative advantage. Using (28), we solve for changes in average cost as we move along the implicit price function.

$$\frac{\gamma_i p_{fi}}{w_i c_i(s_{fi}) + \gamma_i p_{fi}} = \frac{\theta_i}{\theta_i + 1} \quad (30)$$

The contribution of input prices to total cost growth is solely a function of  $\theta$ . The share of labor costs is, by implication:  $\frac{1}{\theta_i + 1}$ . A notable outcome in this calculation is the absence of a role for  $\gamma_i$  in the decomposition of cost growth, which arises because firms react to higher values of  $\gamma_i$  by bringing more stages inside the firm. We revisit this issue when we describe comparative advantage within the supply chain.

**Firms versus tasks:** The mass of firms involved sequentially in production also offers an overall index of fragmentation for the chain. For a given price  $P_i^M$  of imported intermediate goods and range  $S_i$  of tasks to be performed, we obtain:

$$F_i = \frac{\theta_i}{\gamma_i} \log \left[ 1 + \frac{S_i}{\theta_i + 1} \left( \frac{A_i w_i}{P_i^M} \right)^{\frac{1}{\theta_i + 1}} \right] \quad (31)$$

The number (i.e. mass) of firms involved sequentially in production depends negatively on the price of intermediate goods because more expensive components also make transactions more costly since transactions costs depend on the total value of the good. The number of firms also depends negatively on transaction costs and positively on  $\theta_i$  the parameter for diseconomies of scope.

In addition, we can examine the (endogenous) mass of firms to complete a specific range of tasks at any point on the chain. In our framework with a continuum of tasks and a continuum of firms, the mass of firms needed by unit of tasks is the inverse of the range of tasks  $s_f$  performed by firm  $f$ . The integral of the  $1/s_f$  across all tasks corresponds to the total mass of firms involved in the chain. For each country  $i$ :  $\int_0^{S_i} \frac{1}{s_f(\bar{s})} d\bar{s} = F_i$  if we integrate along the chain.

These various indexes to document the extend of fragmentation are summarized in the following lemma:

**Lemma 1** *Production fragmentation within countries – captured either by the GO/VA ratio or by the range of firms involved in the chain – increases with coordination costs  $\theta_i$  and decreases with transaction costs  $\gamma_i$ . In particular, the GO/VA ratio equals  $\frac{\theta_i}{\gamma_i}$ .*

### 3.2 Cross-border fragmentation

Now that we have described the allocation of tasks along the chain within borders, we turn to the optimal allocation of tasks and firms across borders. In particular, we need to characterize the ordering of countries  $i(n)$  on the chain, with  $i(1)$  being the most downstream and  $i(N)$  the most upstream country.<sup>17</sup>

Given the optimal fragmentation of production across firms in each country  $i = i(n)$ , summarized by the price function from equation (21):  $\tilde{P}_i(S, P^M)$ , the optimal global value chain corresponds to the following minimization program:

$$\min P_1 \tag{32}$$

under the constraints:

$$P_n = \tilde{P}_{i(n)}(S_n, \tau P_{n+1}) \quad \text{and} \quad \sum_{i=n}^N S_n = 1$$

and where the function  $\tilde{P}_i(S, P^M)$  is the solution of the optimization described in equation (21) in the previous section:

$$\tilde{P}_i(S, P^M) = \left[ \frac{S}{\theta_i + 1} (A_i w_i)^{\frac{1}{\theta_i + 1}} + (P^M)^{\frac{1}{\theta_i + 1}} \right]^{\theta_i + 1} \tag{33}$$

For a given sequence of countries  $i(n)$ , we can go quite far in characterizing prices, range of tasks and labor demand along the chain. First, it is useful to explicitly express the Lagrangian:

$$\mathcal{L} = P_1 - \sum_{n=1}^N q_n \left[ P_n - \tilde{P}_{i(n)}(S_n, \tau P_{n+1}) \right] - \lambda_G \left[ \sum_{n=1}^N S_n - 1 \right] \tag{34}$$

The Lagrange multipliers associated with price equations correspond to quantities required for each unit of final good. To be more precise,  $q_n$  correspond to quantities  $q_{i(n),0}/q_{i(1),0}$  required at the most downstream task performed in the  $n^{th}$  country  $i(n)$  per unit of final good  $q_{i(1),0}$ . The first-order condition  $\frac{\partial \mathcal{L}}{\partial P_{n+1}} = 0$  is equivalent to imposing  $q_{n+1} = \tau q_n e^{\gamma_{i(n)} F_n}$  (using the price derivative described in equation 26).

The first-order condition  $\frac{\partial \mathcal{L}}{\partial S_n} = 0$  associated with the range of tasks  $S_n$  yields that the marginal cost of producing an additional task is equalized across countries, up to quantities  $q_n$ :

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<sup>17</sup>Recall that we drop for now the variety subscript  $\omega$  while most parameters vary across varieties.

$\lambda_G = q_n \frac{\partial \tilde{P}_{i(n)}}{\partial S_n}$ . Using the price derivative from equation (18), it also implies:

$$q_i \lambda_i = q_j \lambda_j \quad (35)$$

for any pair of countries  $i$  and  $j$  along the chain, where  $\lambda_i$  is the shadow cost of fragmentation within country  $i$  (per unit of goods exported by the country). This equality, which reflects the optimal allocation of tasks across countries, has a simple interpretation: at the optimum, the marginal cost of completing another task should be equalized across all countries on the chain. This marginal cost equals the shadow cost of fragmentation  $\lambda_i$  in country  $i$  times the quantities of intermediate goods  $q_i$  to be produced by  $i$ .

The tight links between the Lagrange multipliers in successive countries serves to link the shadow price of stages across markets. In this manner, Coasian behavior is linked across markets and the activities of firms in different countries coordinated by the shadow market for stages. The shadow price of stages, discounted by quantities, is determined jointly in international equilibrium. At the same time, these shadow prices pin down behavior of firms across countries, so that the entire chain is produced at minimum cost.

Since a move upstream along the chain increases quantities (because of transaction costs and cross-border trade costs), the shadow price  $\lambda_{i(n)} > \lambda_{i(n+1)}$  must decrease. Concretely, a first implication is that firm scope tends to decrease as we go upstream, not just within countries but also across countries. The F.O.C. in  $S_i$  implies the following expression which generalizes equation (3.1) across countries along the chain:

$$q_n e^{\gamma_{i(n)} f} w_{i(n)} c'_{i(n)}(s_{nf}) = \lambda_G \quad (36)$$

where  $q_n e^{\gamma_{i(n)} f}$  corresponds to the quantities of intermediate goods required for each unit of final good. Since the latter increases with upstreamness, we obtain that firm scope  $s_{nf}$  would be smaller if a country  $i = i(n)$  specializes upstream than if it specializes downstream. Therefore, a country with large within-firm coordination costs would have a relatively larger cost downstream than upstream compared to a country with low coordination costs.<sup>18</sup>

This feature has important implications for the sorting of countries along the chain. Because firm scope can be smaller upstream, diseconomies of scope have a smaller impact on upstream stages than downstream stages. Hence, we should then expect countries with high- $\theta$  to specialize upstream while low- $\theta$  countries tend to specialize downstream. Formally, we can confirm

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<sup>18</sup>Note, however, that firm scope does not necessarily increase across countries as we go upstream since firm scope also depends on transaction costs. We find that transaction-costs-adjusted firm scope  $\frac{s_{if}}{\gamma_i}$  decreases with a move upstream, but firm scope is not necessarily lower in a country specializing upstream than in a country specializing downstream.

this insight by examining second-order conditions of the optimization problem described in Equation (32), which yields the following Proposition:

**Proposition 1** *Let us denote by  $i(n)$  the ranking of countries involved in the same production chain,  $i(1)$  being the most downstream and  $i(N)$  the most upstream country. In equilibrium, the relative position of countries along the chain is fully determined by coordination costs  $\theta_i$ ; countries with smaller coordination costs specialize downstream:*

$$\theta_{i(1)} < \theta_{i(2)} < \dots < \theta_{i(N)}$$

Proposition 1 describes comparative advantage within a supply chain, conditional on a country's participation in the chain. Two implications are of primary interest here: the central role of  $\theta_i$  in determining within-chain comparative advantage, but also the absence of a role for the transaction cost parameter  $\gamma_i$ . The lack of a role for  $\gamma_i$  would seem to run counter to Costinot et al. (2011), where cross-country differences in the rates of mistakes in production drive comparative advantage within the chain. The closest counterpart in our model to the mistakes in Costinot et al. (2011) is the  $\gamma_i$  parameter.<sup>19</sup>

What our model shares with Costinot et al. (2011) is the dependence of comparative advantage on the parameter that determines the convexity of the price function as the value accumulates along the chain. In both models, prices are increasing at an increasing rate as the measure of completed tasks increases. In Costinot et al. (2011), convexity arises because the losses due to mistakes are a constant proportion of the value of gross output, and the value of gross output is rising along the chain. In our model, coordination costs are the key source of convexity. In both frameworks, the less convex the cost growth in a country, the further downstream it will be.

Another way to see this is to exploit the insights in Costinot (2009), who links comparative advantage to the mathematics of log super-modularity. The accumulation of value added along the chain insures that the cost of intermediate goods is rising along the chain. This means that if production costs are log-supermodular in a parameter and input prices, then countries that have low values of that parameter will locate downstream. Using previous results on costs decomposition (equation 30), we find:

$$\frac{\partial \log \left\{ \frac{w_i c_i(s_{fi}) + \gamma_i p_{fi}}{s_{fi}} \right\}}{d \log p_{fi}} = \frac{\gamma_i p_{fi}}{w_i c_i(s_{fi}) + \gamma_i p_{fi}} = \frac{\theta_i}{1 + \theta_i}. \quad (37)$$

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<sup>19</sup>Costinot et al. (2011) offer cross-country differences in contract enforcement as a rationale for differences in the rates of mistakes. The parameter in our framework most closely related to contract enforcement is clearly  $\gamma_i$ .

In Costinot et al. (2011),  $s_{fi}$  is fixed, so average cost is log supermodular in  $p_{fi}$  and  $\gamma_i$ . The middle term  $\frac{\gamma_i p_{fi}}{w_i c_i(s_{fi}) + \gamma_i p_{fi}}$  would be increasing in  $\gamma_i$  if firm scope is fixed. This implies that transaction costs  $\gamma_i$  have the least impact on average cost when  $p_{fi}$  is low (i.e. early in the chain), so that lower transaction costs create a comparative advantage in downstream tasks.

In contrast,  $\gamma_i$  does not appear in (37), and thus does not affect comparative advantage within the chain. The simple explanation is that in our model, firm scope is endogenous to changes in  $\gamma_i$ ; in countries with larger transaction costs, firms will endogenously increase firm scope to mitigate the role of higher transaction costs. These endogenous responses nullify the role that transaction cost would otherwise play in convexifying the price function, and so  $\gamma_i$  has no role in determining comparative advantage within the chain. Instead,  $\theta_i$  plays a singular role in determining countries' positions within the chain. As described in equation (37), the cost of performing a task is log-supermodular in input prices and  $\theta_i$ . This explains Proposition 1: countries with higher coordination costs  $\theta_i$  should specialize upstream to mitigate the effect of input prices on value added.<sup>20</sup>

**Equilibrium allocation of tasks across countries:** Given the ranking of countries described in Proposition 1, we now describe the range of tasks performed by each one. Using marginal conditions imposed by the optimization problem, we can also determine prices and firm scope along the chain depending on wages and relative productivity. Specifically, the first-order conditions determine the c.i.f. price between consecutive countries  $i(n)$  and  $i(n+1)$ . First-order conditions between three consecutive countries  $i(n-1)$ ,  $i(n)$  and  $i(n+1)$  then yield the range of tasks performed in  $i(n)$ . Denoting  $A_n$ ,  $w_n$  and  $\theta_n$  the productivity, wages and the coordination cost parameter in the  $n^{th}$  country  $i(n)$  along the chain, we obtain:

$$\begin{cases} \tau P_{n+1} &= (A_n w_n)^{\frac{\theta_{n+1}+1}{\theta_{n+1}-\theta_n}} (\tau A_{n+1} w_{n+1})^{-\frac{\theta_{n+1}}{\theta_{n+1}-\theta_n}} \\ \frac{S_n}{\theta_{n+1}} &= \left( \frac{A_{n-1} w_{n-1}}{\tau A_n w_n} \right)^{\frac{1}{\theta_n - \theta_{n-1}}} - \left( \frac{A_n w_n}{\tau A_{n+1} w_{n+1}} \right)^{\frac{1}{\theta_{n+1} - \theta_n}} \end{cases} \quad (38)$$

where  $\tau$  is the trade cost between any two countries.

Given the range of tasks performed in country  $i(n)$ , it is interesting to derive the share of local labor in exports to the next country in the chain. Because ours is a single-factor model, this corresponds to the value added locally in the exports of country  $i(n)$ , a key statistic for

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<sup>20</sup>A related implication is that there will be no international fragmentation without cross-country variation in  $\theta_i$ . Also, Proposition 1 has implications for back-and-forth trade between countries. In this model, a good may be shipped as an intermediate good and back to the country as a final good for consumers, but the model does not allow back-and-forth trade along the chain. The condition on the ranking of  $\theta_i$  prevents a downstream country  $\theta_{i-1}$  from shipping a good back to upstream country  $i$ . In section 3.5, we develop an extension of the model where countries are more productive for some tasks than other where the position of countries may be altered.

economic policy.<sup>21</sup> Here, we find that the demand for labor (in value) in country  $i(n)$  per dollar of good exported to the next country  $i(n-1)$  in the chain is:

$$\frac{w_i l_i}{P_i} = 1 - \left( \frac{w_i A_i}{\tau w_{i+1} A_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}} \left( \frac{\tau w_i A_i}{w_{i-1} A_{i-1}} \right)^{\frac{1}{\theta_i - \theta_{i-1}}} \quad (39)$$

Intuitively, the share of local value added in exports is higher when the relative labor cost is lower, as lower labor costs allows the country to serve as the low cost location for a larger measure of stages. This operates through margins upstream and downstream. A lower labor cost makes country  $i(n)$  more competitive at the margin than the previous upstream country  $i(n+1)$  as well as the next country  $i(n-1)$  downstream.

The effect of trade costs on this statistic also operates through two channels: higher trade costs reduce the contribution of country  $i(n)$  in the downstream country  $i(n-1)$  operations, but they also reduce the upstream country's contribution. For a country in the middle of the chain, trade costs have a positive effect on local labor content only if there are stronger complementarities with downstream rather than upstream countries, i.e. when the differences in  $\theta_n$  are larger with the downstream country than with the upstream country:  $\theta_n - \theta_{n-1} > \theta_{n+1} - \theta_n$ .

Conditional on the set of countries  $i = 1, 2, \text{etc.}$  participating (with  $\theta_i$  increasing with  $i$  along the chain), we can go further and obtain a simple expression for the price of final goods (i.e. price of downstream goods in country 1) as a function of costs parameters  $A$ ,  $\theta$  and wages  $w$ . Conditional on the set of countries, we can also derive simple expressions for the share of labor costs from a specific country.

**Lemma 3** *Conditional on the set of countries  $i = 1, 2, \text{etc.}$  participating (with  $\theta_i$  increasing with  $i$  along the chain), the price of the final good is:*

$$P_1 = \frac{A_1 w_1}{(\theta_1 + 1)^{\theta_1 + 1}} \Theta(\mathbf{wA}, \tau) \quad (40)$$

where  $\Theta(\mathbf{wA}, \tau) < 1$  captures the gains from fragmentation for the chain:

$$\Theta(\mathbf{wA}, \tau) = \left[ 1 - \sum_{n=1}^{N-1} (\theta_{n+1} - \theta_n) \left( \frac{w_n A_n}{\tau w_{n+1} A_{n+1}} \right)^{\frac{1}{\theta_{n+1} - \theta_n}} \right]^{\theta_1 + 1}$$

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<sup>21</sup>For example Koopman et al. (2010) investigate the share of domestic value added in China's exports.

Moreover, country  $i(n)$ 's contribution to each dollar of final good being produced is equal to:

$$\frac{l_n w_n}{P_1} = \frac{d \log P_1}{d \log w_n} = \frac{d \log \Theta}{d \log w_n} = \frac{\left( \frac{w_{n-1} A_{n-1}}{\tau w_n A_n} \right)^{\frac{1}{\theta_n - \theta_{n-1}}} - \left( \frac{w_n A_n}{\tau w_{n+1} A_{n+1}} \right)^{\frac{1}{\theta_{n+1} - \theta_n}}}{\left( \frac{P_1}{A_1 w_1} \right)^{\frac{1}{\theta_1 + 1}}} \quad (41)$$

In the expression for the final good price above, the first term  $\frac{A_1 w_1}{(\theta_1 + 1)^{\theta_1 + 1}}$  is the cost of production in country 1 if there is no possibility to fragment production across countries, while the second term  $\Theta(\mathbf{w}\mathbf{A}, \tau)$  is price reduction obtained from fragmenting production across countries. We can verify that this term decreases with trade costs. It also decreases with labor requirements  $A$  in each upstream countries.

Reductions in trade costs allow chains to reorganize some of the tasks abroad, which in turn has an effect on all other firms along the chain. Equation (36) shows that the marginal cost of increasing firm scope has to be equalized across all stages. A decrease in trade costs leading to a decrease in the final good's price also lead to a decrease in firm scope at other stages. The price of the final good is itself tightly linked to the shadow cost of fragmentation:

$$\lambda_G = \frac{A_1 w_1}{(\theta_1 + 1)^{\theta_1}} \Theta(\mathbf{w}\mathbf{A}, \tau)^{\frac{\theta_1}{\theta_1 + 1}} \quad (42)$$

As expressed with the  $\Theta$  term, there is a tight connection between the gains from fragmentation (decrease in the final good's price) and the shadow cost of fragmentation. Any increase in fragmentation and decrease in the final good price follows:  $d \log \lambda_G = \frac{\theta_1}{\theta_1 + 1} d \log \Theta$ .

A change in trade costs and wages along the chain has implications for firm scope everywhere on the chain. Each firm equalizes the cost of the marginal task to the shadow cost  $\lambda_G$  of performing the task somewhere else. Hence, a change in the shadow cost of fragmentation  $\lambda_G$  has implications for firm scope everywhere along the chain. In particular, the marginal cost of increasing firm scope in the most downstream firm in the most downstream country,  $w_1 c'(s_{1,f=0})$  is equal to  $\lambda_G$ , which implies:

$$s_{1,f=0} = \frac{\gamma_1}{\theta_1} \Theta(\mathbf{w}\mathbf{A}, \tau)^{\frac{1}{\theta_1 + 1}} \quad (43)$$

Hence:  $d \log s_{1,f=0} = \frac{1}{\theta_1 + 1} d \log \Theta$ , which formalizes how a change in fragmentation and trade costs (changes in  $\Theta$ ) affects firm scope for the last firm in the chain, the one that produces the finished good.

Interestingly, there is a one-to-one relationship between the change in the final good's price (which depends on the cost all along the chain) and the cost of production for firms in the last

country on the chain:  $d \log c_1(s_{1f}) = d \log \Theta = d \log P_1$ . Given that the cost is more convex in firm scope as we go upstream, fragmentation leads to a smaller decrease in firm scope and costs as we go upstream (holding quantities fixed in equation 36):  $d \log s_{if} = \frac{\theta_1}{\theta_i} d \log s_{1f}$  and  $d \log c_i(s_{if}) = \frac{\theta_i+1}{\theta_i} \cdot \frac{\theta_1}{\theta_1+1} d \log c_0(s_{1f})$ . Following a decrease in trade costs and  $\Theta$ , firm scope decreases everywhere along the chain, which in turn requires an increase in the number of firms involved sequentially to complete the final good.

Note, however, that the scope of the average firm in an upstream country  $i(n)$  (with  $n > 1$ ) does not decrease with trade costs. As trade costs decrease, a country moves downstream where firms tend to be larger. Upstream firms, which tend to be smaller in scope, exit or relocate. More specifically, we find that both the size of the most downstream and the most upstream firm within a country increase as trade costs decrease:

$$s_{i,0} = \frac{(\theta_i+1)\gamma_i}{\theta_i} \left( \frac{A_{i-1}w_{i-1}}{\tau A_i w_i} \right)^{\frac{1}{\theta_i - \theta_{i-1}}} \quad \text{and:} \quad s_{i,F_i} = \frac{(\theta_i+1)\gamma_i}{\theta_i} \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}} \quad (44)$$

Proposition 2 below summarizes the effect of trade costs on a chain in partial equilibrium (exogenous wages) for a given set of countries involved in the chain:

**Proposition 2** *Given wages  $w_i$  of countries involved along the chain, a decrease in cross-border trade costs leads to:*

- i) a decrease in the price of the final good*
- ii) an increase in the value share of imported inputs at any stage of the chain*
- iii) an increase in the range of tasks being offshored*
- iv) a decrease in the shadow cost of fragmentation  $\lambda_G$*
- v) a decrease in firm scope  $s_{i,f}$  at a given stage  $f$*
- vi) an increase in average firm scope in upstream countries  $i > 1$ .*

While the ranking of countries along the chain (from downstream to upstream stages) is dictated by the ranking in  $\theta_i$  (Proposition 1), it is more difficult to characterize the participation of a specific country in the chain. The expression above for  $S_i$  can be used to obtain a necessary condition for  $S_i > 0$ , but in general there is no simple *sufficient and necessary* condition to characterize the participation of country  $i$  in the chain because each country's participation depends upon the allocation of tasks to every other country in the chain. Moreover, the reader should keep in mind that we have dropped the variety subscript  $\omega$  to simplify the notation, but all costs parameters  $A_i$  and  $\theta_i$  are assumed to be specific to a particular variety of final good

$\omega$ . Hence, the organization of the chains across firms and countries is specific to each variety and country of final destination.

We address this problem below in a two-country case with simple analytical expressions. We also examine numerically a ten-country case calibrated using input-output data (Section 5). Using expressions (40) and (41) from Lemma 3, we can dramatically reduce the complexity of the numerical problem and reformulate the problem into a simpler linear programming problem that allows us to solve for large scale economies with numerous final goods.

## 4 General equilibrium and aggregation

### 4.1 A two-country case

**Two-country setting:** In this subsection, we consider only two countries: country  $D$  and country  $U$ . Country  $D$  has a parameter value  $\theta_D$  for coordination costs, while country  $U$  has a parameter value  $\theta_U$ . To justify these country names, we assume that  $\theta_U > \theta_D$ .

As specified in equation (9) in section 2, labor efficiency  $a_D(\omega)$  and  $a_U(\omega)$  are distributed Frechet with coefficient  $T_D$  and  $T_U$  respectively for countries  $D$  and  $U$ . We make no assumption about the relative ranking of  $T_D$  and  $T_U$ . We also make no assumption about relative transaction costs  $\gamma_D$  and  $\gamma_U$  for countries  $D$  and  $U$ . Also, we normalize  $w_D = 1$ .

As demonstrated in the previous sections (equation 22), it is useful to instead define an adjusted labor costs parameter  $A_D(\omega) = a_D(\omega) \left( \gamma_D \frac{\theta_D+1}{\theta_D} \right)^{\theta_D}$  and  $A_U(\omega) = a_U(\omega) \left( \gamma_U \frac{\theta_U+1}{\theta_U} \right)^{\theta_U}$ . The effect of transaction costs is equivalent to a shift in labor productivity. The resulting  $A_D(\omega)$  and  $A_U(\omega)$  parameters also follow a Frechet distribution with adjusted shift parameters:<sup>22</sup>

$$\begin{aligned}\tilde{T}_D &= T_D \left( \gamma_D \frac{\theta_D+1}{\theta_D} \right)^{-\xi\theta_D} \\ \tilde{T}_U &= T_U \left( \gamma_U \frac{\theta_U+1}{\theta_U} \right)^{-\xi\theta_U}\end{aligned}$$

Following Dornbusch et al. (1977), we rank varieties  $\omega$  between 0 and 1 and specify the following relative cost:

$$\frac{A_U(\omega)}{A_D(\omega)} = \left[ \frac{\tilde{T}_D}{\tilde{T}_U} \left( \frac{\omega}{1-\omega} \right) \right]^{\frac{1}{\xi}} \equiv A(\omega) \quad (45)$$

where  $A(\omega)$  is defined as the relative labor requirement in country  $U$ . This ordering implies that  $U$  has a comparative advantage in low- $\omega$  chains while country  $D$  has a comparative advantage in high- $\omega$  chains. For the sake of exposition, we normalize  $A_D(\omega)$  to unity. It is otherwise equivalent to redefine all prices as relative to  $A_D(\omega)$ .

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<sup>22</sup>Our parameter  $\xi$  is the same as the dispersion parameter  $\theta$  in Eaton and Kortum (2002).

**Definition of an equilibrium:** The optimal organization of chains is described by the optimization program as in (10). In addition, labor demand must equal labor supply in each country.

**Sourcing patterns:** As shown in Proposition 1, the ranking  $\theta_D < \theta_U$  determines the relative position on the chain. A chain that involves the two countries necessarily features country  $U$  specializing upstream and country  $D$  specializing downstream. Some chains may also involve country  $U$  only. However, when country  $D$  produces the final good, we find that country  $U$  is also involved in the chain, at least for some of the most upstream tasks.

When country  $D$  produces the final good (with country  $U$  involved in upstream tasks), the price of the final good in  $D$  is:

$$P_D(\omega) = \frac{1}{(\theta_D + 1)^{\theta_D + 1}} \left[ 1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \right]^{\theta_D + 1} \quad (46)$$

Consumers in  $U$  can also import these goods at a price  $\tau P_D(\omega)$ . When country  $U$  produces the entire range of tasks, the price of final goods in  $U$  is:

$$P_U(\omega) = \frac{w_U A(\omega)}{(\theta_U + 1)^{\theta_U + 1}} \quad (47)$$

while consumers in country  $D$  can also import these goods for a price  $\tau P_U(\omega)$ .

Given the patterns of labor costs across varieties, the ratio of prices  $\frac{P_D(\omega)}{P_U(\omega)}$  strictly increases with  $\omega$ . For each final destination  $X \in \{D, U\}$ , there is a unique threshold  $\omega_X^*$  for which the two prices are equal. These thresholds  $\omega_D^*$  and  $\omega_U^*$  are implicitly defined by:<sup>23</sup>

$$P_D(\omega_D^*) = \tau P_U(\omega_D^*) \quad (48)$$

$$\tau P_D(\omega_U^*) = P_U(\omega_U^*) \quad (49)$$

As in Dornbush, Fisher and Samuelson (1977), these cutoffs  $\omega_D^*$  and  $\omega_U^*$  correspond to the goods for which consumers (resp. in  $D$  and  $U$ ) are indifferent between purchasing locally or importing.

These results are illustrated in Figure 1. Figure 1 plots the price of final goods for each sourcing strategy. The threshold  $\omega_D^*$  is defined by the intersection between the curves for  $P_D$  and  $\tau P_U$  (prices for consumers in  $D$  while for final goods purchased from  $D$  and  $U$ ), while  $\omega_U^*$  is defined by the intersection between the curves for  $\tau P_D$  and  $P_U$ . Consumers in  $D$  thus purchase goods  $\omega \in [0, \omega_D^*]$  locally (with upstream tasks being offshored to  $U$ ) and Consumers

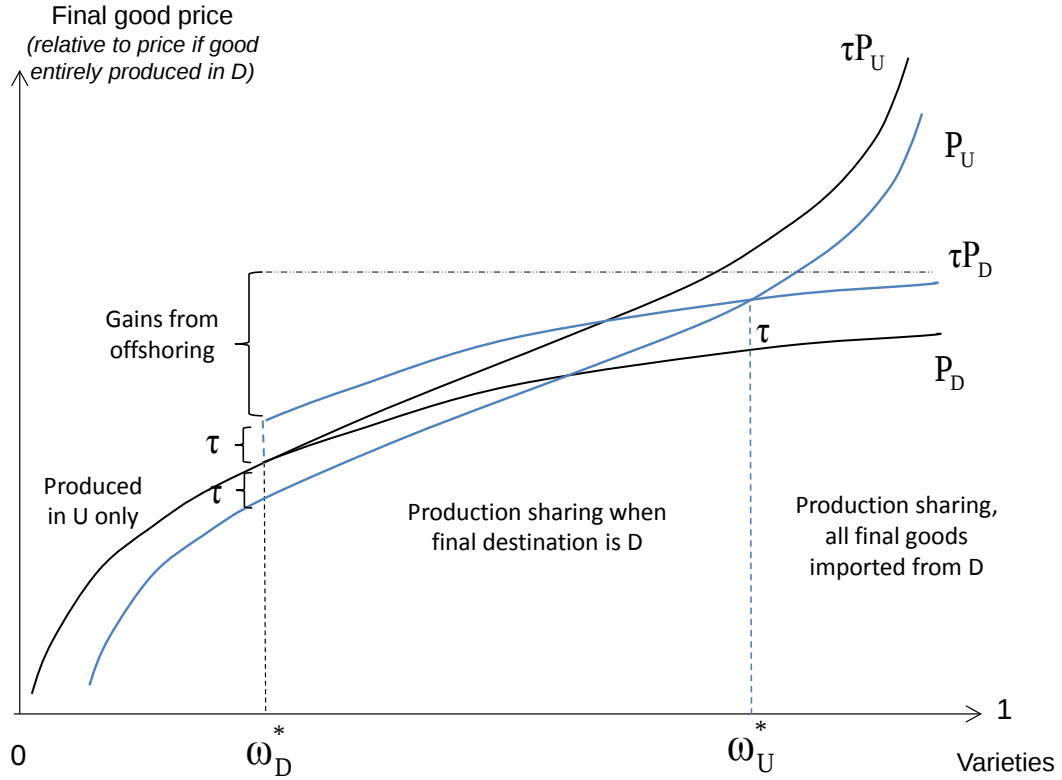
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<sup>23</sup>The solution for  $\omega_D^*$  has an analytical expression:  $\omega_D^* = \frac{\bar{T}_U \tau^{-\xi} w_U^{-\xi} (\theta_D + 1)^{-(\theta_U - \theta_D)\xi}}{\bar{T}_D + \bar{T}_U \tau^{-\xi} w_U^{-\xi} (\theta_D + 1)^{-(\theta_U - \theta_D)\xi}}$ .

in  $U$  purchase goods  $\omega \in [\omega_U^*, 1]$  in their own country.

The effect of fragmentation on prices is reflected by the upward slope of the price schedule  $P_D$  and  $\tau P_D$  (when the final goods is purchased from  $D$ ) which would have been flat without cross-border fragmentation (i.e. no offshoring of upstream tasks in  $U$ ). As described below, this generates a stronger effect of trade costs on  $\omega_U^*$  than in a situation with no fragmentation.

Figure 1: Final goods prices depending on source and destination countries



Since the production of final goods in  $D$  relies on country  $U$  to perform upstream tasks, the demand for labor does not only relate to the demand in final goods but also depends on intermediate goods. Using the results from Lemma 3, the demand for labor in  $U$  for each dollar of final goods produced in  $D$  (at a price  $P_D$ ) equals:

$$\frac{w_U l_U(\omega)}{P_D(\omega)} = \frac{(\theta_D + 1) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}}}{1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}}} \quad (50)$$

Wages at equilibrium are determined by a labor market clearing condition or, equivalently,

a trade balance condition. Here, trade balance imposes:

$$w_U L_U (1 - \omega_U^*) = L_D \omega_D^* + L_D \int_{\omega=\omega_D^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} d\omega + w_U L_U \int_{\omega=\omega_U^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} d\omega \quad (51)$$

where the left-hand side correspond to exports of final goods by  $D$  and the right-hand side corresponds to exports of final and intermediate goods by  $U$ . Based on this labor market clearing condition, we can show that there is a unique equilibrium in the wage  $w_U$  of country  $U$  relative to country  $D$ , and that  $\tau w_U$  decreases as trade costs  $\tau$  decrease.<sup>24</sup>

**Effect of trade costs on final goods trade:** We examine trade in final goods before intermediate goods and the value added content of trade. The share of final goods consumed in  $D$  that are imported from  $U$  corresponds to the threshold  $\omega_D^*$ , while the share of goods consumed by  $U$  and imported from  $D$  equals  $1 - \omega_U^*$ . We find that the elasticity of final good imports with respect to trade costs depends on the final destination of consumption and more specifically on the local labor content of the exporter. For country  $D$ , this elasticity is the same as in Eaton and Kortum (2002), i.e.  $\xi$  in our notation:

$$\varepsilon_D^F \equiv \frac{d \log \left( \frac{\omega_D^*}{1 - \omega_D^*} \right)}{d \log \tau} = -\xi$$

essentially because the exporter (country  $U$ ) does not rely on imported goods for its exports: from country  $D$ 's perspective, a 1% increase in trade costs from  $U$  is exactly compensated by a 1% decrease in labor costs in  $U$ .

Country  $D$ , however, relies on imports from  $U$  to produce goods that it exports back to  $U$ . As in Yi (2010), this back and forth trade generates a higher trade elasticity. There are two reasons for that. When trade costs increase by 1%, it affects the price of imported goods by  $U$  from  $D$  by more than 1% since the production of these goods in  $D$  relies itself on goods imported in  $U$  (double penalty). The second reason is that country  $D$  would need to decrease its labor cost by more than 1% to offset a 1% increase in the price of its exports since its labor only contributes to a fraction of the value of the good. Combining these two effects, the elasticity of imports in  $U$  to trade costs equals:

$$\varepsilon_U^F \equiv \frac{d \log \left( \frac{1 - \omega_U^*}{\omega_U^*} \right)}{d \log \tau} = -\xi \cdot \frac{1 + \frac{w_U l_U(\omega_U^*)}{P_D(\omega_U^*)}}{1 - \frac{w_U l_U(\omega_U^*)}{P_D(\omega_U^*)}} < -\xi$$

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<sup>24</sup>While we can get clear-cut results in terms of trade-costs-adjusted wages  $w_U \tau$ , the effect of trade costs on  $w_U$  itself is ambiguous like in a typical Ricardian trade model: the effect of trade on the relatively wage of country  $U$  tends to be larger if  $U$  is smaller.

where  $\frac{w_U l_U(\omega_U^*)}{P_D(\omega_U^*)}$  is the foreign labor content of production in country  $D$  for the marginal variety  $\omega_U^*$  imported by country  $U$  (see equation 50). The numerator, higher than unity, reflects the effect of trade costs on the price after the double penalty. The denominator, lower than unity, corresponds to the share of  $D$ 's labor costs in total costs.

The lower the trade costs, the higher the trade elasticity. Because lower trade costs leads to more fragmentation, the foreign labor content for the marginal variety increases. When trade becomes frictionless, the foreign labor content for this marginal variety converges to unity and the trade elasticity  $\varepsilon_U^F$  goes to infinity.

**Vertical specialization and the value-added content of trade:** Some of the goods are produced in two locations and some of them are even re-exported to consumers in other countries. There are not many combinations with a two-country model but we can still provide predictions about how the model fits with some of indexes used to describe the extent of fragmentation across countries. We focus here on Johnson and Noguera (2012a)'s "VAX ratio", which is itself a generalization of Hummels, Ishii and Yi (2001)'s vertical specialization index. The VAX ratio for an exporter is the ratio of value added exports and gross exports. In turn, value added exports correspond the value added to the production of goods eventually consumed by foreign consumers.

For country  $D$ , the VAX ratio is smaller than unity because country  $D$  relies on imported intermediate goods to produce the goods that are then exported:

$$VAX_D = \frac{1}{1 - \omega_U^*} \int_{\omega_U^*}^1 \left( 1 - \frac{w_U l_U(\omega)}{P_D(\omega)} \right) d\omega$$

where  $1 - \omega_U^*$  is the share of imported goods by consumers in  $U$  and where  $\frac{w_U l_U(\omega)}{P_D(\omega)}$  is the share of foreign labor in the production of variety  $\omega$  in country  $D$ . As trade costs decrease, we show that the foreign labor content increases and therefore that the VAX ratio for country  $D$  decreases.

For country  $U$ , all exported goods rely on domestic labor. Hence, the index developed by Hummels et al. (2001) would be equal to one for  $U$ . The VAX ratio, however, is again lower than unity:

$$VAX_U = \frac{L_D \omega_D^* + L_D \int_{\omega_D^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} d\omega}{L_D \omega_D^* + L_D \int_{\omega_D^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} d\omega + w_U L_U \int_{\omega_U^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} d\omega}$$

The numerator corresponds to the value added by  $U$  in the production of goods that are consumed by  $D$ , which corresponds to the sum of final goods exports and intermediate goods used to produced goods for local consumption. The denominator include these two terms plus the amount of intermediate goods that are exported to  $D$  to produced final goods that are then

reexported back to  $U$ . Because of this back-and-forth trade, the VAX ratio is strictly less than unity. Moreover, we show that this back-and-forth trade grows faster than other trade flows as trade costs decrease, which implies that the VAX ratio for country  $U$  decreases as trade costs decrease.

Finally, the VAX ratio for this economy of two countries equals a weighted average of each VAX ratio and decreases as trade costs decrease. We summarize these results in the following Proposition:

**Proposition 3** *The effect of trade costs on trade is such that:*

- i) The elasticity of trade in final goods to trade costs is higher than without fragmentation.*
- ii) This elasticity is larger than trade costs are smaller.*
- iii) The VAX ratio (value-added content of trade) decreases as trade costs decrease.*

The VAX ratio is a natural indicator of the extent of fragmentation across borders. There are alternative indicators that capture the same idea: the cross-border fragmentation of production is characterized by a growing difference between trade measured in gross flows and the value added by each exporter (Johnson 2014).<sup>25</sup>

The results of Proposition 3 are intuitive and supported by recent empirical evidence. In particular, Johnson and Noguera (2013, 2012b) use multi-country input-output tables to show that the VAX ratio has decreased over the past decades and that the bilateral VAX ratio depends positively on bilateral trade costs.

**Gains from trade:** How does trade affect welfare in upstream and downstream countries? A key policy question is whether a country is affected differently depending on its position on international production chains. To examine this question, we derive an exact expression for the price index and the gains from trade compared to autarky and compared to standard models without cross-border fragmentation of production. In particular, we use the formula developed by Arkolakis et al. (2012) as a benchmark.

For country  $D$ , which tends to specialize downstream, the change in the real wage compared to autarky is:

$$\Delta \log \left( \frac{1}{P_D} \right) = -\frac{1}{\xi} \log(1 - \omega_D^*) + \frac{1}{\xi} \int_{\omega_D^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} \frac{d\omega}{1 - \omega} \quad (52)$$

where  $P_D = \exp \left[ \int_0^1 \log P_D(\omega) d\omega \right]$  is the price index (the nominal wage  $w_D$  is normalized to unity in country  $D$ ). The first term  $\frac{1}{\xi} \log(1 - \omega_D^*)$  corresponds to the Arkolakis et al (2012)

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<sup>25</sup>As noted in Fally (2012), the inverse of the VAX ratio for the world can also be interpreted as the embodied number of border crossings.

formula based on final demand trade: the log of the gains from trade are proportional to the log of the domestic content of consumption, where the proportionality coefficient is the inverse of the trade elasticity  $\xi$ . For country  $D$ , expression (52) indicates that Arkolakis et al (2012) formula underestimate the gains from trade as we need to adjust for the foreign labor content in the production of final goods by  $D$ :  $\frac{w_U l_U(\omega)}{P_D(\omega)}$ .

Conversely, we find that the Arkolakis et al (2012) formula based on final goods overstates the gains from trade for the upstream country  $U$ . Specifically, we find that the difference in real wage compared to autarky equals:

$$\Delta \log \left( \frac{w_U}{P_U} \right) = \frac{1}{\xi} \int_{\omega_U^*}^1 \left( \frac{w_U l_U(\omega)}{P_D(\omega)} \right) d \log \omega < -\frac{1}{\xi} \log (\omega_U^*) \quad (53)$$

While these results are shown here only for a two-country case, our counterfactual simulations in Section 5 suggest that this insight holds more generally. Conditional on final goods trade, our results suggest that gains from trade tend to be underestimated for downstream (and generally richer) countries and overstated for upstream (and often poorer) countries. We calibrate our model and compute gains from trade by using input-output tables and information on domestic and foreign labor content which, as shown above, are crucial to obtain a more adequate measure of the gains from trade when production is fragmented across borders.

**Fragmentation and firm scope along the chain:** Last but not least, we now examine the effect of trade on fragmentation and firm scope along the chain within each country.

A key determinant of firm scope along the chain is the Lagrange multiplier associated with the total range of tasks, i.e. the shadow cost of fragmentation  $\lambda_G(\omega)$  (which varies across varieties). At optimum, this shadow cost depends negatively on the relative wage in  $U$  adjusted for trade costs  $\tau$ :

$$\lambda_G(\omega) = A_D(\omega) w_D \left[ \frac{1}{\theta_D + 1} - \frac{\theta_U - \theta_D}{\theta_D + 1} (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \right]^{\theta_i} \quad (54)$$

(for final goods produced in  $D$ ). Using Lemma 5, we obtain that the shadow cost of fragmentation decreases with trade cost, which lead to more fragmentation.

We can also express firm scope at all stages along the chain as a function of relative wages. Firm scope at the downstream end of the chain  $s_{D,f=0}$  in  $D$  and in other firms  $f$  is:

$$s_{D,f=0}(\omega) = \frac{\gamma_1}{\theta_1} \left[ 1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \right] \quad (55)$$

$$s_{D,f}(\omega) = e^{-\frac{\gamma_i}{\theta_i} f} \cdot \frac{\gamma_1}{\theta_1} \left[ 1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \right] \quad (56)$$

A decrease in trade costs leads to a decrease in trade-cost adjusted wage  $\tau w_U$  and therefore a decrease in firm scope in  $D$  at each stage.

Overall, the range of tasks performed in  $D$  decreases with trade for a given chain:

$$S_D(\omega) = 1 - (\theta_U + 1) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \quad (57)$$

(for variety  $\omega$ ) while the range of tasks performed by country  $U$ :  $S_U(\omega) = 1 - S_D(\omega)$  increases when trade costs decrease. Note that these expressions hold for varieties  $\omega > \omega_U^*$  among those consumed in  $U$  and varieties  $\omega > \omega_D^*$  among those consumed in  $D$  (the production of other varieties is not fragmented across countries).

While firm scope decreases for each firm in each country, average firm scope in a country does not decrease. Since both countries  $D$  and  $U$  tend to move downstream, each country tends to only keep its largest firms when trade costs decrease. Hence, average firm size in each country tends to increase once we account for this margin of adjustment along the chain. In particular, firm scope  $s_{D,F_D}$  for firm  $F_D$  at the upstream end of the chain in  $D$  increases with trade because country  $D$  tends to specialize downstream, where firm scope is larger. Similarly, firm scope  $s_{U,0}$  at the downstream end of the chain in  $U$  increases:

$$s_{D,f=F_D} = \frac{\gamma_D(\theta_D + 1)}{\theta_1} (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \quad (58)$$

$$s_{U,f=0} = \frac{\gamma_U(\theta_U + 1)}{\theta_U} (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \quad (59)$$

These results are illustrated in Figure 2.<sup>26</sup> Proposition 4 below also summarizes the key results on fragmentation in this two-country setting:

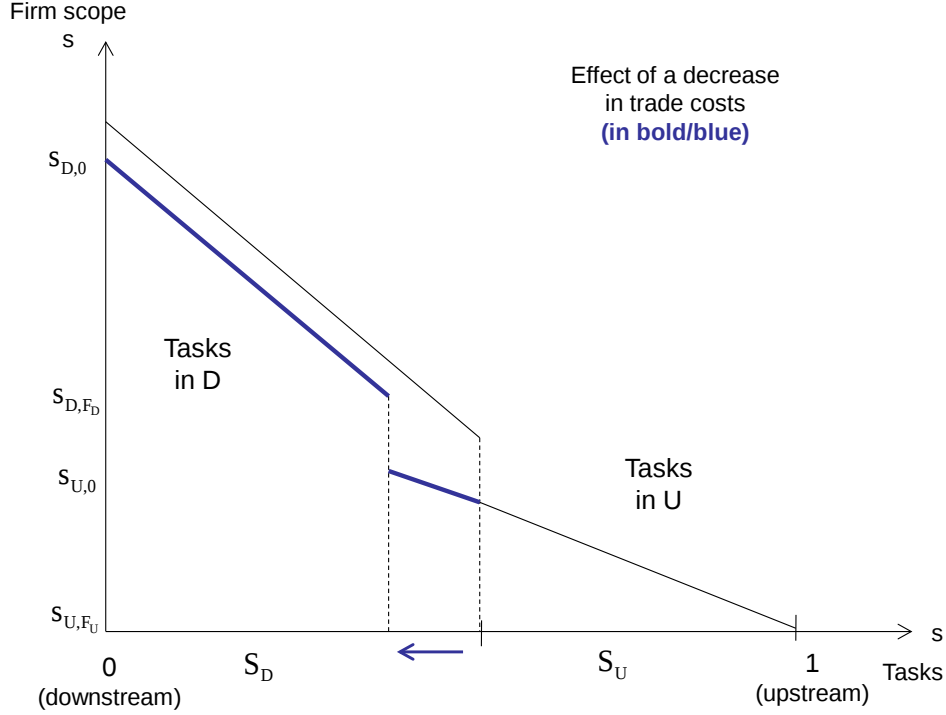
**Proposition 4** *In general equilibrium, a decrease in trade costs  $\tau$  leads to:*

- i) For a given variety, a decrease in the shadow cost of fragmentation  $\lambda_G$ .*
- ii) A greater share of inputs from  $U$  embodied in final goods produced in  $D$*
- iii) A larger share of imports of final goods from  $D$  by  $U$*
- iv) At any given stage, a smaller firm scope across all firms along the chain*
- v) A larger share of imports of final goods from  $U$  by  $D$*
- vi) And therefore a decrease in production sharing for goods consumed in  $D$ .*

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<sup>26</sup>Instead of expressing firm scope as a function of upstreamness  $f$  (in terms of firms), we plot firm scope as a function of the position on the range of tasks (ordered from 0 to 1) which yields linear relationships.

Figure 2: Effect of a decrease in trade costs on firm scope for a given chain



## 4.2 General equilibrium and aggregation: general case

In the quantitative section 5, we examine a situation with 10 countries involved in general equilibrium. Several comments are in order to describe the difference between the two-country case above and the calibrated model in Section 5.

First, we change our assumptions about  $\theta_i(\omega)$ . Empirical evidence suggests large heterogeneity in a country's position on supply chains. As shown in the data, all countries export a mix of final goods and intermediate goods. According to Proposition 1, this would not happen if  $\theta_i$  is constant across all varieties. We extend the approach taken by Eaton and Kortum (2002) and specify that  $\theta_i(\omega)$  varies across varieties and is the realization of a random variable. We assume in the calibration section that it is log-normally distributed, with i.i.d. shocks across varieties within countries. There are however systematic differences that can be captured here by differences in countries' average  $\theta_i$ .

Another difference with more than two countries is a higher elasticity of trade to trade costs. Suppose, for instance, that we have two identical countries  $D$  as well as one country  $U$  as above. An increase in trade costs between the three countries would have a stronger effect on goods that are produced in one of the two downstream countries and exported to the other downstream country. Because part of the value is actually coming from the third country  $U$  and because trade costs are incurred twice, such an increase in trade costs may trigger a

disproportionate switch in imports of final goods (from  $U$  instead of  $D$ ) for the a consumer in the final destination. This effect is similar to Yi (2010) and what we described above for country  $U$  in the two-country case.

### 4.3 Extensions

Details on extensions are left for future drafts. In brief, we can extend our model in at least two interesting directions. First, we can easily add another stage of production to model assembly and processing activities. It would be difficult to model production chains in Asia while ignoring these specific activities. In our model, an assembly stage can be added at the downstream end of each chain. If labor productivity is homogenous across countries, this stage would naturally locate in low-wage countries such as China. It would then be interesting to examine implications for the location of other firms that are more upstream in the chain. Quantitatively, we could use available data on the prevalence of the processing industry in China and other countries to quantify its effect on other parts of the production chain. An assembly sector can also be used to transform this model of ‘snakes’ into a model of ‘spiders’, using the terminology of Baldwin and Venables (2010).

Another extension would be the incorporation of multiple sectors. This would allow our calibration to better reflect cross-country variation in industry output, which is important because industries differ in the length of international supply chains. There is also potentially interesting cross-industry variation in the ordering of production chains. International supply chains in Textiles and Apparel, for example, might be organized with early stages in the North and later stages in the South. Other industries, such as Chemicals or Transportation Equipment, might be organized so that components move from South to North as value accrues.

## 5 Quantitative analysis

### 5.1 Data

Our main sources of data are the Asian input-output tables developed by IDE-JETRO. These tables provide information on gross output, value-added, and (most importantly) input purchases by product, parent industry (downstream industry), source country and destination country. For instance, we can track the amount of metals purchased from China by the auto industry in Japan. These 4-dimensional input-output tables, are, as far as we know, the only tables that track international transactions directly, rather than imputing them from trade flows. This is an exceptional data set for investigating the organization and evolution of international

production fragmentation in a region of the world where fragmentation is an important feature of international trading relationships.

The dataset covers 9 Asian countries and the US.<sup>27</sup> Our analysis mostly focuses on the year 2000 (the most recent year available), but we also compare our results to IDE-JETRO data from 1975 and 1990. This period we cover marks a time in which the region began to emerge as an important location for internationally fragmented production (see Baldwin and Lopez-Gonzalez (2012) for example).

Information on input purchases and production is disaggregated at the 76-sector level in 2000. For the sake of comparison to previous input-output tables (1975 and 1990), we construct a more aggregated 46-sector classification to obtain harmonized product categories across years. The sector classification is far more detailed for manufacturing goods and commodities than services (among the 46 sectors, only 5 of them are service industries). We thus mostly restrict our attention to tradable goods: commodities and manufacturing goods.

The information provided in these tables goes beyond a simple aggregation of country-level input-output tables. Besides the harmonization of product categories, input flows by parent and source countries are estimated by means of additional surveys and thus deviate from the proportionality assumption<sup>28</sup> which, according to Puzello (2012), is rejected in these data. This information therefore constitute an important advantage of using the IDE-JETRO input-output compared to previous attempts at constructing input-output tables based on the proportionality assumption (as in Johnson and Noguera 2012, for example).

## 5.2 Measuring the position along the chain: indexes $N$ , $N^*$ , $D$ & $D^*$

To better understand the degree of fragmentation in vertical production chains we adopt four indexes that generalize the two indexes proposed in Fally (2012) and applied there to US data. The indexes are designed to describe industries' position in vertical production chains by exploiting information about relationships in the input-output table. The 'D' index measures an industry's weighted average distance to final demand, where distance is measured by the apparent number of plants visited by the industry's output before reaching consumers.<sup>29</sup> The 'N' index calculates, for each industry, the number of stages that are embodied in each

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<sup>27</sup>The countries in the data base are the US, Japan, China, Taiwan, Korea, Singapore, Malaysia, Thailand, Indonesia and the Philippines.

<sup>28</sup>The proportionality assumption is made to construct input purchase by source country and parent industry when only partial information is provided. For instance, traditional country-level input-output tables describe how much steel is used by the auto industry in each country. Using trade flow data (which describe how much steel is imported from a particular country), previous international input-output tables have been constructed by allocating the use of input across source countries on a proportional basis.

<sup>29</sup>The measure is equivalent to the 'Upstreamness' measure in Antras, et al. (2012).

industry’s production. These two calculations are distinct for each industry, and in the US data there is only a weak correlation between them.

**Distance to final demand or “upstreamness”:** We turn to a formal representation of the two indices. Consider a variable  $D_{ik}$ , which is intended to measure the distance of a product  $k$  from final demand. Some part of product  $k$ ’s sales will be intermediate trade purchased by downstream industries, so the industry in question’s distance measure will depend upon which industries buy its output, and in turn how far those downstream industries are from final demand. Because an industry’s sales go to several industries, which will vary in their respective measures of  $D$ , the industry measure must be weighted, and it must also be defined recursively. Let  $D_{ik}$  indicate the distance measure in region  $i$  for product  $k$ . We define  $D_{ik}$  as:

$$D_{ik} = 1 + \sum_{jl} \varphi_{ikjl} D_{jl}$$

where  $\varphi_{ikjl}$  denotes the amount of output from product  $k$  in country  $i$  that is used to produce one dollar’s worth of product in sector  $l$  in country  $j$ . The entire system of equations that includes a  $D_{ik}$  for each industry and country can be solved to produce a measure for each sector-country pair.

As shown in Antras, et al. (2012), this index can be interpreted as the average number of stages that goods cross before reaching final consumers. Using the input-output matrix, we can decompose the different trajectories taken by the good across industries. Each trajectory is associated with a specific number of transactions across or within industries. Index  $D$  would then correspond to the average number of transactions weighted by the fraction of output corresponding to each trajectory.

Notice that  $D_{ik}$  does not only rely on inter-industry linkages but also depends on the extent of fragmentation within each industry. If an industry’s production is partly used as an input by other firms in the industry (e.g. electronic parts used as parts for other electronic parts within the same country), the coefficient  $\varphi_{ikik}$  would be strictly positive and would contribute to a higher index  $D_{ik}$  (since it would also correspond to a higher number of transactions).<sup>30</sup>

How to interpret ‘ $D$ ’ in the model? First, suppose that products  $k$  correspond to stages  $f$ . When  $f$  is strictly positive, i.e. when it does not refer to the most downstream stage in the  $n^{th}$

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<sup>30</sup>One may argue that the right industry classifications are too aggregated and create biases in computing  $D_{ik}$  and  $N_{ik}$  compared to what would be obtained with more precise data. Fally (2012) examines the aggregation properties of indexes  $D$  and  $N$  and shows that aggregating industries does not affect much the average of  $D$  and  $N$  for these industries.

country  $i(n)$ , then all sales are made to the next plant  $f - df$  in the chain:

$$D_{i(n),f+df} = df + D_{i(n),f}$$

If  $f = 0$  and  $i(n)$  is not the most downstream country  $i(1)$ , then all sales go towards the most upstream firm in the next country in the chain. After integrating, we obtain that the model counterpart of  $D_{if}$  corresponds to the total range of firms located downstream:

$$D_{i(n),f} = f + \sum_{n' < n} F_{i(n')}$$

summing across all downstream countries  $i(n')$  with  $n' < n$ .

In the light of the model, we can also interpret  $D_{i,k}$ , for any country  $i$ , as a semi-elasticity of required quantities w.r.t. to transaction costs.<sup>31</sup> Formally,  $D_{if}$  corresponds to:

$$D_{i,f} = \sum_j \frac{\partial \log q_{i,f}}{\partial \gamma_j}$$

**Embodied stages:** The  $N_{ik}$  index captures a weighted average of the number of plants involved sequentially in the production of good  $k$  in country  $i$ . It is defined recursively by:

$$N_{ik} = 1 + \sum_{jl} \mu_{ikjl} N_{jl}$$

where  $\mu_{ikjl}$  denotes the amount of input  $l$  from country  $j$  used to produce one dollar of product  $k$  in country  $i$ . This is a single equation, but, as with the D index, the system of equations can be solved to produce a measure of  $N$  for each sector-country pair. As shown in Fally (2012),<sup>32</sup> this index can also be expressed as a weighted average of the number of stages required to produce good  $k$  in country  $i$ , weighted by how much each stage of production contribute to the final value of that good.

We can also interpret  $N$  in the light of our theoretical framework. In the model, the amount of input purchased by other firms corresponds to the price of the good minus the labor cost incurred at each stage, i.e.:  $\frac{w_i c_i(s_{if}) df}{p_{if}}$ , where  $p_{if}$  denotes the price of the good in country  $i$  at stage  $f$ . The model counterpart of index  $N$  would thus correspond to the following recursive

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<sup>31</sup>In a model with a discrete number of firms instead of a continuum of suppliers, transaction costs would correspond to  $\delta = e^\gamma$  (as in Kikuchi et al 2014) and  $D$  would corresponds to the elasticity of quantities w.r.t transaction costs instead of the semi-elasticity.

<sup>32</sup>See Proposition 1 in Fally (2012).

definition:

$$N_{i,f} = df + \left(1 - \frac{c_i(s_{if})df}{p_{if}}\right) N_{i,f+df}$$

with a similar equation when the chain crosses a border. The solution to this differential equation equals the average of the number of production stages required to produce a good at stage  $f$  in country  $i$ .

There is a strong connection between the  $N$  and  $D$  index. Since the number of stages between firm  $f'$  in the  $m^{th}$  country  $i(m)$  and firm  $f$  in the  $n^{th}$  country  $i(n)$  corresponds to  $D_{i(m),f'} - D_{i(n),f}$ , we obtain formally:

$$N_{i(n),f} = \frac{1}{q_{i(n),f} p_{i(n),f}} \left[ \int_{(m,f') > (n,f)} (D_{i(m),f'} - D_{i(n),f}) q_{i(m),f'} c_{i(m)}(s_{i(m),f'}) \right]$$

where the integral is taken across all upstream firms either in  $i(n)$  at a more upstream stage  $f' > f$  or in more upstream countries  $i(m)$  with  $m > n$ , and where the price  $p_{if}$  can be itself reexpressed as the sum of all costs incurred in upstream stages, adjusting for quantities:

$$q_{i(n),f} p_{i(n),f} = \int_{(m,f') > (n,f)} q_{i(m),f'} c_{i(m)}(s_{i(m),f'}).$$

The connection between the two indexes  $N$  and  $D$  is clearest if we look at the most downstream stage. For the most downstream country  $i = 1$  and the most downstream firm  $f = 0$  in the country, index  $N$  corresponds to a weighted average of  $D$ :

$$N_{i(1),f=0} = \frac{1}{q_{1,0} p_{1,0}} \left[ \sum_j \int_{f'=0}^{F_j} D_{j,f'} q_{jf'} c_j(s_{jf'}) df' \right]$$

with the price  $p_{i=1,f=0} = \sum_j \int_{f'=0}^{F_j} q_{jf'} c_j(s_{jf'}) df'$  being the sum of all upstream costs.

As for  $D$ , we can also use the model to interpret  $N_{ik}$  as a semi-elasticity of w.r.t. to transaction costs, looking at prices instead of quantities. Formally,  $N_{if}$  corresponds to:<sup>33</sup>

$$N_{if} = \sum_j \frac{\partial \log p_{if}}{\partial \gamma_j}$$

**Borders vs. stages:** The  $N$  and  $D$  calculations are independent of whether or not the shipments in question cross international borders. Since the organization of international production networks is a key question for this literature, and for this study, we propose alternative forms of the indexes in Fally (2012). Using analogous methods to those used in the calcula-

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<sup>33</sup>Based on the results in Fally (2012), we should also note that  $N_{if}$  equals the aggregate gross-output-to-value-added ratio across upstream activities. It can therefore be interpreted as a weighted average of  $\frac{\theta_i}{\gamma_i}$  across upstream activities.

tion of  $D$  and  $N$  we ask how many international borders are crossed for each region-industry pair's outputs and inputs.  $D^*$  measures the average number of national borders crossed before final consumption.  $N^*$  measures the weighted average number of production stages that are embodied in the output of an industry.

Formally,

$$D_{ik}^* = \frac{X_{ik}}{Y_{ik}} + \sum_{jl} \varphi_{ikjl} D_{jl}^*$$

and

$$N_{ik}^* = \frac{M_{ik}}{Y_{ik}} + \sum_{jl} \mu_{ikjl} N_{jl}^*$$

with most of the variables defined above.  $X_{ik}$  represents exports by sector  $k$  in  $i$ ,  $M_{ik}$  represents imports, and  $Y_{ik}$  is sector gross output.

In our model, the equivalent is  $D_{if}^*$  reflecting the number of country borders to cross before reaching final consumers. Index  $N_{if}^*$ , on the other hand, reflects the average number of border crossings between the firm  $f$  in  $i$  and each upstream supplier weighed by value added by each supplier.

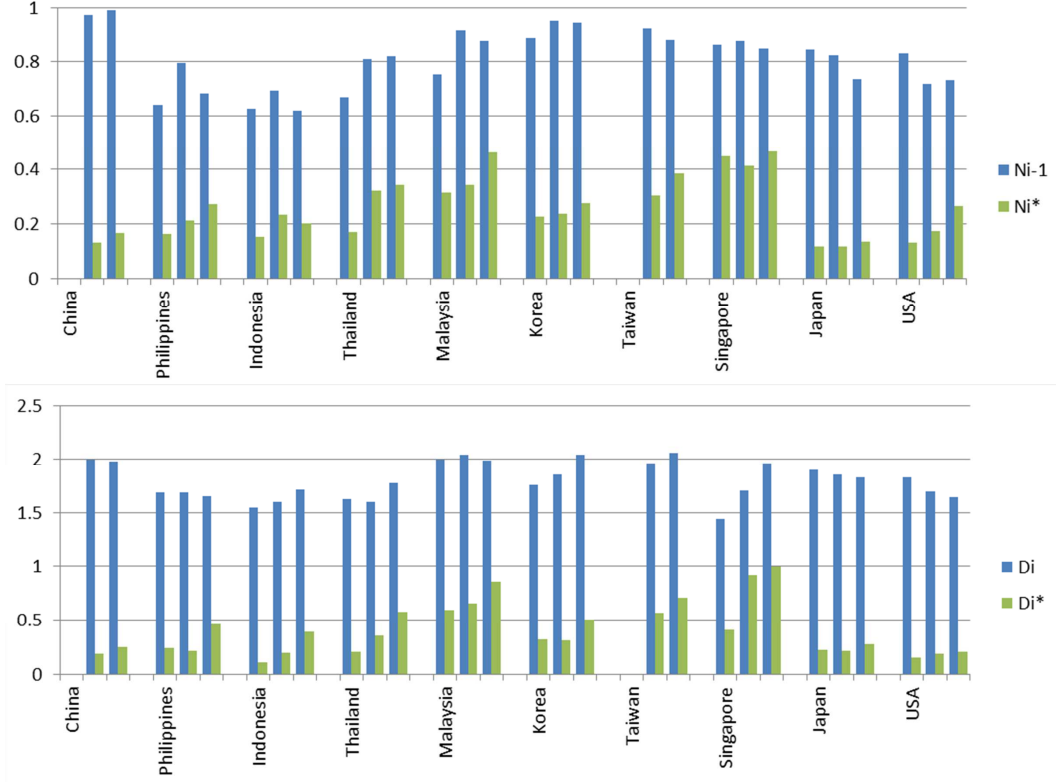
In the calibrated model, we calculate these indexes in benchmark and simulated data. The purpose of this exercise is to understand how changes in productivity levels and in trade and transaction costs affect the organization of production. Before we do so, however, it is useful to apply the measures to real data in order to better understand how the measures reflect organization of production in the past.

**Descriptive statistics:** We calculate the four indices at the sector level using the IDE-JETRO data from 1975, 1990 and 2000. In order to present this information succinctly, we offer two aggregates, where the aggregates are calculated as averages weighted by sector  $k$  output. We report the aggregate measures below in graphical form in order to show cross-country variation and within country variation over time.

In the Figure 3 we see the results for all tradable goods. There is some variation in the levels and trends of the  $D$  and  $N$  measures across countries. While the cross-country variation is, in some cases, interesting in its own right, the key takeaway is the absence of a consistent story in the simple measures that are neutral with respect to national borders. By contrast, one can see a general pattern of growth in the  $N^*$  and  $D^*$  measures. There seems to be particular growth in  $D^*$ , which suggests that the countries in question moved into upstream positions within internationalizing production chains.

The electronics sector is particularly interesting over this period. Complex international production chains are, anecdotally, an important phenomenon in East Asian manufacturing. Even more notably so within the electronics sector. Moreover, there has been important growth

Figure 3: Indexes  $N$ ,  $N^*$ ,  $D$  and  $D^*$  for tradable goods (excluding services)

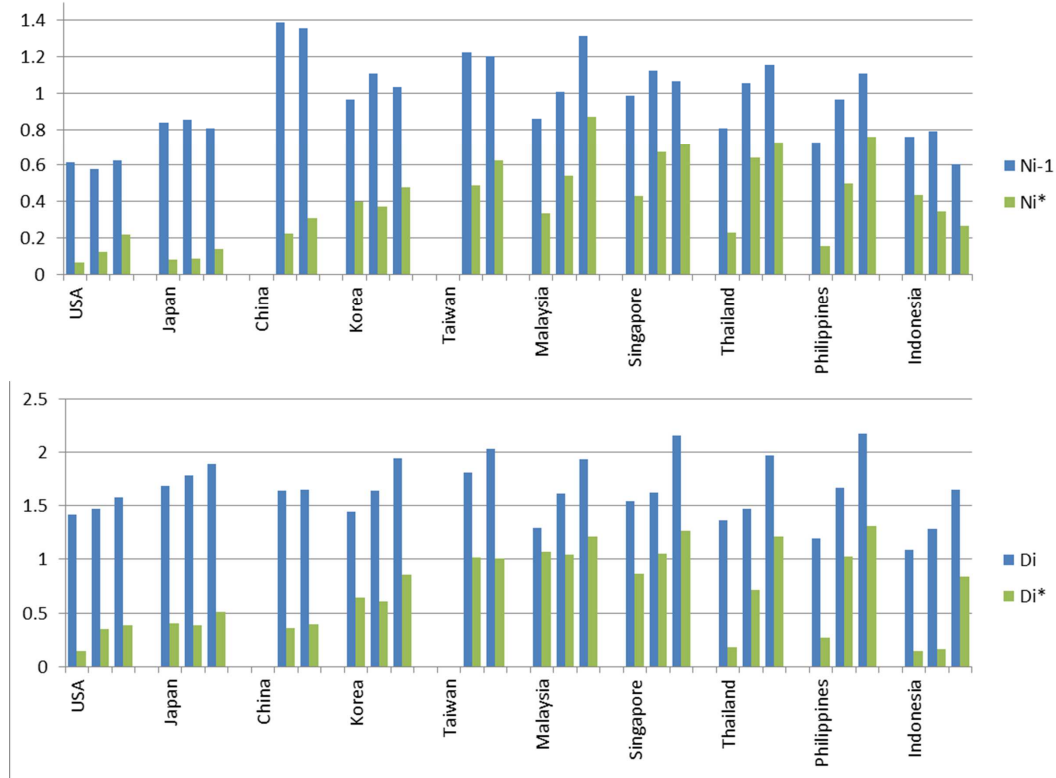


in the region's trade in electronics, which constituted only 8% of Asian exports in 1975, and 34% in 2000. In Figure 4 we report results of our calculations for the electronics sector, once again, by country and by year.

These measures indicate quite a bit more heterogeneity in the levels of the border-neutral indexes. Production chains appear to be somewhat shorter in the U.S. than in Asia. Moreover there is upward movement in the border-neutral measures in most all cases. One explanation would be that this is due to electronics becoming much more important as inputs into production of other sectors (i.e. automobiles). Once again there is a sharp upward movement in most all of the border-specific indexes. Thailand, Philippines, and Indonesia, in particular see sharp upward movements in their  $D^*$ . Most likely, this represents the integration of these countries into multinational production networks in which these countries produce early stages.

**Correlation between upstreamness and value-added content:** The model predicts that: i) countries with high coordination costs  $\theta$  should specialize upstream while countries with low  $\theta$  should specialize downstream; ii) the value-added-to-gross-output ratio decreases with  $\theta$  since it equals the ratio of  $\theta$  and transaction costs  $\gamma$ . By combining these two predictions, we should

Figure 4: Indexes  $N$ ,  $N^*$ ,  $D$  and  $D^*$  for the electronics industry



observe a negative correlation between upstreamness and the value-added-to-gross-output ratio.

Figure 5: Value-added-to-gross-output ratio as a function of upstreamness  $D_{ik}$

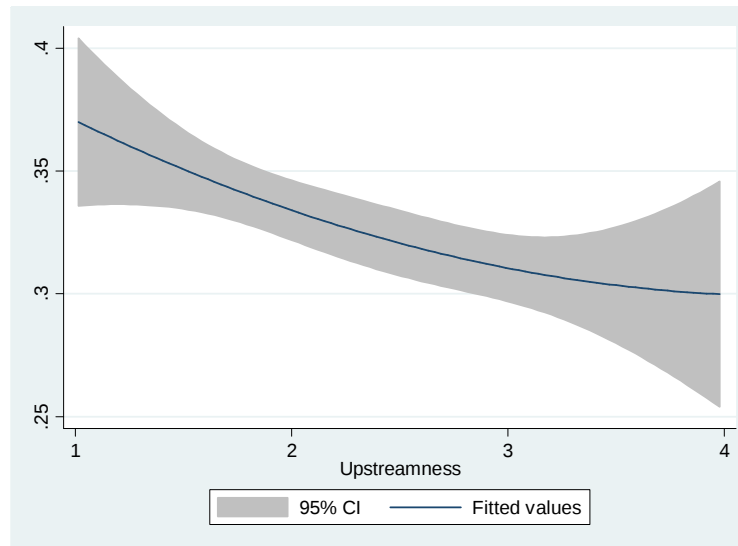


Figure 5 shows that we indeed observe such a negative correlation between upstreamness and the value added content.<sup>34</sup> This finding supports the prediction that firm scope tends to be smaller upstream than downstream. In Table 1, we regress the value-added-to-gross-output ratio on upstreamness to find a significant and negative correlation between the two, whether we include no fixed effect (column 1), country fixed effects (column 2), industry fixed effects (column 3) or both (column 4). Consistently with the model, the correlation is the strongest when most of the variation is driven by cross-country variation, i.e. when we include industry fixed effects but no country fixed effects.

Table 1: Correlation between upstreamness  $D_{ik}$  and the value-added-to-gross-output ratio

|                 | (1)                 | (2)                 | (3)                | (4)                |
|-----------------|---------------------|---------------------|--------------------|--------------------|
| Dependent var.: | VA/GO               |                     |                    |                    |
| Upstreamness    | -0.025<br>[0.012]** | -0.060<br>[0.008]** | -0.019<br>[0.008]* | -0.028<br>[0.008]* |
| Industry FE     | No                  | Yes                 | No                 | Yes                |
| Country FE      | No                  | No                  | Yes                | Yes                |
| R2              | 0.106               | 0.429               | 0.152              | 0.542              |
| N Obs.          | 478                 | 478                 | 478                | 478                |

*Notes:* Notes: OLS regression with robust s.e.; manufacturing industries, trimming observations with upstreamness above 4; \* significant at 5%; \*\* significant at 1%.

### 5.3 Calibration

Our calibration exercise focuses on the 10 countries that are covered by the IDE-JETRO input-output tables. The general equilibrium model described above is calibrated so as to reproduce key features of the data. The parsimony of the model allows us to consider only a small number of parameters to calibrate, those listed in the left column of Table 2.

**Simulation and calibration method:** Thanks to Lemma 3 and the analytical results described in section 3.2, we can reduce the optimization problem described in equation (10) to a linear programming problem for each chain. Numerical simulations are performed with the GAMS software. In this preliminary calibration we assume that there are 10,000 different final goods (future calibrations will be scaled up to 100,000 varieties of goods). Conditional on wages and exogenous parameters, we can then compute labor demand for each country. Equilibrium

<sup>34</sup>Figure 5 covers manufacturing industries only, trimming observations with upstreamness above 4.

in the labor market is solved by adjusting wages (in counterfactuals) or by adjusting labor productivity (in the initial calibration).

We now describe each calibrated parameter and its targeted moment, as described respectively in the left and right columns of Table 2.

**Labor productivity:** There is a tight link between wages and labor productivity in country  $i$ . As in Eaton and Kortum (2002), average labor productivity is driven by  $\bar{A}_i \equiv T_i^{-\frac{1}{\xi}}$  where  $T_i$  is a shift parameter for the Frechet distribution of  $A_i(\omega)$  in country  $i$  (equation 9). Given the connection between  $\bar{A}_i$  and wages, we use data on per capita income as a proxy for labor cost to be matched by the model. In turn, the dispersion parameter  $\xi$  is calibrated using the main estimate of Simonovska and Waugh (2014). Data on per capita income is obtained from the Penn World Tables for the year 2000. As shown in Table 2, there is almost a log-linear (downward-sloping) relationship between wages and  $\theta$  in our benchmark calibration.

**Coordination costs:** As shown in Proposition 1, the coordination cost parameter  $\theta_i$  is a key determinant of the position of a country along the chain, downstream or upstream. A country tends to export final goods when coordination costs are low and export intermediate goods when these costs are higher. Since all countries export a mix of final and intermediate goods, we assume that  $\theta_i$  is heterogeneous across varieties  $\omega$ , as discussed in section 4.2. We assume that it is log-normally distributed. In calibration countries are allowed a different shift parameter  $\bar{\theta}_i$  and a different standard deviation  $\sigma_{i\theta}$ . We use  $D^*$  as the primary moment to calibrate  $\bar{\theta}_i$  and  $\sigma_{i\theta}$  to fit countries' intermediate share in total exports. Our intuition with respect to  $\bar{\theta}_i$  is confirmed by Table 2: the calibration indicates that higher values of this parameter tend to be associated with a larger share of intermediate goods in a country's exports.

**Transaction costs:** Another key parameter of the model is  $\gamma_i$ , the cost of transactions between two firms. This cost is assumed to be positive even for transactions that occur within borders. Transaction costs are difficult to estimate in practice, but our model indicates that the gross-output-to-value-added ratio equals the ratio of coordination and transaction costs parameters  $\frac{\theta_i}{\gamma_i}$  and thus can be used to retrieve an estimate of  $\gamma_i$  once we know  $\bar{\theta}_i$  (on average). Results are provided in Table 2. As a credibility check we compare our results to plausible real-world counterparts of the  $\gamma_i$  parameter using the Doing Business Database (World Bank). Reassuringly, we find expected correlations of our calibrated  $\gamma_i$  variables with the costs of enforcing a contract claim (0.64), the time to enforce contracts (0.23), and the recovery rate in insolvency proceedings (-0.40).<sup>35</sup>

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<sup>35</sup>We could regress  $\gamma_i$  on each type of transaction cost (contract vs. bankruptcy, etc.) but with only 10 countries this regression would be meaningless.

**Trade costs:** In addition to transaction costs that are also incurred within borders, cross-border transactions face an additional burden. The nature and size of the extra cost affecting international transactions is the matter of an extensive debate in the trade literature (transport costs, asymmetric information, marketing cost, technical barriers, or cultural differences). There is however a consensus that these costs are large and have large effect on cross-border trade. While distance usually plays a key role in explaining the pattern of international trade (see Disdier and Head, 2008), distance is not as crucial for trade among Asian countries.<sup>36</sup> We therefore assume that cross-border trade costs are uniform across all country pairs in our sample. We fit the trade cost parameter by asking the model to replicate the global ratio of trade to output.

**Labor supply:** Finally, each country is endowed with an exogenous supply of factors. In the benchmark case, we consider only one factor of production: labor. For each country, we choose the labor force  $L_i$  to match aggregate value-added in tradeable goods sectors (i.e. excluding services) divided by the cost of labor (proxied by income per capita in our benchmark simulation).

**Simulation results on other moments:** Before turning to the counterfactual results we briefly describe the benchmark equilibrium. By construction, our model is able to reproduce key indicators of fragmentation such as the gross-output-to-value-added ratio and values of  $D^*$ . Alternatively, we can examine how the fitted model fares in terms of other indexes such as indexes  $D$ ,  $N$  and  $N^*$  described above.

Table 3 compares indexes from the model vs. data. In broad terms the magnitudes are consistent with the data, even though they are constructed in very different ways. These indexes from the data are computed at the industry level then averaged across industries. Index  $N$  in the benchmark calibration is computed for the most downstream firm in the chain while index  $D$  is a weighted average across firms weighted by value-added at each stage (and the same for  $N^*$ ).

Indexes  $D$  and  $N$  tend to be too high in our calibrated model (too much fragmentation), but they are strongly correlated with their data counterpart (89% correlation for  $N$  and 46% correlation for  $D$ ). The richest and poorest countries tend to be more downstream (lower index  $D$ ) and smaller number of embodied stages (index  $N$ ). Middle-income countries in our sample such as Taiwan and Malaysia end up with the highest indexes  $D$  and  $N$  both in the calibrated model and the data.

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<sup>36</sup>In a standard gravity equation of trade using the IDE-JETRO data, the coefficient for distance is not significant while the estimate border effect is large and significant, economically and statistically. Of course, this is a small sample of only 10 countries.

Table 2: Parameter choice and moments to match

| <i>Parameters:</i>                                                                     |     |         | <i>Moments to match:</i>                            |     |         |
|----------------------------------------------------------------------------------------|-----|---------|-----------------------------------------------------|-----|---------|
| Average $\bar{A}_i = \tilde{T}^{-\frac{1}{\xi}}$<br>by country<br>(relative to the US) | USA | 1.000   | GDP per capita<br>(PWT)                             | USA | 35,080  |
|                                                                                        | JPN | 1.806   |                                                     | JPN | 26,721  |
|                                                                                        | SGP | 1.418   |                                                     | SGP | 32,808  |
|                                                                                        | TWN | 2.430   |                                                     | TWN | 21,891  |
|                                                                                        | KOR | 2.866   |                                                     | KOR | 17,208  |
|                                                                                        | MYS | 6.315   |                                                     | MYS | 7,917   |
|                                                                                        | THA | 10.105  |                                                     | THA | 5,178   |
|                                                                                        | IDN | 16.912  |                                                     | IDN | 2,549   |
|                                                                                        | CHN | 19.434  |                                                     | CHN | 2,442   |
|                                                                                        | PHL | 25.997  |                                                     | PHL | 2,210   |
| Labor supply<br>in tradeable goods<br>(x1000 workers)                                  | USA | 53,551  | Total value-added<br>in tradeable goods<br>(in \$M) | USA | 1,878.6 |
|                                                                                        | JPN | 41,665  |                                                     | JPN | 1,113.3 |
|                                                                                        | SGP | 735     |                                                     | SGP | 24.1    |
|                                                                                        | TWN | 3,889   |                                                     | TWN | 85.1    |
|                                                                                        | KOR | 10,491  |                                                     | KOR | 180.5   |
|                                                                                        | MYS | 5,637   |                                                     | MYS | 44.6    |
|                                                                                        | THA | 10,410  |                                                     | THA | 53.9    |
|                                                                                        | IDN | 36,585  |                                                     | IDN | 93.3    |
|                                                                                        | CHN | 266,707 |                                                     | CHN | 651.3   |
|                                                                                        | PHL | 13,618  |                                                     | PHL | 30.1    |
| Average coordination costs $\tilde{\theta}_i$<br>by country                            | USA | 1.182   | D* Index                                            | USA | 0.208   |
|                                                                                        | JPN | 1.221   |                                                     | JPN | 0.278   |
|                                                                                        | SGP | 0.667   |                                                     | SGP | 1.062   |
|                                                                                        | TWN | 0.759   |                                                     | TWN | 0.699   |
|                                                                                        | KOR | 0.856   |                                                     | KOR | 0.503   |
|                                                                                        | MYS | 0.947   |                                                     | MYS | 0.912   |
|                                                                                        | THA | 0.670   |                                                     | THA | 0.591   |
|                                                                                        | IDN | 1.029   |                                                     | IDN | 0.521   |
|                                                                                        | CHN | 0.786   |                                                     | CHN | 0.278   |
|                                                                                        | PHL | 0.437   |                                                     | PHL | 0.483   |
| Transaction costs $\gamma_i$<br>by country                                             | USA | 0.524   | aggregate GO / VA ratio                             | USA | 2.666   |
|                                                                                        | JPN | 0.541   |                                                     | JPN | 2.773   |
|                                                                                        | SGP | 0.693   |                                                     | SGP | 4.676   |
|                                                                                        | TWN | 0.599   |                                                     | TWN | 3.951   |
|                                                                                        | KOR | 0.580   |                                                     | KOR | 3.359   |
|                                                                                        | THA | 0.768   |                                                     | THA | 3.452   |
|                                                                                        | MYS | 0.667   |                                                     | MYS | 3.101   |
|                                                                                        | IDN | 0.812   |                                                     | IDN | 2.035   |
|                                                                                        | CHN | 0.484   |                                                     | CHN | 3.11    |
|                                                                                        | PHL | 0.618   |                                                     | PHL | 2.629   |
| Simple average border cost                                                             | All | 25%     | Trade/output ratio                                  | All | 40%     |

Table 3: Fragmentation indexes: model vs. data

| Index | D*      | D     |       | N*    |       | N     |       |
|-------|---------|-------|-------|-------|-------|-------|-------|
|       | Matched | Data  | Model | Data  | Model | Data  | Model |
| USA   | 0.208   | 2.252 | 2.494 | 0.316 | 0.215 | 2.422 | 3.385 |
| JPN   | 0.278   | 2.370 | 2.672 | 0.182 | 0.246 | 2.364 | 3.533 |
| SGP   | 1.062   | 2.558 | 6.107 | 0.535 | 0.178 | 2.656 | 4.423 |
| TWN   | 0.699   | 2.567 | 4.698 | 0.423 | 0.268 | 2.542 | 4.266 |
| KOR   | 0.503   | 2.537 | 3.688 | 0.358 | 0.289 | 2.536 | 3.915 |
| MYS   | 0.912   | 2.755 | 4.887 | 0.501 | 0.217 | 2.515 | 3.765 |
| THA   | 0.591   | 2.373 | 3.645 | 0.400 | 0.292 | 2.443 | 3.567 |
| IDN   | 0.521   | 2.509 | 2.842 | 0.244 | 0.279 | 2.109 | 2.967 |
| CHN   | 0.278   | 2.707 | 2.833 | 0.183 | 0.299 | 2.620 | 3.855 |
| PHL   | 0.483   | 2.006 | 3.027 | 0.307 | 0.335 | 2.216 | 3.305 |

## 5.4 Counterfactual simulations

East-Asian economies have been the setting for tremendous changes over the past decades. Arguably the most significant changes are the increased fragmentation of production, China's opening to international trade and its subsequent rapid economic growth. In our theory these phenomena can certainly be related, as China's opening to trade could have facilitated fragmentation along chains in which it is now involved. Rapid economic growth may be associated with trade-related increases in productivity, but multi-factor productivity growth not specifically related to trade might also have been important. With a calibrated model at hand, we can now examine various counterfactual simulations to study how structural changes would affect economic outcomes such as output, trade, welfare and the fragmentation of production.

We see at least four experiments that would provide interesting insight into the reorganization of supply chains in Asia:

- Counterfactual 1): Reduction in trade costs. Trade costs have fallen significantly over the past decades and their reduction is cited as the most likely source of the increased fragmentation of production, especially in Asia. Trade costs may decline even further in the near future, as there is still room to improve trade agreements, especially on a multi-lateral basis (Baldwin, 2008). We model this structural change by a 10% reduction in cross-border trade costs.
- Counterfactual 2): Arguably the most dramatic change in the Asian economy over the past two decades has been the very high rates of growth in the Chinese economy, along with its opening to trade. With GDP growth rates reaching 10%, the Chinese economy

is inducing very large changes in how production in Asia is organized. To examine the role of China in the light of our model, we shock the productivity parameter there. We first simulate a 10% productivity increase in China. Formally, this corresponds to a 10% increase in  $T_{CHN}^{\frac{1}{\xi}}$ .

- Counterfactual 3): We simulate a reduction in the transaction costs  $\gamma_{CHN}$  for China. This scenario could be used to understand growing transparency in contractual disputes, for example. Reduced transaction costs should encourage relatively more domestic outsourcing in China, and raise the share of domestic value added in production/exports.<sup>37</sup>

#### 5.4.1 Reduction in trade costs

Our first scenario is a 10% reduction in international trade costs  $\tau$ . These results are reported in Table 4. The welfare changes in columns 2 are larger than those calculated with the Arkolakis et al (2012) formula (column 3). In the calibrated model we allow fragmentation over more than two countries, and so there are additional gains from trade. The additional fragmentation can be seen in the falling VAX ratio in every country, and in the growth of both  $D^*$  and  $N^*$  in every country in the model. The distribution of welfare gains across countries suggests that countries with larger economies benefit least. This likely reflects the fact that these larger economies are less exposed to changes in international trade costs.

Table 4: Counterfactual 1): 10% decrease in border trade costs

| (10 x change) | Welfare | $\frac{1}{\xi} \log \pi_{ii}^F$ | D*    | D      | N*    | N      | VAX    |
|---------------|---------|---------------------------------|-------|--------|-------|--------|--------|
| USA           | 0.104   | 0.043                           | 0.090 | -0.100 | 0.062 | 0.014  | -0.061 |
| JPN           | 0.147   | 0.062                           | 0.094 | -0.103 | 0.079 | 0.027  | -0.061 |
| SGP           | 0.232   | 0.215                           | 0.211 | 0.248  | 0.004 | -0.010 | -0.045 |
| TWN           | 0.244   | 0.165                           | 0.092 | -0.195 | 0.087 | -0.190 | -0.105 |
| KOR           | 0.212   | 0.133                           | 0.090 | -0.095 | 0.092 | 0.019  | -0.097 |
| MYS           | 0.234   | 0.144                           | 0.134 | 0.000  | 0.074 | -0.064 | -0.074 |
| THA           | 0.229   | 0.175                           | 0.098 | -0.029 | 0.096 | -0.031 | -0.104 |
| IDN           | 0.260   | 0.150                           | 0.076 | -0.131 | 0.118 | 0.003  | -0.099 |
| CHN           | 0.153   | 0.088                           | 0.096 | -0.058 | 0.103 | 0.128  | -0.084 |
| PHL           | 0.226   | 0.189                           | 0.100 | 0.020  | 0.080 | -0.020 | -0.088 |

<sup>37</sup>Kee and Tang (2013) and Li and Liu (2014) provide evidence that the share of domestic value added in Chinese exports has been growing over time.

### 5.4.2 Increasing productivity in China

Table 5 reports results from a 10% shock to productivity in China,  $T_{CHN}^{\frac{1}{\xi}}$ . This is a uniform shock that improves productivity at all points in the chain. Our interest is in seeing how such shocks affect China's relative position in chains, and the degree to which such shocks spill over into other countries.

The welfare changes reported in column 2 suggest that the vast majority of the welfare gains accrue to China, which sees an 8 % increase in welfare from a 10% productivity shock. The gains elsewhere are limited, and reasonably similar across countries. The most notable changes have to do with changes in relative position in supply chains. Changes in China's  $D$  and  $D^*$  indices indicate that the technology shock moves Chinese production significantly closer to final demand. Lower unit labor costs in China allow a relatively more improvement in the unit costs of its varieties with relatively low values of  $\theta$ . China's move upstream can also be seen in columns 8, which shows a reduction in China's VAX ratio. A decline in the VAX ratio would occur for example, if China were to offshore activities that were once done onshore.

Table 5: Counterfactual 2): 10% increase in productivity in China

| (10 x change) | Welfare | $\frac{1}{\xi} \log \pi_{ii}^F$ | $D^*$  | $D$    | $N^*$  | $N$    | VAX    |
|---------------|---------|---------------------------------|--------|--------|--------|--------|--------|
| <b>CHN</b>    | 0.815   | -0.044                          | -0.114 | -0.709 | -0.010 | -0.436 | -0.011 |
| USA           | 0.018   | 0.006                           | 0.022  | 0.055  | 0.007  | 0.032  | 0.005  |
| JPN           | 0.017   | 0.007                           | 0.036  | 0.129  | 0.005  | 0.039  | 0.005  |
| SGP           | 0.022   | 0.034                           | 0.144  | 0.626  | -0.027 | 0.237  | 0.017  |
| TWN           | 0.004   | 0.014                           | 0.128  | 0.563  | -0.025 | 0.220  | 0.023  |
| KOR           | 0.004   | 0.009                           | 0.078  | 0.483  | -0.014 | 0.229  | 0.012  |
| MYS           | 0.014   | 0.023                           | 0.095  | 0.410  | -0.012 | 0.201  | 0.011  |
| THA           | 0.011   | 0.017                           | 0.056  | 0.311  | -0.017 | 0.142  | 0.010  |
| IDN           | 0.008   | 0.009                           | 0.074  | 0.355  | -0.010 | 0.118  | 0.009  |
| PHL           | 0.012   | 0.025                           | 0.071  | 0.474  | -0.033 | 0.195  | 0.021  |

### 5.4.3 Reduced transaction costs in China

The welfare effects of a 10% reduction in transaction costs in China are even larger than were calculated for the Chinese productivity shock. Welfare rises by almost 9%. The welfare effects on the rest of the world are substantially larger, by nearly an order of magnitude. In this case, China's production moves upstream, as indicated by the movements in  $D^*$ ,  $D$  and  $N^*$ . The change in  $N$  reflects the a fragmentation of production within China. In broad terms the move upstream is consistent with the evidence presented in Kee and Tang (2013), who find that

Chinese exporters have been shifting their supply from foreign to domestic sources. The effects on other countries' positions in global supply chains are somewhat mixed. On the one hand, China's move upstream will push countries upstream of China even further upstream. On the other hand, as China shifts to upstream activities some countries will expand downstream.

Table 6: Counterfactual 3): 10% decrease in Chinese transaction costs  $\gamma_i$

| (10 x change) | welfare | D*     | D      | N*     | N     | VAX    |
|---------------|---------|--------|--------|--------|-------|--------|
| <b>CHN</b>    | 0.896   | 0.411  | 6.995  | -0.106 | 5.566 | 0.060  |
| USA           | 0.098   | -0.015 | -0.020 | 0.079  | 0.513 | 0.003  |
| JPN           | 0.096   | -0.001 | 0.013  | 0.069  | 0.464 | -0.018 |
| SGP           | 0.078   | 0.070  | 1.089  | 0.013  | 0.621 | 0.008  |
| TWN           | 0.100   | 0.061  | 0.429  | 0.019  | 0.542 | -0.012 |
| KOR           | 0.106   | 0.044  | 0.354  | 0.035  | 0.543 | -0.024 |
| MYS           | 0.122   | 0.006  | 0.519  | -0.029 | 0.291 | 0.010  |
| THA           | 0.099   | -0.015 | 0.265  | 0.048  | 0.830 | -0.059 |
| IDN           | 0.124   | 0.035  | 0.436  | 0.046  | 0.753 | -0.040 |
| PHL           | 0.096   | 0.045  | 0.536  | 0.007  | 0.606 | -0.007 |

## 6 Concluding remarks

Recent empirical work has documented sizable differences in supply chain length. In this paper we attempt to explain such variation in an integrated framework that links the internalization decisions of firms within a supply chain to the organization of the chain across countries. We develop a continuous firm representation of the optimal organization of a multi-country supply chain, with an endogenous allocation of tasks across firms and countries. We derive formal and intuitive representations of the gains from fragmentation within a chain and relate these to the implicit price of tasks and the price of the final good.

In this Coasian setting, we show that same parameters that shape the boundaries of firms also determine comparative advantage within international supply chains. Conditional on participation in a supply chain, the lower a country's coordination costs the more downstream it will be. Low within-firm coordination costs also imply an ability to host larger firms. By contrast, countries with high levels of the transaction costs will tend to participate downstream because their disadvantages can only be offset in chains for which they have low within-firm-coordination costs and larger firms.

In order to link the model to the prominent literature on the welfare gains of trade we use a conventional Ricardian framework to produce a general equilibrium model with multiple

chains. We assume that productivity differences *across chains* follow a Frechet distribution as in Eaton and Kortum (2002). We derive implications for trade elasticities and welfare, relative to standard theoretical benchmarks (Arkolakis et al 2012). Among a number of theoretical results we show that the elasticity of final goods trade to trade costs is larger in the presence of fragmentation. Relative to Arkolakis (2012) formula without fragmentation, we show that welfare effects are smaller for upstream countries and larger for downstream countries in the presence of fragmentation.

To illustrate the quantitative implications of the model we conduct a calibration exercise with counterfactual exercises. In our model, the Coasian structural parameters determine the gross-output-to-value added ratio, a fact that facilitates calibration. We shock international trade costs and find numerical evidence that is consistent with our theoretical results. Shocks to Chinese productivity and to the coordination cost parameter in China have similar implications. Both cause Chinese production activity to move downstream.

In order to better tie the model to the available data we plan to improve and extend the calibration exercise in a subsequent version of the paper. An explicit representation of assembly activities as distinct from activities up the chain would help us better formalize the participation of China in the quantitative framework. Incorporating multiple industries will allow us to better exploit the detail available in the IDE-JETRO tables. These and other extensions are feasible and we expect to incorporate them in a subsequent version of the paper.

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# Mathematical Appendix

## Proofs for Section 3.1: within-country fragmentation

**FOCs:** The first-order conditions of this planning program correspond to equations (3.1) and (14):

$$\begin{aligned} \text{For } s_{fi} : \quad & e^{\gamma_i f} w_i c'_i(s_{if}) = \lambda_i \\ \text{For } F_i : \quad & e^{\gamma_i F_i} w_i c_i(s_{i,F_i}) + e^{\gamma_i F_i} P_i^M \gamma_i = s_{i,F_i} \lambda_i \end{aligned}$$

Using our parameterization of the cost function, the first-order condition for  $s_{if}$  can be rewritten:

$$e^{\gamma_i f} a_i w_i s_{if}^{\theta_i} = \lambda_i$$

which yields:

$$s_{if} = \left( \frac{\lambda_i}{a_i w_i} \right)^{\frac{1}{\theta_i}} e^{-\frac{\gamma_i f}{\theta_i}}$$

By combining the first-order condition in  $F_i$  and the first-order condition in  $s_{fi}$ , we obtain:

$$e^{\gamma_i F_i} a_i w_i \frac{s_{i,F_i}^{\theta_i+1}}{\theta_i + 1} + e^{\gamma_i F_i} P_i^M \gamma_i = s_{i,F_i} \cdot e^{\gamma_i F_i} a_i w_i s_{i,F_i}^{\theta_i}$$

which can be simplified into:

$$\frac{w_i a_i \theta_i}{\theta_i + 1} s_{i,F_i}^{\theta_i+1} = \gamma_i P_i^M$$

and thus:

$$s_{i,F_i} = \left[ \frac{(\theta_i + 1) \gamma_i}{\theta_i} \frac{P_i^M}{a_i w_i} \right]^{\frac{1}{\theta_i + 1}}$$

**Lagrangian multiplier:** It is the solution of:

$$\int_0^{F_i} s_{if} df = S_i$$

where  $s_{if}$  and  $F_i$  functions of the Lagrangian multiplier as shown above. The left-hand side can be rewritten:

$$\begin{aligned} \int_0^{F_i} s_{if} df &= \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{1}{\theta_i}} \int_0^{F_i} e^{-\frac{\gamma_i f}{\theta_i}} df \\ &= \frac{\theta_i}{\gamma_i} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{1}{\theta_i}} \left[ 1 - e^{-\frac{\gamma_i F_i}{\theta_i}} \right] \\ &= \frac{\theta_i}{\gamma_i} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{1}{\theta_i}} \left[ 1 - \left( \frac{\lambda_i}{w_i a_i} \right)^{-\frac{1}{\theta_i}} s_{i,F_i} \right] \\ &= \frac{\theta_i}{\gamma_i} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{1}{\theta_i}} - \frac{\theta_i s_{i,F_i}}{\gamma_i} \end{aligned}$$

We obtain the following solution in  $\lambda_i$  such that the expression above equals  $S_i$ :

$$\lambda_i = w_i a_i \left[ \frac{\gamma_i S_i}{\theta_i} + \left( \frac{(\theta_i + 1) \gamma_i}{\theta_i} \frac{P_i^M}{a_i w_i} \right)^{\frac{1}{\theta_i + 1}} \right]^{\theta_i}$$

**Final price:** Expression for  $P_i$ :

$$\begin{aligned} P_i &= \int_{f=0}^{F_i} e^{\gamma_i f} w_i c_i(s_{if}) df + e^{\gamma_i F_i} P_i^M \\ &= \int_{f=0}^{F_i} e^{\gamma_i f} \frac{w_i a_i s_{if}^{\theta_i + 1}}{\theta_i + 1} df + e^{\gamma_i F_i} P_i^M \\ &= \frac{w_i a_i}{\theta_i + 1} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{\theta_i + 1}{\theta_i}} \int_{f=0}^{F_i} e^{-\frac{\gamma_i f}{\theta_i}} df + e^{\gamma_i F_i} P_i^M \\ &= \frac{w_i a_i}{\gamma_i} \frac{\theta_i}{\theta_i + 1} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{\theta_i + 1}{\theta_i}} \left[ 1 - e^{-\frac{\gamma_i F_i}{\theta_i}} \right] + e^{\gamma_i F_i} P_i^M \\ &= \frac{w_i a_i}{\gamma_i} \frac{\theta_i}{\theta_i + 1} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{\theta_i + 1}{\theta_i}} - \frac{w_i a_i}{\gamma_i} \frac{\theta_i}{\theta_i + 1} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{\theta_i + 1}{\theta_i}} e^{-\frac{\gamma_i F_i}{\theta_i}} + \frac{w_i a_i}{\gamma_i} \left( \frac{\gamma_i P_i^M}{w_i a_i} \right) e^{\gamma_i F_i} \\ &= \frac{w_i a_i}{\gamma_i} \frac{\theta_i}{\theta_i + 1} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{\theta_i + 1}{\theta_i}} - \frac{1}{\gamma_i} \frac{\theta_i}{\theta_i + 1} \lambda_i s_{i, F_i} + \frac{w a}{\gamma} \frac{\theta}{\theta + 1} s_{i, F_i}^{\theta_i + 1} e^{\gamma_i F_i} \\ &= \frac{w_i a_i}{\gamma_i} \frac{\theta_i}{\theta_i + 1} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{\theta_i + 1}{\theta_i}} - \frac{1}{\gamma_i} \frac{\theta_i}{\theta_i + 1} \left[ \lambda_i s_{i, F_i} - w_i a_i s_{i, F_i}^{\theta_i + 1} e^{\gamma_i F_i} \right] \\ &= \frac{w_i a_i}{\gamma_i} \frac{\theta_i}{\theta_i + 1} \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{\theta_i + 1}{\theta_i}} + 0 \end{aligned}$$

Using the expression above for  $\lambda_i$ , we obtain equations (21) and (22) in the text:

$$P_i = \left[ \frac{S_i}{\theta_i + 1} (A_i w_i)^{\frac{1}{\theta_i + 1}} + (P_i^M)^{\frac{1}{\theta_i + 1}} \right]^{\theta_i + 1}$$

with

$$A_i = a_i \left( \gamma_i \frac{\theta_i + 1}{\theta_i} \right)^{\theta_i}$$

It is also useful to note that:

$$\lambda_i = (w_i A_i)^{\frac{1}{\theta_i + 1}} (P_i)^{\frac{\theta_i}{\theta_i + 1}} \quad (60)$$

**Prices along the chain:** To obtain a simple expression for the value-added-to-gross-output ratio  $\frac{c_i(s_{if})}{p_{if}}$ , the first step is to compute  $p_{if}$  is the price along the chain.

$$\begin{aligned} p_{if} &= \int_{f'=f}^{F_i} e^{\gamma_i(f'-f)} c(s_{if'}) df' + e^{\gamma_i(F_i-f)} P_i^M \\ &= \frac{w_i a_i}{\theta_i + 1} \int_{f'=f}^{F_i} e^{\gamma_i(f'-f)} s_{if'}^{\theta_i + 1} df' + e^{\gamma_i(F_i-f)} P_i^M \end{aligned}$$

$$\begin{aligned}
&= \frac{w_i a_i}{\theta_i + 1} e^{\gamma_i(F_i - f)} \int_{f'=f}^{F_i} e^{-\gamma_i(F_i - f')} s_{if'}^{\theta_i + 1} df' + e^{\gamma_i(F_i - f)} P_i^M \\
&= \frac{w_i a_i}{\theta_i + 1} e^{\gamma_i(F_i - f)} s_{i,F_i}^{\theta_i + 1} \int_{f'=f}^{F_i} e^{-\gamma_i(F_i - f')} e^{\gamma_i \left( \frac{\theta_i + 1}{\theta_i} \right) (F_i - f')} df' + e^{\gamma_i(F_i - f)} P_i^M \\
&= \frac{w_i a_i}{\theta_i + 1} e^{\gamma_i(F_i - f)} s_{i,F_i}^{\theta_i + 1} \int_{f'=f}^{F_i} e^{\frac{\gamma_i(F_i - f')}{\theta_i}} df' + e^{\gamma_i(F_i - f)} P_i^M \\
&= \frac{w_i a_i \theta_i}{(\theta_i + 1) \gamma_i} e^{\gamma_i(F_i - f)} s_{i,F_i}^{\theta_i + 1} \left[ e^{\frac{\gamma_i(F_i - f)}{\theta_i}} - 1 \right] + e^{\gamma_i(F_i - f)} P_i^M \\
&= \frac{w_i a_i \theta_i}{(\theta_i + 1) \gamma_i} s_{if}^{\theta_i + 1} - \frac{e^{\gamma_i(F_i - f)}}{\gamma_i} \left[ \frac{w_i a_i \theta_i}{\theta_i + 1} s_{i,F_i}^{\theta_i + 1} - \gamma_i P_i^M \right] \\
&= \frac{w_i a_i \theta_i}{(\theta_i + 1) \gamma_i} s_{if}^{\theta_i + 1} - 0 \\
&= \frac{\theta_i}{\gamma_i} w_i c_i(s_{if})
\end{aligned}$$

Hence the gross-output-to-value-added ratio at the firm level is:

$$\frac{p_{if}}{c_i(s_{if})} = \frac{\theta_i}{\gamma_i}$$

We also obtain the same expression for the aggregate gross-output-to-value-added ratio. If we define gross output as the total value of all transactions:

$$GO_i = \int_0^{F_i} q_{if} p_{if} df$$

we obtain:

$$\frac{GO_i}{VA_i} = \frac{\int_0^{F_i} q_{if} p_{if} df}{\int_0^{F_i} q_{if} w_i c_i(s_{if}) df} = \frac{\int_0^{F_i} \frac{\theta_i}{\gamma_i} q_{if} w_i c_i(s_{if}) df}{\int_0^{F_i} q_{if} w_i c_i(s_{if}) df} = \frac{\theta_i}{\gamma_i}$$

## Proof of Proposition 1

To simplify exposition, we index countries by  $i$ , with  $i = 1$  referring to the most downstream country and  $i = N$  the most upstream country. The goal is to minimize:

$$\min P_1 \tag{61}$$

under the constraints:

$$P_{i+1} = \tilde{P}_i(S_i, \tau P_{i+1}) \quad \text{and} \quad \sum_{i=n}^N S_i = 1$$

with:

$$\tilde{P}_i(S, P^M) = \left[ \frac{S}{\theta_i + 1} (A_i w_i)^{\frac{1}{\theta_i + 1}} + (P^M)^{\frac{1}{\theta_i + 1}} \right]^{\theta_i + 1}$$

Under which condition is country  $i$  downstream from country  $i + 1$ ? Let us take as given the

price in country  $i + 2$  and consider the following function:

$$m(x)^{\theta_{i+1}} = \tilde{P}_i(S_i - x, \tau \tilde{P}_i(S_{i+1} + x, \tau P_{i+2}))$$

This function  $m(x)$  indicates by how much the price of output in  $i$  will increase if we shift a measure  $x$  of tasks from country  $i$  to country  $i + 1$ .

$$m(x) = \frac{(S_i - x)}{\theta_i + 1} (A_i w_i)^{\frac{1}{\theta_i + 1}} + \left[ \frac{(S_{i+1} + x)}{\theta_{i+1} + 1} (A_{i+1} w_{i+1})^{\frac{1}{\theta_{i+1} + 1}} + (\tau P_{i+2})^{\frac{1}{\theta_{i+1} + 1}} \right]^{\frac{\theta_{i+1} + 1}{\theta_i + 1}}$$

If we are at equilibrium, the function  $m(x)$  must be at its minimum at  $x = 0$ . The first-order condition imply that  $m'(x) = 0$ . We obtain that:

$$m'(x) = -\frac{(A_i w_i)^{\frac{1}{\theta_i + 1}}}{\theta_i + 1} + \frac{(A_{i+1} w_{i+1})^{\frac{1}{\theta_{i+1} + 1}}}{\theta_{i+1} + 1} \left[ \frac{(S_{i+1} + x)}{\theta_{i+1} + 1} (A_{i+1} w_{i+1})^{\frac{1}{\theta_{i+1} + 1}} + (\tau P_{i+2})^{\frac{1}{\theta_{i+1} + 1}} \right]^{\frac{\theta_{i+1} - \theta_i}{\theta_i + 1}} \quad (62)$$

must equal zero at  $x = 0$ .

More importantly, to prove Proposition 1, one needs to examine the second order condition, which imposes  $m''(x) > 0$ . If  $m''(x)$  were negative,  $x = 0$  would not be a local minimum and it would be more efficient to shift some tasks to either country  $i$  or  $i + 1$ .

As one can see in equation (62), the right-hand-side term is increasing in  $x$  (i.e.  $m''(x) > 0$ ) only if the exponent  $\frac{\theta_{i+1} - \theta_i}{\theta_i + 1}$  is positive. This proves that we must have  $\theta_{i+1} > \theta_i$  at equilibrium.

Finally, it is not difficult to verify that two consecutive countries cannot have the same  $\theta_i = \theta_{i+1}$  as long as we have non-zero trade costs  $\tau - 1 > 0$ .

## Other proofs for Section 3.2

**Prices along the chain:** Using again equation (62), the first-order condition  $m'(0) = 0$  implies:

$$\begin{aligned} \frac{(A_i w_i)^{\frac{1}{\theta_i + 1}}}{\theta_i + 1} &= \frac{(A_{i+1} w_{i+1})^{\frac{1}{\theta_{i+1} + 1}}}{\theta_{i+1} + 1} \left[ \frac{S_{i+1}}{\theta_{i+1} + 1} (A_{i+1} w_{i+1})^{\frac{1}{\theta_{i+1} + 1}} + (\tau P_{i+2})^{\frac{1}{\theta_{i+1} + 1}} \right]^{\frac{\theta_{i+1} - \theta_i}{\theta_i + 1}} \\ &= \frac{(A_{i+1} w_{i+1})^{\frac{1}{\theta_{i+1} + 1}}}{\theta_{i+1} + 1} (P_{i+1})^{\frac{1}{\theta_{i+1}} \cdot \frac{\theta_{i+1} - \theta_i}{\theta_{i+1} + 1}} \end{aligned}$$

This yields expression (38) for the price of goods sold by country  $i + 1$ :

$$\tau P_{i+1} = (A_i w_i)^{\frac{\theta_{i+1} + 1}{\theta_{i+1} - \theta_i}} (\tau A_{i+1} w_{i+1})^{-\frac{\theta_{i+1}}{\theta_{i+1} - \theta_i}}$$

For country  $i$ , this gives:

$$P_i = (A_{i-1} w_{i-1} / \tau)^{\frac{\theta_i + 1}{\theta_i - \theta_{i-1}}} (A_i w_i)^{-\frac{\theta_{i-1} + 1}{\theta_i - \theta_{i-1}}}$$

**Allocation of tasks across countries:** The range of tasks performed by country  $i$  can then be obtained as:

$$\begin{aligned} \frac{S_i}{\theta_i + 1} &= (A_i w_i)^{-\frac{1}{\theta_i + 1}} \left[ P_i^{\frac{1}{\theta_i + 1}} - (\tau P_{i+1})^{\frac{1}{\theta_i + 1}} \right] \\ &= (A_i w_i)^{-\frac{1}{\theta_i + 1}} \left[ (A_{i-1} w_{i-1} / \tau)^{\frac{1}{\theta_i - \theta_{i-1}}} (A_i w_i)^{-\frac{\theta_{i-1} + 1}{(\theta_i + 1)(\theta_i - \theta_{i-1})}} - (A_i w_i)^{\frac{\theta_{i+1} + 1}{(\theta_i + 1)(\theta_{i+1} - \theta_i)}} (\tau A_{i+1} w_{i+1})^{-\frac{1}{\theta_{i+1} - \theta_i}} \right] \end{aligned}$$

which can be simplified into expression (38) given in the text:

$$\frac{S_i}{\theta_i + 1} = \left( \frac{A_{i-1} w_{i-1}}{\tau A_i w_i} \right)^{\frac{1}{\theta_i - \theta_{i-1}}} - \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}}$$

For the last country  $N$  in the chain, we obtain:

$$\frac{S_N}{\theta_N + 1} = \left( \frac{A_{N-1} w_{N-1}}{\tau A_N w_N} \right)^{\frac{1}{\theta_N - \theta_{N-1}}}$$

Finally, the range of tasks performed by the last country in the chain is:

$$\begin{aligned} S_1 &= 1 - \sum_{i=2}^{N-1} S_i \\ &= 1 - (\theta_N + 1) \left( \frac{A_{N-1} w_{N-1}}{\tau A_N w_N} \right)^{\frac{1}{\theta_N - \theta_{N-1}}} - \sum_{i=2}^{N-1} (\theta_i + 1) \left[ \left( \frac{A_{i-1} w_{i-1}}{\tau A_i w_i} \right)^{\frac{1}{\theta_i - \theta_{i-1}}} - \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}} \right] \\ &= 1 - \sum_{i=2}^N (\theta_i + 1) \left( \frac{A_{i-1} w_{i-1}}{\tau A_i w_i} \right)^{\frac{1}{\theta_i - \theta_{i-1}}} + \sum_{i=2}^{N-1} (\theta_i + 1) \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}} \\ &= 1 - \sum_{i=1}^{N-1} (\theta_{i+1} + 1) \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}} + \sum_{i=2}^{N-1} (\theta_i + 1) \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}} \\ &= 1 - (\theta_1 + 1) \left( \frac{A_1 w_1}{\tau A_2 w_2} \right)^{\frac{1}{\theta_2 - \theta_1}} - \sum_{i=1}^{N-1} (\theta_{i+1} - \theta_i) \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}} \end{aligned}$$

**Final good price:** using the above expressions for  $S_1$  and  $P_2$ , we obtain the price of the final good:

$$\begin{aligned} P_1 &= \left[ \frac{S_1}{\theta_1 + 1} (A_1 w_1)^{\frac{1}{\theta_1 + 1}} + (\tau P_2)^{\frac{1}{\theta_1 + 1}} \right]^{\theta_1 + 1} \\ &= \left[ \frac{S_1}{\theta_1 + 1} (A_1 w_1)^{\frac{1}{\theta_1 + 1}} + (A_1 w_1)^{\frac{\theta_2 + 1}{(\theta_1 + 1)(\theta_2 - \theta_1)}} (\tau A_2 w_2)^{-\frac{1}{\theta_2 - \theta_1}} \right]^{\theta_1 + 1} \\ &= \frac{A_1 w_1}{(\theta_1 + 1)^{\theta_1 + 1}} \left[ S_1 + (\theta_1 + 1) \left( \frac{A_1 w_1}{\tau A_2 w_2} \right)^{\frac{1}{\theta_2 - \theta_1}} \right]^{\theta_1 + 1} \end{aligned}$$

$$\begin{aligned}
&= \frac{A_1 w_1}{(\theta_1 + 1)^{\theta_1 + 1}} \left[ 1 - \sum_{i=1}^{N-1} (\theta_{i+1} - \theta_i) \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}} \right]^{\theta_1 + 1} \\
&= \frac{A_1 w_1}{(\theta_1 + 1)^{\theta_1 + 1}} \Theta(\mathbf{wA}, \tau)
\end{aligned}$$

This corresponds to expression 40 in the text with the term in  $\Theta$  reflecting gains from fragmentation:

$$\Theta(\mathbf{wA}, \tau) = \left[ 1 - \sum_{n=1}^{N-1} (\theta_{n+1} - \theta_n) \left( \frac{w_n A_n}{\tau w_{n+1} A_{n+1}} \right)^{\frac{1}{\theta_{n+1} - \theta_n}} \right]^{\theta_n + 1}$$

**Demand for labor:** By the envelop theorem, demand for labor in upstream countries can be obtained by:

$$\frac{l_n w_n}{P_1} = \frac{d \log P_1}{d \log w_n} = \frac{d \log \Theta}{d \log w_n}$$

This gives expression (41) in the text:

$$\frac{l_n w_n}{P_1} = \frac{\left( \frac{w_{n-1} A_{n-1}}{\tau w_n A_n} \right)^{\frac{1}{\theta_n - \theta_{n-1}}} - \left( \frac{w_n A_n}{\tau w_{n+1} A_{n+1}} \right)^{\frac{1}{\theta_{n+1} - \theta_n}}}{\left( \frac{P_1}{A_1 w_1} \right)^{\frac{1}{\theta_1 + 1}}}$$

**Lagrangian multiplier:** The Lagrangian multiplier  $\lambda_G$  is equal to the Lagrangian multiplier  $\lambda_1$  in the most downstream country (since  $q_1 = 1$ ). Using (60), we obtain:

$$\lambda_G = (A_1 w_1)^{\frac{1}{\theta_1 + 1}} P_1^{\frac{\theta_1}{\theta_1 + 1}} = \frac{A_1 w_1}{(\theta_1 + 1)^{\theta_1}} \Theta(\mathbf{wA}, \tau)^{\frac{\theta_1}{\theta_1 + 1}}$$

**Firm scope:** For the most downstream firm in the most downstream country, equation (36) becomes:

$$w_i c'_i(s_{1,f=0}) = \lambda_G$$

This gives:

$$w_i a_i s_{1,f=0}^{\theta_1} = \lambda_G$$

Using the expression above for  $\lambda_G$ , we obtain:

$$\begin{aligned}
s_{1,f=0} &= \left( \frac{\lambda_G}{w_i a_i} \right)^{\frac{1}{\theta_1}} \\
&= \frac{\gamma_i (\theta_i + 1)}{\theta_i} \left( \frac{\lambda_G}{w_i A_i} \right)^{\frac{1}{\theta_1}} \\
&= \frac{\gamma_1}{\theta_1} \Theta(\mathbf{wA}, \tau)^{\frac{1}{\theta_1 + 1}}
\end{aligned}$$

To obtain downstream firm scope for other countries (expression 44), we use the first-order

condition for firm scope for  $f = 0$ :

$$w_i c'_i(s_{i,f=0}) = \lambda_i$$

which gives:

$$w_i a_i s_{i,f=0}^{\theta_i} = \lambda_i$$

Using  $\lambda_i = (w_i A_i)^{\frac{1}{\theta_i+1}} (P_i)^{\frac{\theta_i}{\theta_i+1}}$  (expression 60) together with the expression for  $P_i$ , we obtain:

$$\begin{aligned} s_{i,f=0} &= \left( \frac{\lambda_i}{w_i a_i} \right)^{\frac{1}{\theta_i}} \\ &= \frac{\gamma_i(\theta_i + 1)}{\theta_i} \left( \frac{\lambda_i}{w_i A_i} \right)^{\frac{1}{\theta_i}} \\ &= \frac{\gamma_i(\theta_i + 1)}{\theta_i} \left( \frac{P_i}{A_i w_i} \right)^{\frac{1}{\theta_i+1}} \\ &= \frac{\gamma_i(\theta_i + 1)}{\theta_i} (A_i w_i)^{-\frac{1}{\theta_i+1}} (A_{i-1} w_{i-1} / \tau)^{\frac{1}{\theta_i - \theta_{i-1}}} (A_i w_i)^{-\frac{\theta_{i-1}+1}{(\theta_i+1)(\theta_i-\theta_{i-1})}} \\ &= \frac{\gamma_i(\theta_i + 1)}{\theta_i} \left( \frac{A_{i-1} w_{i-1}}{\tau A_i w_i} \right)^{\frac{1}{\theta_i - \theta_{i-1}}} \end{aligned}$$

We follow similar steps to find the scope of the most upstream firm in each country,  $s_{i,F_i}$ :

$$s_{i,F_i} = \frac{(\theta_i + 1)\gamma_i}{\theta_i} \left( \frac{A_i w_i}{\tau A_{i+1} w_{i+1}} \right)^{\frac{1}{\theta_{i+1} - \theta_i}}$$

**Proposition 2:** Results in Proposition 2 are obtained simply by taking the derivative of the expressions above w.r.t trade costs  $\tau$ . In particular, we find:

$$\frac{\partial \Theta(\mathbf{wA}, \tau)}{\partial \tau} > 0$$

which implies that: i) the price in the final good and iv) the shadow cost  $\lambda_G$  decrease when trade costs decrease. Given equation (36)

$$q_i e^{\gamma_i f} w_i c'_i(s_{if}) = \lambda_G,$$

we obtain that a decrease in  $\lambda_G$  affects firm scope everywhere along the chain and leads to a decrease in  $s_{if}$ , conditional on the position on the chain, wages and the set of countries involved in the chain (point v). As trade costs decrease, however, countries tend to move downstream. Since firms scope is larger downstream, moving up the chain implies larger average firm scope for each country  $i > 1$  (except the most downstream one). This can be seen in expressions (44): firm scope at both end of the chain in country  $i$  is a decreasing function of  $\tau$  (point vi in Proposition 2). Finally, we can also see above that  $S_1$  is an increasing function of trade costs (conditional on wages), which proves point iii).

## Two-country case: proof of Proposition 3

**Final good prices and consumption choices:** Using the results from above, final goods prices are:

$$P_D(\omega) = \frac{1}{(\theta_D+1)^{\theta_D+1}} \left[ 1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \right]^{\theta_D+1}$$

$$P_U(\omega) = \frac{w_U A(\omega)}{(\theta_U+1)^{\theta_U+1}}$$

respectively when country  $D$  or  $U$  produces the final stages. This leads to the following thresholds defined in the text:

$$\begin{aligned} P_D(\omega_D^*) &= \tau P_U(\omega_D^*) \\ \tau P_D(\omega_U^*) &= P_U(\omega_U^*) \end{aligned}$$

There is no analytical solution for  $\omega_U^*$  but it is easy to check the following solution in  $\omega_D^*$ :

$$\omega_D^* = \frac{\tilde{T}_U \tau^{-\xi} w_U^{-\xi} (\theta_D+1)^{-(\theta_U - \theta_D)\xi}}{\tilde{T}_D + \tilde{T}_U \tau^{-\xi} w_U^{-\xi} (\theta_D+1)^{-(\theta_U - \theta_D)\xi}}$$

We can also verify that the foreign content for the marginal variety  $\omega_D^*$  is equal to one:

$$\frac{w_U l_U(\omega_D^*)}{P_D(\omega_D^*)} = 1$$

where  $\frac{w_U l_U(\omega)}{P_D(\omega)}$  is the share of value-added from country  $U$  in final goods sold by  $D$ :

$$\frac{w_U l_U(\omega)}{P_D(\omega)} = \frac{(\theta_D+1) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}}}{1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}}} \quad (63)$$

**General equilibrium:** We prove here that  $\tau w_U$  decreases as trade costs  $\tau$  decrease. Trade balance in gross flows imposes:

$$w_U L_U (1 - \omega_U^*) = L_D \omega_D^* + L_D \int_{\omega=\omega_D^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} d\omega + w_U L_U \int_{\omega=\omega_U^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} d\omega \quad (64)$$

which is equivalent to a trade balance in value-added content:

$$w_U L_U \int_{\omega=\omega_U^*}^1 \left( 1 - \frac{w_U l_U(\omega)}{P_D(\omega)} \right) d\omega = L_D \int_{\omega=0}^1 \min \left\{ \frac{w_U l_U(\omega)}{P_D(\omega)}, 1 \right\} d\omega \quad (65)$$

where  $\frac{w_U l_U(\omega)}{P_D(\omega)}$  denotes the foreign value-added content of final goods sold by  $D$  (equation 63).

We arrive at a contradiction if we assume that  $\tau w_U$  increases while  $\tau$  decreases. The right-hand-side term of expression (65) would decrease since it is a strictly decreasing function of  $\tau w_U$ : country  $D$  sources less from  $U$  if trade-cost-adjusted wages increase in  $U$ . On the other hand the

term on the left would increase because of higher income  $L_U w_U$ , a lower import threshold  $\omega_U^*$  (since goods from  $D$  would become relatively cheaper) and higher foreign value-added content  $1 - \frac{w_U l_U(\omega)}{P_D(\omega)}$ . Hence it must be that  $\tau w_U$  decreases when  $\tau$  decreases.

**Trade elasticity:** For country  $D$ , it is easy to check that the elasticity is the same as in Eaton and Kortum (2002):

$$\varepsilon_D^F \equiv \frac{d \log \left( \frac{\omega_D^*}{1 - \omega_D^*} \right)}{d \log \tau} = -\xi$$

For country  $U$ , we take the derivative of  $\tau P_D(\omega_U^*) = P_U(\omega_U^*)$  with respect to  $\log \tau$ , which gives:

$$1 + \frac{\partial \log P_D}{\partial \log \tau} \cdot \left[ 1 + \frac{d \log A(\omega_U^*)}{d \log \tau} \right] = \frac{\partial \log P_U}{\partial \log \tau} \frac{d \log A(\omega_U^*)}{d \log \tau}$$

In the expression above, the partial derivative  $\frac{\partial \log P_U}{\partial \log \tau}$  is equal to unity. The partial derivative  $\frac{\partial \log P_D}{\partial \log \tau}$  is lower than one and equals the share of value coming from  $U$  for the threshold variety  $\omega_U^*$ :

$$\frac{d \log P_D}{d \log \tau} = \frac{w_U l_U(\omega_U^*)}{P_D(\omega_U^*)}$$

After solving for  $\frac{d \log A(\omega_U^*)}{d \log \tau}$ , we find:

$$\frac{d \log A(\omega_U^*)}{d \log \tau} = \frac{1 + \frac{w_U l_U(\omega_U^*)}{P_D(\omega_U^*)}}{1 - \frac{w_U l_U(\omega_U^*)}{P_D(\omega_U^*)}}$$

The trade elasticity in final goods for country  $U$  is then:

$$\varepsilon_U^F = \frac{d \log \left( \frac{1 - \omega_U^*}{\omega_U^*} \right)}{d \log \tau} = \frac{1}{\xi} \frac{d \log A(\omega_U^*)}{d \log \tau} = \frac{1}{\xi} \frac{1 + \frac{w_U l_U(\omega_U^*)}{P_D(\omega_U^*)}}{1 - \frac{w_U l_U(\omega_U^*)}{P_D(\omega_U^*)}}$$

**VAX ratios:** For country  $D$ , the value-added content of exports to country  $U$  is:

$$\begin{aligned} VAX_D &= \frac{1}{1 - \omega_U^*} \int_{\omega_U^*}^1 \left( 1 - \frac{w_U l_U(\omega)}{P_D(\omega)} \right) d\omega \\ &= \frac{1}{1 - \omega_U^*} \int_{\omega_U^*}^1 \left( 1 - \frac{(\theta_D + 1) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}}}{1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}}} \right) d\omega \end{aligned}$$

For a given  $\omega$ , the term in the integral sum increases with trade-cost-adjusted wages  $\tau w_U$ , which itself increases with  $\tau$  (larger domestic value added share as trade costs increase). This is a direct effect. There is also a composition effect:  $\omega_U^*$  increases with  $\tau$ , so that country  $D$  only exports high-value-added goods (varieties  $\omega$  closer to one) when trade costs are higher. This second effect also leads to an increase in  $VAX_D$  when trade costs increase.

A similar intuition holds for the VAX ratio for country  $U$ , as described in the text.

## Two-country case: gains from trade

**Gains from trade for country  $D$ :** For country  $D$ , the wage and the price index under autarky are normalized to zero (in log). Hence the log of the price index with trade also reflects the gains from trade. Gains from trade are given by:

$$\Delta \log \left( \frac{1}{P_D} \right) = \int_0^{\omega_D^*} \log (\tau w_U A(\omega)) d\omega + \int_{\omega_D^*}^1 \log \Theta (\tau w_U A(\omega)) d\omega$$

with:

$$\Theta(\tau w_U A(\omega)) = \left[ 1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \right]^{\theta_D + 1}$$

and:

$$\Theta(\tau w_U A(\omega_D^*)) = \tau w_U A(\omega_D^*)$$

at the threshold  $\omega_D^*$ .

The expression for the gains from trade can be rewritten:

$$\begin{aligned} \Delta \log \left( \frac{1}{P_D} \right) &= - \int_0^{\omega_D^*} \log (\tau w_U A(\omega)) d\omega - \int_{\omega_D^*}^1 \log \Theta (\tau w_U A(\omega)) d\omega \\ &= - \int_0^{\omega_D^*} \log \left( \frac{A(\omega)}{A(\omega_D^*)} \right) d\omega - \int_{\omega_D^*}^1 \log \Theta (\tau w_U A(\omega)) d\omega \\ &\quad - \omega_D^* \log \Theta (\tau w_U A(\omega_D^*)) \end{aligned}$$

There are three terms in the above formula. The first term corresponds to Arkolakis et al (2012) formula. After integrating by part, we can see that it equals the ratio of the change in domestic consumption share and the trade elasticity  $\xi$  for country  $D$ :

$$\begin{aligned} - \int_0^{\omega_D^*} \log \left( \frac{A(\omega)}{A(\omega_D^*)} \right) d\omega &= \int_0^{\omega_D^*} \frac{\partial \log A(\omega)}{\partial \log \omega} d\omega \\ &= \frac{1}{\xi} \int_0^{\omega_D^*} \frac{d\omega}{1 - \omega} \\ &= -\frac{1}{\xi} \log (1 - \omega_D^*) \end{aligned}$$

The second and third terms reflect additional gain from fragmentation:

$$\begin{aligned} - \int_{\omega_D^*}^1 \log \Theta (\tau w_U A(\omega)) d\omega - \omega_D^* \log \Theta (\tau w_U A(\omega_D^*)) &= - \int_{\omega_D^*}^1 \frac{\partial \log \Theta}{\partial \log A} \frac{\partial \log A}{\partial \log \omega} d\omega \\ &= \int_{\omega_D^*}^1 \frac{\partial \log \Theta}{\partial \log A} \frac{1}{\xi} \frac{1}{1 - \omega} d\omega = \frac{1}{\xi} \int_{\omega_D^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} \frac{d\omega}{1 - \omega} > 0 \end{aligned}$$

using the equality between  $\frac{\partial \log \Theta}{\partial \log A}$  and the foreign labor content  $\frac{w_U l_U(\omega)}{P_D(\omega)}$ .

**Gains from trade for country  $U$ :** For country  $U$ , the price index under autarky is:

$$\log P_U^{aut} = \int_0^1 \log (w_U^{aut} A(\omega)) d\omega$$

where  $w_U^{aut}$  denotes the wage in autarky. With trade, the price index is:

$$\log P_U = \int_0^{\omega_U^*} \log (w_U A(\omega)) d\omega + \int_{\omega_U^*}^1 \log \tau \Theta (\tau w_U A(\omega)) d\omega$$

where  $\Theta (\tau w_U A(\omega))$  is defined like above:

$$\Theta (\tau w_U A(\omega)) = \left[ 1 - (\theta_U - \theta_D) (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \right]^{\theta_D + 1}$$

with the following equality at the threshold  $\omega_U^*$ :

$$\tau \Theta (\tau w_U A(\omega_U^*)) = w_U A(\omega_U^*)$$

Gains from trade can then be expressed as:

$$\begin{aligned} \Delta \log \left( \frac{w_U}{P_U} \right) &= \int_{\omega_U^*}^1 \log (w_U A(\omega)) d\omega - \int_{\omega_U^*}^1 \log \tau \Theta (\tau w_U A(\omega)) d\omega \\ &= \int_{\omega_U^*}^1 \log \left( \frac{A(\omega)}{A(\omega_U^*)} \right) d\omega - \int_{\omega_U^*}^1 \log \left( \frac{\Theta (\tau w_U A(\omega))}{\Theta (\tau w_U A(\omega_U^*))} \right) d\omega \end{aligned}$$

Like above, the first term corresponds to Arkolakis et al (2012) formula:

$$\int_{\omega_U^*}^1 \log \left( \frac{A(\omega)}{A(\omega_U^*)} \right) d\omega = -\frac{1}{\xi} \log \omega_U^*$$

The second term yields:

$$\begin{aligned} - \int_{\omega_U^*}^1 \log \left( \frac{\Theta (\tau w_U A(\omega))}{\Theta (\tau w_U A(\omega_U^*))} \right) d\omega &= - \int_{\omega_U^*}^1 \frac{\partial \log \Theta}{\partial \log A} \frac{\partial \log A}{\partial \omega} (1 - \omega) d\omega \\ &= - \int_{\omega_U^*}^1 \frac{\partial \log \Theta}{\partial \log A} \frac{1}{\xi \omega} d\omega \\ &= -\frac{1}{\xi} \int_{\omega_U^*}^1 \frac{w_U l_U(\omega)}{P_D(\omega)} \frac{d\omega}{\omega} < 0 \end{aligned}$$

This term is negative, which means that country  $U$  gains less than predicted by the Arkolakis et al (2012) benchmark.

## Two-country case: proof of Proposition 4

**Fragmentation and firm scope along the chain:** The proof of Proposition 4 relies on the general equilibrium result proven above:  $\tau w_U$  decreases when  $\tau$  decreases. This leads to

unambiguous implications of trade costs for fragmentation.

In particular, the shadow cost of fragmentation:

$$\lambda_G(\omega) = A_D(\omega)w_D \left[ \frac{1}{\theta_D+1} - \frac{\theta_U - \theta_D}{\theta_D+1} (\tau w_U A(\omega))^{-\frac{1}{\theta_U - \theta_D}} \right]^{\theta_D}$$

decreases when trade costs decrease since  $\tau w_U$  decreases. As described in the text,  $s_{D,f}(\omega)$  and  $s_{U,f}(\omega)$  can also be expressed as simple functions of  $\tau w_U$ : as  $\tau w_U$  decreases, firm scope decreases. Similar results can be found for  $S_D(\omega)$ , firm scope of the most upstream firm in country  $D$  and firm scope in the most downstream firm in country  $U$  as described in Proposition 4.