Multinational Production, Innovation Relocation, and the Consequences of Globalization

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I propose a multi-country endogenous growth model to understand the innovation relocation led by multinational production (MP). The model squares with the fact that countries with large net outward (inward) MP tend to specialize in product (process) innovation. The calibrated model shows that the decline in the cost of MP over 2004-2015 accounts for 35% of the observed relative decline in process innovation in four large European countries. This relocation of process innovation would hurt production workers in countries that are driven to specialize in product innovation, which is quantitatively important to understanding the welfare consequences of globalization. (*JEL* F12, F23, F43, O19, O31)

When production is offshored by multinationals, will innovation follow? The answer to this question is crucial to understanding the welfare implications of multinational production (MP). If the answer is yes, then countries with large net outward MP should worry that production offshoring undermines their innovation capabilities and damages their growth prospects.[1] The empirical studies suggest that the answer depends on the nature of innovation: *process-oriented*, incremental, and cost-reducing R&D relies more on instant feedback from local plants and is thereby

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[1]Pisano and Shih (2009, 2012) argue that the migration of manufacturing industries away from developed countries would erode their innovation capabilities, since at least part of the innovation activities are closely connected with manufacturing operations.

more likely to be co-located with production,[2] than *product-oriented* R&D focused on the creation of new goods.[3] As a result, the decline in the cost of MP tends to relocate process-oriented R&D activities towards host countries.[4]

Yet, there is a lack of tractable models that can be used to quantify this innovation relocation led by MP liberalization. The seminal work by Arkolakis et al. (henceforth ARRY, 2018) assumes that all R&D activities are conducted in headquarters and thereby does not allow for innovation relocation towards host countries. To fill the gap between theories and empirics, I develop a quantifiable multi-country endogenous growth model with MP. In particular, I divide innovative activities into the one that relies closely on the feedback from local manufacturing, labeled as "process innovation", and the one that does not, labeled as "product innovation".[5] I embed these two types of innovation into a framework that combines the static MP model by ARRY (2018) with the endogenous growth model by Eaton and Kortum (2001). I utilize this model to quantify the welfare consequences of trade and MP shocks, including China's WTO accession, regional trade and investment agreements like TPP and TTIP, and breakups between countries such as Brexit and the recent US-China trade conflicts.

Following ARRY (2018), I model product innovation as the creation of new product varieties. Once being created, the product can be produced and served globally, subject MP and trade frictions. This way I allow product innovation and production to be geographically fragmented. I depart from ARRY (2018) by considering process innovation that improves production efficiency but relies closely on instant feedback from local manufacturing. Specifically, I assume that production requires a continuum of non-tradable intermediate varieties. In each country, intermediate varieties are invented by local specialists and able to be used by all firms that produce in this coun-

[2]Branstetter et al. (2017) consistently identifies the impacts of offshoring manufacturing on innovation in the home country using a policy shock in Taiwan in 2001 that lifted restrictions preventing Taiwanese firms from offshoring their manufacturing to mainland China. In particular, they observe the offshoring of particular products and components and are able to link these products to the firms' patents. They argue that these Taiwanese firms specialize in incremental, process-based innovation and find that manufacturing offshoring has a *negative* impact on firm innovation in Taiwan.

[3]McKendrick et al. (2000) argue that offshoring enabled U.S.-based disk drive manufacturers to retain a technical lead over their Asian competitors. By shifting manufacturing to lower-cost locations, American firms were able to generate resource savings which was then invested in product-enhancing R&D.

[4]Puga and Trefler (2010) document the rise of incremental innovation in some low-wage countries such as China and India. They also find that a large fraction of patents for these incremental innovations are owned by multinational affiliates and involve local inventors in these countries.

[5]The core mechanism of this paper depends only on the fact that some innovative activities rely more on instant feedback from local plants than others. However, as I will show in Section 1, the label "product innovation" and "process innovation" are empirically relevant in this context.

try. When it is less costly to offshore production outside of the home country, product innovation, or creating final varieties, would become more profitable in the home country due to the reduction in production costs. In contrast, process innovation, or creating intermediate varieties, becomes less profitable in the home country since there are fewer firms producing there. The model predicts that countries with large net outward MP tend to specialize in product innovation, whereas countries with large net inward MP tend to specialize in process innovation. These predictions are consistent with international specialization of innovation observed in aggregate data.

The model provides a natural framework to explore the impact of MP liberalization on innovation and welfare. Solving the model analytically in special cases, I find that countries that specialize in product innovation realize smaller gains from MP than implied by ARRY (2018) due to the decline in their process innovation, while countries that specialize in production gain more from MP due to the surge of process innovation. This result resonates with the fear that production offshoring may undermine the innovation capabilities of local manufacturers in countries like the United States and hurt manufacturing workers in these countries. It also explains the success of Chinese manufacturing clusters: a huge number of suppliers are concentrated in those regions to serve large foreign multinationals and joint ventures; learning-by-doing and process innovation by these suppliers preserve the cost advantage of made-in-China, despite of China's rapid wage growth in recent years.

The model is calibrated using trade, MP, and innovation data for 21 countries. I then use the calibrated model to perform several counterfactual exercises. First, I examine innovation relocation and specialization led by MP liberalization. I find that MP liberalization allows countries that initially have large net outward (inward) MP to further specialize in product (process) innovation. The counterfactual results show that the changes in MP costs over 2004-2015 account for, on average, 35% of the relative decline in process innovation observed in four large European countries[6] over this period.

Second, I compare the welfare gains from MP in my model with the gains implied by ARRY (2018) and Ramondo and Rodriguez-Clare (2013). Notably, ARRY (2018) is isomorphic to the special case of my model in which process innovation is not allowed, while Ramondo and Rodriguez-

[6]These four countries, Germany, France, Britain, and the Netherlands, are ones that I have comparable data on innovation between 2004 and 2015.

Clare (2013) shut down both product and process innovation. I find that the U.S. welfare gain from MP in my model is 40% lower than the one implied by ARRY (2018),[7] which is consistent with the analytical results above. Moreover, the welfare gains from MP in the United States implied by Ramondo and Rodriguez-Clare (2013) can be completely offset by the decline in process innovation. In other words, the United States would lose from MP in the model with process innovation but without product innovation. In sum, innovation relocation and specialization are quantitatively important to understanding the welfare implications of MP.

Third, I use the model to quantify the welfare consequences of trade and MP shocks in the real world. The main message of this exercise is that these shocks transmit and propagate via trade and MP networks across countries, and innovation relocation will magnify their impacts in the long run. For example, the model suggests that Brexit, which potentially involves an increase in trade and MP costs between the United Kingdom and the rest of EU, could reduce the real income in the U.K. by 8.24% in the long run. Ireland, a country closely connected with the U.K. via trade and MP, incurs a decline in real income by 3.31% in the long run. The real income in other major EU countries such as Germany and France also decreases by about 1%. In contrast, the U.S. barely incurs any welfare losses and Canada even gains slightly from Brexit, since Brexit could shift UK-EU trade and MP towards North America.

The model is also used to quantify the impacts of the recent US-China trade conflicts. I find that trade conflicts will decrease *bilateral* trade imbalances between the U.S. and China but increase the *total* trade deficit in the U.S. and the *total* trade surplus in China. Intuitively, trade conflicts make the U.S multinationals increase their production in China to avoid high tariffs, which increases the profits of U.S. multinationals earned in China as well as the U.S. total trade deficit. This result highlights the unintended consequences of trade conflicts in the presence of MP: trade wars with China may not be able to address the U.S. trade deficits worried about by President Trump.

Finally, I characterize the countries' optimal innovation policies in the global economy. In this exercise, I allow governments to subsidize R&D for production and process innovation. I find that if countries decide their innovation policies unilaterally, they will heavily subsidize process innovation (or equivalently, production), since multinationals do not internalize the decline in process

[7] ARRY (2018) suggest that the U.S. real income increases by 7.5% from the world economy without MP to the observed world economy, while my model suggest that the U.S. gains only 4.3% from MP.

innovation led by their production offshoring. This result provides a rationale for the policies in some developed countries that aim at bringing offshored production back home.

My paper is closely related to recent quantitative models on the consequences of MP. First, Ramondo and Rodriguez-Clare (2013), Irarrazabal et al. (2013), and Tintelnot (2016) have embedded multinational firms into multi-country general equilibrium framework, allowing for counterfactual analysis in a rich geographic setting. However, there is no innovation in these models. Therefore, they cannot explore the innovation effect of MP and its welfare implications. Second, ARRY (2018) consider international specialization between innovation and production and show that endogenous innovation is important to understanding gains from openness. However, as discussed above, they assume that all innovative activities are conducted in headquarters and no innovation is geographically connected with production. So they do not allow for innovation relocation led by MP. Third, Fan (2016) considers R&D offshoring conducted by multinationals. However, he does not allow some R&D activities rely more on the feedback from local manufacturing than others. So it cannot rationalize innovation relocation and specialization observed in the data.

This paper is also related to a literature on MP and innovation. Rodriguez-Clare (2010) argues that in a dynamic model with endogenous innovation, production offshoring may hurt the host country in the long run by reducing its inputs in innovation. In contrast, Naghavi and Ottaviano (2009) argues that production offshoring may damage innovation in the source country since it reduces feedback from offshored plants to domestic labs. My model complements their arguments by suggesting that some R&D activities rely more on feedback from plants than others. So production offshoring may damage some innovation activities in the source country but benefit others.

My paper builds on endogenous growth model in the open economy. Eaton and Kortum (2001) establish a multi-country framework with trade and growth, which builds on the endogenous growth literature.[8] This paper extends these models to incorporate MP and different types of innovation. The model is highly tractable and quantifiable in a rich geographic setting.

In addition, this paper relates to empirical studies on the response of innovation to openness of trade and MP. Branstetter et al. (2017) suggests that production offshoring tends to reduce process-oriented innovation in the source countries. McKendrick et al. (2000) find that production

[8]See Acemoglu (2008) for surveys and extensive discussions.

offshoring helps the U.S. hard disk industry to concentrate on creating new products. My model is consistent with these empirical findings. There are also empirical assessments on trade and innovation. Bloom et al. (2015) show that Chinese import competition has spurred the innovation in the Europe, while Autor et al. (2017) find that China import competition reduced the U.S. manufacturing innovation. These studies do not distinguish between product and process innovation, which may be a reason for their opposite conclusions.

Finally, this paper relates to the literature of technology spillovers from multinationals. Ethier and Markusen (1996) has argued that local firms could passively absorb the technology of multinational affiliates and steal it. There is also an extensive empirical literature that identifies technology spillovers from multinationals to local firms (for example, Javorcik (2004), Gorodnichenko et al. (2014), and Lu et al. (2017)). Technology diffusion and spillovers are important to understanding MP. However, this paper focuses on active participation of local inventors in process innovation, leaving the quantification of technology diffusion via MP to future exploration.

The rest of this paper is organized as follows. In Section 1, I document some facts found in the aggregate data that motivate the theoretical specification of this paper. Section 2 describes the model and characterizes theoretical implications. I then calibrate the model in Section 3 and perform counterfactual exercises in Section 4. Section 5 concludes.

1 Motivational Facts

1.1 Data Description

To motivate the key elements of my model, I document some important patterns about innovation specialization and multinational production in the aggregate data. First, I need cross-country measures for product and process innovation. This data comes from OECD Innovation Indicators in 2015, which are based on the OECD survey of national innovation statistics and the Eurostat Community Innovation Survey. These innovation surveys have been taken in many OECD countries, guided by Oslo Manual, “the foremost international source of guidelines for the collection and use of data on innovation activities in industry". In particular, these surveys ask firms whether they have conducted the following four types of innovation: product, process, organization, and marketing. The definition of those innovations is summarized in the appendix.[9]

Second, I need measures for inward and outward MP sales. Direct measures for affiliate sales are very limited (see discussions in Ramondo et al. (2015)). However, Ramondo et al. (2015) suggests that MP sales are highly correlated with FDI stocks. Therefore, I utilize data on inward and outward FDI stocks for 2015 from UNCTAD database as a proxy for MP sales.

1.2 Empirical Regularities

As discussed above, empirical literature suggests that process-oriented R&D activities tend to be located close to production. Is this idea consistent with the patterns in aggregate data? Figure 1 shows that countries specialized in process innovation, as measured by the number of process-innovative firms divided by the number of product-innovative firms,[10] are countries whose inward FDI stocks exceed their outward FDI stocks. This pattern shows that (i) there is international specialization in product and process innovation, and (ii) countries that receive a large volume of offshored production are indeed specialized in process innovation. This pattern is consistent with the micro evidence in the literature that has been discussed at the beginning of this paper.

With increasing globalization, the innovation specialization illustrated by Figure 1 has become more pronounced over time. Figure 2 shows that the number of process-innovative firms, relative to product-innovative firms, has decreased in four large European countries between 2004 and 2015.[11] Clearly, these countries are further specialized in product innovation in this period. Over the same period, these countries have increased the share of their FDI to China, a low-wage country that has been becoming the world manufacturing center.

The bottom line of the motivational patterns shown in Figure 1 and 2 is that some innovation activities are more closely connected to local production than others. Moreover, it is empirically relevant to label those innovation activities that are more likely to be co-located with production as “process innovation" and others as “product innovation". In the quantitative framework, I allow for differential reliance of innovation activities on the feedback from local production and let international innovation specialization be determined by multinational production.

[9] More detailed information can be found in http://www.oecd.org/sti/inno-stats.htm.

[10] More specifically, I divide the number of process innovative firms (regardless of any other type of innovation) by the number of product firms (regardless of any other type of innovation).

[11] These four European countries are picked based on data availability.

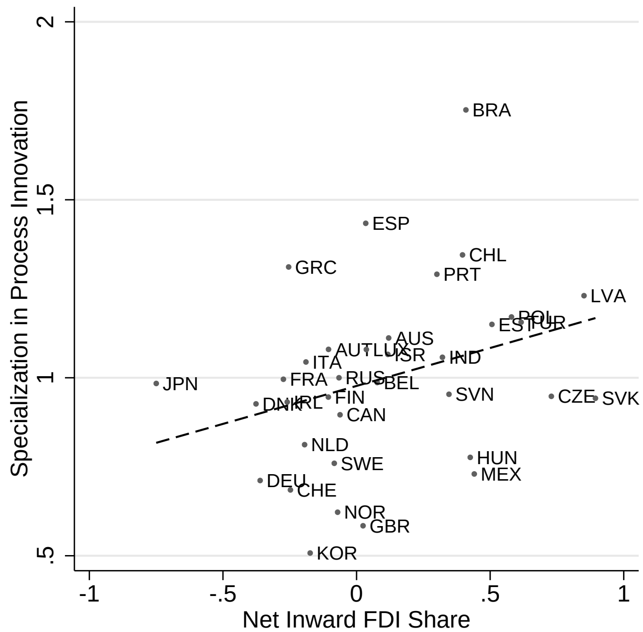
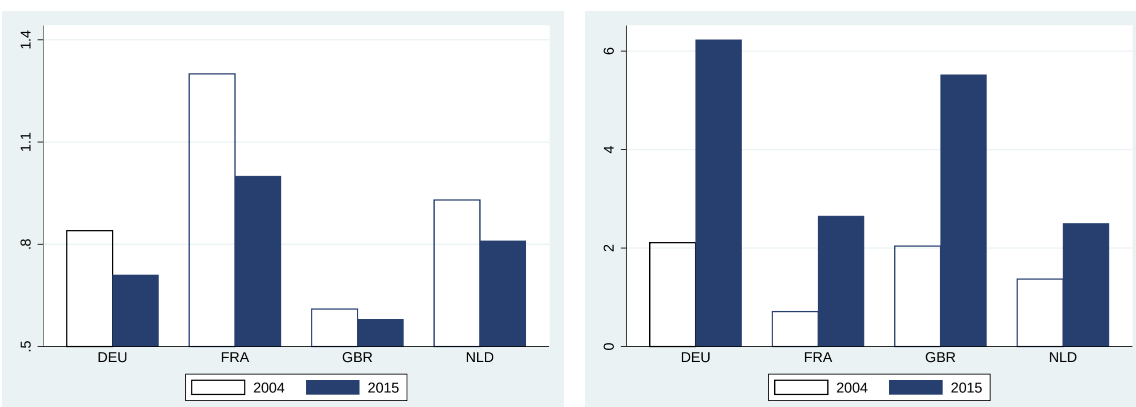


Figure 1: Innovation Specialization and Multinational Production

(Notes: Specialization in process innovation is measured by the number of process-innovative firms divided by the number of product-innovative firms. The innovation data comes from OECD Innovation indicators 2015. Net inward FDI share is defined as inward FDI stock - outward FDI stock divided by their sum. The FDI data comes from UNCTAD database 2015. The slope coefficient is 0.21 with s.e. 0.09. If Brazil is dropped, the slope coefficient is 0.17 with s.e. 0.08.)



(a) Specialization in Process Innovation

(b) FDI in China

Figure 2: Innovation Specialization and FDI in China

(Notes: Specialization in process innovation is measured by the number of process-innovative firms divided by the number of product-innovative firms. The innovation data comes from OECD Innovation indicators and OECD "Innovation in Firms" (2009). FDI in China is measured by the FDI stock in China as % in total outward FDI stock. The FDI data comes from UNCTAD database.)

2 Model

2.1 Preference and Technology

Time is continuous and goes to infinity. There are I countries in the world. At period t, country i is endowed with $L_i(t)$ labor that can work as production workers or researchers for product/process innovation. I assume that labor is immobile across countries but perfectly mobile across occupations within a country.[12] The representative consumer in country i has the following preference:

$$U_i = \int_0^\infty \exp(-\kappa t) \log C_i(t) dt, \tag{1}$$

where

$$C_i(t) = [\int_{\omega \in \Omega_i} q^f(\omega)^{\frac{\sigma-1}{\sigma}} d\omega]^{\frac{\sigma}{\sigma-1}}. \tag{2}$$

Note that $q^f(\omega)$ is the quantity of final variety ω and $\sigma > 1$ is the elasticity of substitution. Each variety is produced by a firm under monopolistic competition using a blueprint and a composite input. The unit cost of producing variety ω is

$$c^f(\omega) = \frac{P^m}{z^f(\omega)}, \tag{3}$$

where $z^f(\omega)$ is the efficiency of blueprint and P^m is the price index of composite inputs. A firm originated from country i can use its blueprint in country $l = 1, \ldots, I$ with efficiency $\mathbf{z}_i^f = (z_{i1}^f, \ldots, z_{iI}^f)$ which follows a multivariate Pareto distribution:

$$G_i^f(\mathbf{z}^f) = 1 - T_i^f(t)[\sum_{l=1}^{I} (z_l^f)^{-\frac{\theta}{1-\rho}}]^{1-\rho}, \quad z_i^f \geq [T_i^f(t) I^{1-\rho}]^{\frac{1}{\theta}}, \quad \theta > \sigma - 1, \tag{4}$$

where $T_i^f(t)$ is an exogenous efficiency shifter of the blueprints from country i. Notably, θ represents the dispersion of the blueprint efficiencies within a country. $\rho \in [0, 1)$ represents the correlation of the blueprint efficiencies across countries within a firm. Country i has a mass $M_i(t)$ of firms at period t, which is determined by product innovation below.

[12] As suggested by ARRY (2018), it is straightforward to incorporate imperfect mobility across occupations into the model.

The composite input is produced by a continuum of intermediates via a CES function

$$Q^m = [\int_{\nu \in V} q^m(\nu)^{\frac{\sigma_m - 1}{\sigma_m}} d\nu]^{\frac{\sigma_m}{\sigma_m - 1}}, \tag{5}$$

where $q^m(\nu)$ is the quantity of intermediate ν and $\sigma_m > 1$ is the elasticity of substitution across intermediates. At period t, country i can produce a mass $N_i(t)$ of intermediate varieties, which is determined by process innovation below. Intermediate market is also of monopolistic competition. Each intermediate variety is produced by labor and composite final goods. The unit cost of producing intermediate variety ν in country ℓ is

$$c_\ell^m(\nu, t) = \frac{w_\ell(t)^\beta P_\ell(t)^{1-\beta}}{z_\ell^m(\nu, t)}, \quad \beta \in (0, 1], \tag{6}$$

where $w_\ell(t)$ is the wage in ℓ, $P_\ell(t)$ is the price index for composite final goods in country ℓ, and $z_\ell^m(\nu, t)$ is the exogenous efficiency for producing intermediate ν. I assume that for all intermediate ν produced in country i, $z_i^m(\nu, t) = T_i^m(t)$.

A firm in country i who wants to produce in country ℓ incurs iceberg MP costs $\gamma_{i\ell}(t) \geq 1$. Shipping final goods from country i to country n incurs an iceberg trade cost $\tau_{\ell n}(t) \geq 1$. Moreover, the firm pays a fixed marketing cost $F_n(t)$ in terms of n's labor to make sales at destination market n.

The intermediates are assumed to be non-tradable. These intermediate varieties resemble the tacit knowledge of production which relies on the instant feedback from the frontier of local manufacturing. This kind of knowledge cannot be learned or created in places far away from production. So the non-tradable intermediates are the key for process innovation to be co-located with production.

2.2 Innovation

In this subsection, I specify the evolution of masses of final and intermediate varieties. New final varieties are invented by researchers. Inspired by Eaton and Kortum (2001), I assume that product innovation is characterized by a simple differential equation:

$$\dot{M}_i(t) = A_i^R(t) r_i(t)^\delta L_i(t), \quad r_i(t) := \frac{L_i^R(t)}{L_i(t)}, \quad \delta \in [0,1], \tag{7}$$

where $A_i^R(t)$ is an exogenous efficiency for product innovation and $L_i^R(t)$ is the quantity of researchers for product innovation. δ represents the degree of decreasing returns to scale in product innovation.

New intermediate varieties are created by local specialists. The mass of intermediate varieties in country ℓ thus depends on country ℓ's local specialists:

$$\dot{N}_\ell(t) = A_\ell^S(t) v_\ell(t)^\mu L_\ell(t), \quad v_\ell(t) := \frac{L_\ell^S(t)}{L_\ell(t)}, \quad \mu \in [0,1], \tag{8}$$

where $A_\ell^S(t)$ is an exogenous efficiency for process innovation and $L_\ell^S(t)$ is the quantity of local specialists.

2.3 The Firm's Static Problem

In this subsection, I solve the firm's static problem of trade and MP, taking the masses of final and intermediate varieties, $(M_i(t), N_i(t))$, and workers devoted to product and process innovation, $(L_i^R(t), L_i^S(t))$, as given. For brevity, I omit time index (t) in this subsection. The price of the composite input in country ℓ can be expressed as:

$$P_\ell^m = \tilde{\sigma}_m N_\ell^{-\eta} \frac{w_\ell^\beta P_\ell^{1-\beta}}{T_\ell^m}, \quad \eta := \frac{1}{\sigma_m - 1}, \quad \tilde{\sigma}_m = \frac{\sigma_m}{\sigma_m - 1}. \tag{9}$$

Suppose that firm ω in country i decides to serve market n. It will choose its production site by solving:

$$\ell(\omega) = \arg \min_{k=1,\ldots,I} \tilde{\sigma} \frac{\xi_{ikn}}{z_{ik}^f(\omega)}, \quad \xi_{i\ell n} = \gamma_{i\ell} P_\ell^m \tau_{\ell n}, \quad \tilde{\sigma} = \frac{\sigma}{\sigma - 1}. \tag{10}$$

Figure 3 illustrates the firm's cost and pricing and how they are determined by product and process innovation in different countries. After being created by product innovation in country i, firm ω solves the problem in Equation (10), given the vector of intermediate prices $\left(P_\ell^m\right)_{\ell=1}^N$.

The fixed marketing cost, F_n, is assumed to be sufficiently large so that for all i there are firms

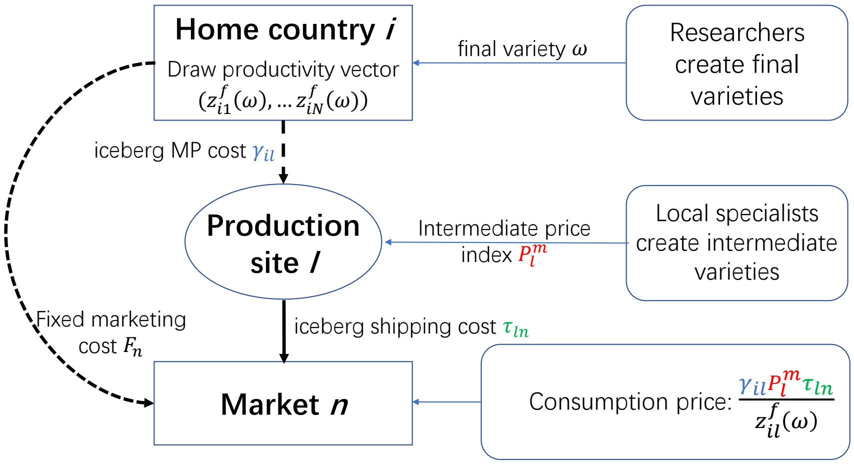


Figure 3: Innovation and Firm's Cost

that decides not to serve market n. Let $X_{i\ell n}$ be the value of final goods originated from country i, produced in country ℓ, and served to market n. Let X_n be the total final expenditure in country n. Following Arkolakis et al. (2017), I have

$$\pi_{i\ell n} := \frac{X_{i\ell n}}{X_n} = \psi_{i\ell n}\lambda_{in},$$
$$\psi_{i\ell n} = \left(\frac{T_i^f \xi_{i\ell n}^{-\theta}}{\Psi_{in}}\right)^{\frac{1}{1-\rho}}, \quad \Psi_{in} = T_i^f [\sum_k \xi_{ikn}^{-\frac{\theta}{1-\rho}}]^{1-\rho}, \quad \lambda_{in} = \frac{M_i \Psi_{in}}{\sum_k M_k \Psi_{kn}}. \tag{11}$$

Intuitively, $\psi_{i\ell n}$ is the probability of firms from country i using their plants in country ℓ to serve market n, whereas λ_{in} is the expenditure share in market n on final goods originated from country i.

Based on the property of Pareto distribution, it is straightforward to show that (i) the fixed marketing cost has a share $s := \frac{\theta-(\sigma-1)}{\theta\sigma}$ in the sales, (ii) the firms' net profits have a share $s^f := \frac{1}{\sigma} - s = \frac{\sigma-1}{\theta\sigma}$ in the sales, (iii) the intermediate suppliers' profits have a share $s^m := \frac{1}{\sigma_m}(1-s^f-s)$ in the sales, and (iv) the producers' wages have a share $s^p := 1-s^f-s-s^m$ in the sales.

Notably, the quantity of production workers in country ℓ, L^P_ℓ, is given in this static problem. Then the wage income of production workers can be expressed as

$$w_\ell L^P_\ell = \beta s^p \sum_{i,n} \pi_{i\ell n} X_n + s X_\ell, \tag{12}$$

where the total expenditure is the sum of final consumption and intermediate expenditure:

$$X_i = w_i L_i + (1-\beta) s^p \sum_{i,n} \pi_{i\ell n} X_n. \tag{13}$$

The price index of final goods in country n is given by

$$P_n^{-\theta} = \left(\frac{w_n F_n}{X_n}\right)^{-\frac{\theta-(\sigma-1)}{\sigma-1}} [\sum_k M_k \Psi_{kn}]. \tag{14}$$

2.4 The Value of Ideas and Dynamic Equilibrium

I then solve the value of ideas for new final and intermediate varieties. Once created, the final blueprints are non-forgettable. Therefore, the value of an idea for a final variety can be expressed by the present value of its expected profits:

$$V_i^f(\omega,t) = V_i^f(t) = \int_t^\infty \exp\{-\kappa(s-t)\} \frac{P_i(t)}{P_i(s)} \frac{\Pi_i^f(\omega,s)}{M_i(s)} ds, \tag{15}$$

where the period profit can be expressed as

$$\Pi_i^f(\omega,t) = \Pi_i^f(t) := s^f \sum_{\ell,n} X_{i\ell n}(t). \tag{16}$$

For the interior solution where $r_i > 0$, the first-order condition implies that

$$\delta A_i^R(t) V_i^f(t) r_i(t)^{\delta-1} = w_i. \tag{17}$$

Similarly, the value of an idea for a intermediate variety can be given by:

$$V_i^m(\omega,t) = V_i^m(t) = \int_t^\infty \exp\{-\kappa(s-t)\} \frac{P_i(t)}{P_i(s)} \frac{\Pi_i^m(\omega,s)}{N_i(s)} ds, \tag{18}$$

where

$$\Pi_i^m(t) = s^m \sum_{k,n} X_{kin}(t). \tag{19}$$

For the interior solution where $v_i > 0$, the first-order condition implies that

$$\mu A_i^S(t) V_i^m(t) v_i(t)^{\mu-1} = w_i. \tag{20}$$

Finally, labor market clearing implies that

$$L_i^P(t) = [1 - r_i(t) - v_i(t)]\, L_i(t). \tag{21}$$

Definition 1 (Dynamic Equilibrium) *The dynamic equilibrium consists of* $(w_i(t), X_i(t), P_i(t))$*,* $(r_i(t), v_i(t), L_i^P(t))$ *and* $(M_i(t), N_i(t))$ *such that*

(i) Given $(M_i(t), N_i(t), r_i(t), v_i(t))$*,* $(w_i(t), X_i(t), P_i(t))$ *satisfy the static labor market clearing in Equation (12), expenditure in Equation (13), and the price Equation (14).*

(ii) The final and intermediate varieties, $(M_i(t), N_i(t))$*, evolves according to Equation (7) and (8), respectively.*

(iii) The shares of researchers and local specialists, $(r_i(t), v_i(t))$*, satisfy the first-order condition (17) and (20), respectively.*

(iv) Labor market clearing condition in Equation (21) holds.

2.5 Balanced-Growth-Path Equilibrium

In this subsection, I solve the balance-growth-path (BGP) equilibrium in which each country has a constant growth rate. It can be used to characterize the long-term effects of trade and MP policies on innovation and welfare. Following Eaton and Kortum (2001), I consider the semi-endogenous growth in which (i) $g_L = \frac{\dot{L}_i(t)}{L_i(t)} > 0$ for all i and t, and (ii) all exogenous technologies and frictions are constant, i.e. $\dot{T}_i^f(t) = \dot{T}_\ell^m(t) = \dot{\gamma}_{i\ell}(t) = \dot{\tau}_{\ell n}(t) = \dot{F}_n(t) = \dot{A}_i^R(t) = \dot{A}_i^s(t) = 0$. Without the loss of generality, I normalize $w_\ell(t) = w_\ell$ and $w_1 = 1$ on the BGP.

Since $\dot{A}_i^R(t) = \dot{A}_i^s(t) = 0$ and $\dot{V}_i^f(t) = \dot{V}_i^m(t) = 0$ from the first order conditions in Equation (17) and (20). Moreover, by Equation (7),

$$\frac{\dot{M}_i(t)}{M_i(t)} = A_i^R r_i^\delta \frac{L_i(t)}{M_i(t)}. \tag{22}$$

Therefore, $\frac{\dot{M}_i(t)}{M_i(t)} = g_M = g_L$. Similarly, $\frac{\dot{N}_i(t)}{N_i(t)} = g_N = g_L$. Let the de-trended $M_i(t)$ and $N_i(t)$ be, respectively, $\tilde{M}_i := M_i(t)\exp(-g_L t)$ and $\tilde{N}_i := N_i(t)\exp(-g_L t)$ and let the de-trended total labor be $\tilde{L}_i = L_i(t)\exp(-g_L t)$. Then

$$\frac{\tilde{M}_i}{\tilde{L}_i} = \frac{A_i^R r_i^\delta}{g_L}, \quad \frac{\tilde{N}_i}{\tilde{L}_i} = \frac{A_i^S v_i^\mu}{g_L}. \tag{23}$$

The evolution of the price index satisfies

$$\frac{\dot{P}_i(t)}{P_i(t)} = g_P := -\frac{1}{\theta}\left[\frac{\theta-(\sigma-1)}{\sigma-1} + 1 + \theta\eta\right] g_L. \tag{24}$$

The de-trended final price index can therefore be defined as $\tilde{P}_i = P_i(t)\exp(-g_P t)$. To guarantee the discounted utility is bounded, I assume that $g_P < \kappa$. Then the value of idea can be expressed as

$$V_i^f(t) = \frac{1}{\kappa - g_P}\frac{\Pi_i^f(t)}{M_i(t)}, \quad V_i^m(t) = \frac{1}{\kappa - g_P}\frac{\Pi_i^m(t)}{N_i(t)}. \tag{25}$$

Then the first order conditions in Equation (17) and (20) imply that

$$r_i = \frac{\delta g_L}{\kappa - g_P}\frac{\Pi_i^f(t)}{w_i L_i(t)}, \tag{26}$$

and

$$v_i = \frac{\mu g_L}{\kappa - g_P}\frac{\Pi_i^m(t)}{w_i L_i(t)}. \tag{27}$$

Since r_i and v_i are constant on the BGP, $L_i^P(t)$ grows at the rate g_L for all i on the BGP. Let the de-trended production labor be $\tilde{L}_i^P = L_i^P(t)\exp(-g_L t)$. Then the labor market clearing implies that

$$\tilde{L}_i^P = [1 - r_i - v_i]\tilde{L}_i. \tag{28}$$

Definition 2 (BGP Equilibrium) *The BGP equilibrium consists of* $(w_i, X_i, \tilde{P}_i)$, $(r_i, v_i, \tilde{L}_i^P)$, *and* $(\tilde{M}_i, \tilde{N}_i)$ *such that*

(i) The static equilibrium conditions (12), (13), and (14) are satisfied.

(ii) The de-trended masses of final and intermediate varieties satisfy Equation (23).

(iii) Equilibrium researchers and local specialists satisfy Equation (26) and (27).

(iv) Labor market clears as Equation (28).

To highlight the role of innovation specialization in shaping the welfare gains from MP liberalization, I also consider the static model with which $(M_i(t), N_i(t)$ are constant over time and exogenously given. Given the dynamic equilibrium in Definition 1, the static equilibrium can be defined by shutting innovation down:

Definition 3 (Static Equilibrium) *The static equilibrium consists of* (w_i, X_i, P_i) *such that:*

(i) $\mu = \delta = 0$ *so that* $M_i(t) = M_i(0)$ *and* $N_i(t) = N_i(0)$ *for all t and all workers are production workers:*

$$w_\ell L_\ell = \beta s^p \sum_{i,n} \pi_{i\ell n} X_n + s X_\ell. \tag{29}$$

(ii) All profits are allocated to production workers. So the total expenditure is given by

$$X_i = w_i L_i + \Pi_i^f + \Pi_i^m + (1-\beta) s^p \sum_{i,n} \pi_{i\ell n} X_n. \tag{30}$$

(iii) The price index satisfies the price Equation (14).

To isolate the impacts of product and process innovation, I define the product-innovation-only equilibrium by imposing $\mu = 0$ in the BGP and allocating $\Pi_i^m(t)$ to production workers. Analogously, I define the process-innovation-only equilibrium by imposing $\delta = 0$ in the BGP and allocating $\Pi_i^f(t)$ to production workers. Notably, these special cases nested by my BGP equilibrium are isomorphic to several important models:

Table 1: Special Cases nested by the BGP Equilibrium

Model	Parameters	Special Case
ARRY (2018)	$\delta = \beta = 1$ and $\eta = \mu = 0$	Product-innovation-only
Ramondo and Rodriguez-Clare (2013)	$\delta = \eta = \mu = 0$	Static
Melitz (2003)	$\gamma_{i\ell} = \infty$ for all $i \neq n$ and $\beta = 1$	Trade

2.6 Equilibrium Characterization

2.6.1 Innovation Specialization and Multinational Production

How does MP affect a country's specialization between product and process innovation? The model delivers a simple expression for this effect in the BGP:

Proposition 4 *Consider the BGP equilibrium. Let* $Y_i^f := \sum_{\ell,n} X_{i\ell n}$ *be the total sales of firms originated from country* i *and* $Y_i^m := \sum_{k,n} X_{kin}$ *be the total value of final goods produced in country* i*. Then the ratio of process-innovation workers to product-innovation workers can be expressed as*

$$\frac{v_i}{r_i} = \tilde{\Lambda}\frac{Y_i^m}{Y_i^f}, \quad \tilde{\Lambda} = \frac{\mu}{\delta}\frac{s^m}{s^f}. \tag{31}$$

An immediate corollary of Proposition 4 is that, without MP, $Y_i^f = Y_i^m$ and thereby $\frac{v_i}{r_i} = \tilde{\Lambda}$ for all i. So the model implies that, without MP, there is no international specialization between product and process innovation.

In contrast, in the global economy with MP, $Y_i^m > Y_i^f$ if country i's inward MP sales exceeds its outward MP sales. Proposition 4 suggests that countries that have large net inward FDI tend to specialize in process innovation (i.e. with high $\frac{v_i}{r_i}$). This theoretical prediction is consistent with the data patterns shown in Figure 1.

2.6.2 BGP Equilibrium in Relative Changes

Instead of solving for the BGP equilibrium in levels, I derive the changes in BGP equilibrium outcomes under policy changes. To achieve this, I utilize the "exact-hat" algebra developed by Dekle, Eaton, and Kortum (2008) which is now a standard device in quantitative trade analysis.

Definition 5 *Let* $\mathbf{Y} := (w_i, r_i, v_i, \tilde{L}_i^P, \tilde{M}_i, \tilde{N}_i, X_i, \tilde{P}_i)$ *be a BGP equilibrium outcome under trade and MP costs* $(\tau_{\ell n}, \gamma_{i\ell})$ *and let* $\mathbf{Y}'$ *be a BGP equilibrium outcome under trade and MP costs* $(\tau'_{\ell n}, \gamma'_{i\ell})$*. Define* $\hat{\mathbf{Y}}$ *as a BGP equilibrium under* $(\tau'_{\ell n}, \gamma'_{i\ell})$ *relative to* $(\tau_{\ell n}, \gamma_{i\ell})$ *where a variable with a hat "*$\hat{y}$*" represents the relative change of the variable, namely* $\hat{y} = y'/y$*. Using Equations (12), (13), (14), (26), (27), (23), and (28), the equilibrium conditions in relative changes satisfy: Production wage* *income:*

$$\hat{w}_\ell \hat{\tilde{L}}_\ell^P w_\ell \tilde{L}_\ell^P = \beta s^p \sum_{i,n} \hat{\pi}_{i\ell n} \hat{X}_n \pi_{i\ell n} X_n + s \hat{X}_\ell X_\ell, \tag{32}$$

where the changes in trade and MP shares are given by

$$\hat{\pi}_{i\ell n} = \hat{\psi}_{i\ell n} \hat{\lambda}_{in}, \quad \hat{\psi}_{i\ell n} = \frac{\hat{\xi}_{i\ell n}^{-\frac{\theta}{1-\rho}}}{\sum_k \psi_{ikn} \hat{\xi}_{ikn}^{-\frac{\theta}{1-\rho}}}, \quad \hat{\lambda}_{in} = \frac{\hat{\tilde{M}}_i \left[\sum_k \psi_{ikn} \hat{\xi}_{ikn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}}{\sum_h \lambda_{hn} \hat{\tilde{M}}_h \left[\sum_k \psi_{hkn} \hat{\xi}_{hkn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}}, \tag{33}$$

$$\hat{\xi}_{i\ell n} = \hat{\gamma}_{i\ell} \hat{P}_\ell^m \hat{\tau}_{\ell n}, \quad \hat{P}_\ell^m = \hat{\tilde{N}}_\ell^{-\eta} \hat{w}_\ell^\beta \hat{\tilde{P}}_\ell^{1-\beta}.$$

Total expenditure:

$$\hat{X}_\ell X_\ell = \hat{w}_\ell w_\ell \tilde{L}_\ell + (1-\beta) s^p \sum_{i,n} \hat{\pi}_{i\ell n} \hat{X}_n \pi_{i\ell n} X_n. \tag{34}$$

De-trended final price index:

$$\hat{\tilde{P}}_n^{-\theta} = \left(\frac{\hat{w}_n}{\hat{X}_n}\right)^{-\frac{\theta-(\sigma-1)}{\sigma-1}} \sum_h \lambda_{hn} \hat{\tilde{M}}_h \left[\sum_k \psi_{hkn} \hat{\xi}_{hkn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}. \tag{35}$$

Researchers and local specialists:

$$\hat{r}_\ell = \frac{\hat{\Pi}_\ell^f}{\hat{w}_\ell}, \quad \hat{v}_\ell = \frac{\hat{\Pi}_\ell^m}{\hat{w}_\ell}, \tag{36}$$

where

$$\hat{\Pi}_i^f = \frac{\sum_{\ell,n} \hat{\pi}_{i\ell n} \hat{X}_n \pi_{i\ell n} X_n}{\sum_{\ell,n} \pi_{i\ell n} X_n}, \quad \hat{\Pi}_\ell^m = \frac{\sum_{i,n} \hat{\pi}_{i\ell n} \hat{X}_n \pi_{i\ell n} X_n}{\sum_{i,n} \pi_{i\ell n} X_n}. \tag{37}$$

De-trended masses of final and intermediate varieties:

$$\hat{\tilde{M}}_i = \hat{A}_i^R \hat{r}_i^\delta, \quad \hat{\tilde{N}}_i = \hat{A}_i^S \hat{v}_i^\mu. \tag{38}$$

Labor market clearing:

$$r_i \hat{r}_i + v_i \hat{v}_i + \frac{\tilde{L}_\ell^P}{\tilde{L}_\ell} \hat{\tilde{L}}_\ell^P = 1. \tag{39}$$

Armed by the equilibrium in relative changes, I can perform policy experiments without calibrating the level of productivity and trade and MP costs. In Section 3, I will calibrate parameters

$(\delta, \mu, \eta, \theta, \rho, \sigma, \beta)$ and impute trade flows $(X_{i\ell n})$ from trade and MP data. Moreover, the "exact-hat" algebra for the product-innovation-only (process-innovation-only) model and the static model is presented in the appendix.

2.6.3 Gains from Openness in the BGP

How important is it to account for product and process innovation in order to quantify the welfare effects of counterfactual changes in trade and MP costs? To achieve this, I utilize the "sufficient statistics" approach developed by Arkolakis, Costinot, and Rodriguez-Clare (ACR, 2011) that expresses welfare gains from openness by a few structural parameters and observable statistics in the data. I consider changes in trade and MP costs, $(\hat{\tau}_{\ell n}, \hat{\gamma}_{i\ell})$, on the BGP. The changes in BGP welfare can thus be given by:

Proposition 6 (Gains from Openness on the BGP) *Suppose $\beta = 1$. Then the changes in the BGP welfare with respect to trade and MP liberalization satisfy*

$$\log\left(\hat{W}_i\right) := \log\left(\frac{\hat{w}_i}{\hat{\hat{P}}_i}\right) = \underbrace{-\frac{1-\rho}{\theta}\log\left(\hat{\pi}_{iii}\hat{\lambda}_{ii}^{\frac{\rho}{1-\rho}}\right)}_{\text{ACR terms}} + \underbrace{\frac{\delta}{\theta}\log\left(\frac{\hat{Y}_i^f}{\hat{X}_i}\right)}_{\text{Product innovation}} + \underbrace{\eta\mu\log\left(\frac{\hat{Y}_i^m}{\hat{X}_i}\right)}_{\text{Process innovation}}, \tag{40}$$

where Y_i^f and Y_i^m are defined in Proposition 4.

The first term on the right-hand side of Equation (40) is the standard gains from the increase in varieties that have been studied in ACR (2011). Due to the specialization in product and process innovation, there are two additional terms on the right-hand side of Equation (40). $\frac{\delta}{\theta}\log\left(\frac{\hat{Y}_i^f}{\hat{X}_i}\right)$ characterizes the gains from specializing in product innovation, which depend on the curvature of researchers on product innovation, δ, and the economies of scale in firm entry, $\frac{1}{\theta}$. This term is also captured by the model in ARRY (2018). The novel feature of this paper is the term $\eta\mu\log\left(\frac{\hat{Y}_i^m}{\hat{X}_i}\right)$ that characterizes the gains from specializing in process innovation. It depends on the curvature of local specialists on process innovation, μ, and the economies of scale in production, η. Given the observations on $(\hat{\pi}_{iii}, \hat{\lambda}_{ii}, \hat{Y}_i^f, \hat{Y}_i^m, \hat{X}_i)$, the economies of scale in production shift the gains from openness from countries that further specialize in product innovation into countries that further specialize in process innovation and production.

2.6.4 The Impacts of MP Liberalization: An Illustrative Three-Country Case

To illustrate some key insights of the model, I consider the case where $I = 3$ with $T_i^f = A_i^R = A_i^S = F_i = 1$ and $T_i^m = \tilde{\sigma}_m$ for $i = 0,1,2$. Country 1 and 2 are two small countries while country 0 is the rest of the world: $\tilde{L}_0 >> \tilde{L}_1 = \tilde{L}_2 = 1$. To get analytical solutions, I set $\rho = 0$, $\delta = \mu = \beta = g_L = \theta\eta = \kappa - g_P = 1$, and $s^f = s^m + s^p$. Trade is frictionless, i.e. $\tau_{\ell n} = 1$ for all (ℓ, n). MP is only possible from country 1 to country 2, i.e. $\gamma_{12} = \gamma \in [1,\infty]$ and $\gamma_{i\ell} = \infty$ for all $i \neq \ell$ and $(i,\ell) \neq (1,2)$. The wage in country 0 is taken as the numeraire.

How does MP liberalization affect innovation specialization in this special case?

Proposition 7 *Consider the BGP of the three-country case above. The reduction of γ makes the home country specialize in product innovation, i.e. $-\frac{\partial r_1}{\partial \gamma} > 0$ and $-\frac{\partial v_1}{\partial \gamma} < 0$. In the meantime, the host country specializes in process innovation, i.e. $-\frac{\partial r_2}{\partial \gamma} < 0$ and $-\frac{\partial v_2}{\partial \gamma} > 0$.*

Notably, the country with net outward MP tends to specialize in product innovation, which is consistent with the evidence in the aggregate data. The intuition behind this results relies on the co-location of product and process innovation with production. When γ decreases, it is cheaper for firms in country 1 to offshore their production to country 2. As more firms produce in country 2, the demand for intermediates increases, spurring process innovation in country 2. The process innovation in country 2 further reduces its production cost and attract more production offshoring from country 1. This feedback loop continues until the wage of production workers in country 2 is sufficiently high. Moreover, the wage increase in country 2 shifts workers from product innovation to process innovation and production.

The opposite happens in country 1, the home country. As production is offshored, the demand for intermediates decreases, depressing process innovation in country 1. This further increases the production cost in country 1, leading to more production offshoring and the decline in the wage of production workers. The wage decrease then shifts workers from production and process innovation to product innovation.

How does innovation specialization affect the welfare implications of MP liberalization?

Proposition 8 *Consider the BGP of the three-country case above. Define welfare gains from MP as $GMP_i = \frac{W_i(\gamma=1)}{W_i(\gamma=\infty)}$. Consider the baseline model as well as the product-innovation-only model in* *which* $\mu = \eta = 0$. *Then* $GMP_1^{baseline} < GMP_1^{product\text{-}innovation\text{-}only}$ *and* $GMP_2^{baseline} > GMP_2^{product\text{-}innovation\text{-}only} = GMP_0^{product\text{-}innovation\text{-}only}$.

As summarized in Table 1, the BGP of product-innovation-only case is isomorphic to ARRY (2018). Proposition 8 suggests that incorporating process innovation into ARRY (2018) is important to understanding the welfare gains from MP. For the home country, the benefits from the decline in production costs and the increase in product innovation are, at least partially, offset by the decline in process innovation. In other words, the relocation of process innovation associated with production offshoring does hurt the production workers in the home country. It also hurts the firms that keep their production in the home country. Both effects are welfare-reducing. The opposite happens in the host country since the inward MP spurs process innovation, which reduces production costs and attract further inward MP.

2.6.5 Transitional Dynamics and Multiple BGP

In this subsection, I discuss (i) the transitional dynamics given initial technology stocks, and (ii) the uniqueness of BGP for arbitrary initial conditions.

First, I will show that this “semi-endogenous growth" model does feature transitional dynamics:

Proposition 9 (Transitional Dynamics) *Suppose that* $g_P := -\frac{1}{\theta}\left[\frac{\theta-(\sigma-1)}{\sigma-1} + 1 + \theta\eta\right] g_L < \kappa$. *As long as* $(M_i(0), N_i(0))$ *do not lie at their BGP, there will be transitional dynamics.*

The proof to Proposition 9 is presented in the appendix.

Do economies starting from different initial technology stocks converge to the same BGP? They may not if there exist tremendous external economies of scale in production, i.e. η is large. I will illustrate this multiplicity of BGP by a simple two-country numeric example. Let $\tilde{L}_i = A_i^R = A_i^S = 1$ for $i = 1,2$ and $\beta = \delta = \mu = 1$. Also $\gamma_{i\ell} = \tau_{\ell n} = 2$ for all $i \neq \ell$ and $\ell \neq n$. Moreover, I assume that $\theta = \sigma = 4$ and $\rho = 0$.

I derive all BGP equilibria under different values of η. Figure 4 illustrates the relative researcher shares, $\frac{r_1}{r_2}$, in different BGP equilibria. When η is sufficiently large ($\eta \geq 0.8$), there are three BGP equilibria. Since two countries are identical ex ante, there is a symmetric BGP equilibrium in which $\frac{r_1}{r_2} = \frac{v_1}{v_2} = \frac{w_1}{w_2} = 1$. In addition, there are two asymmetric BGP equilibria in which

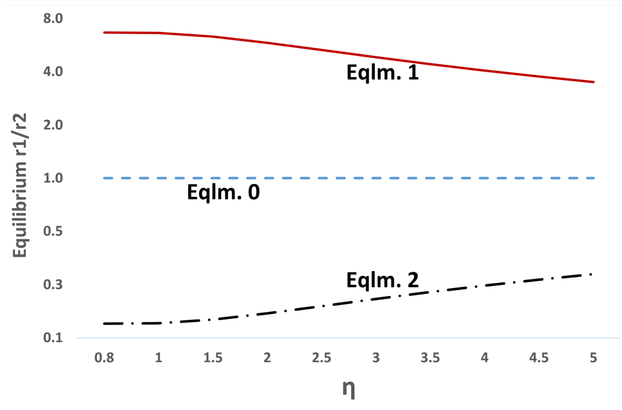


Figure 4: Multiple BGP Equilibria w.r.t. η

country 1 specializes in product or process innovation. Interestingly, with $\eta \in [0.8, 1]$, the innovation specialization under asymmetric equilibria is extreme. The intuition is that when external economies of scale in production are in the medium range, a country has to allocate a substantial fraction of its labor to process innovation to support its innovation specialization in the equilibrium. In contrast, when external economies of scale in production are sufficiently strong, a modest labor share in process innovation can ensure a country's comparative advantage in process innovation.

The numeric example shows the existence of multiple BGP. However, it suggests that multiple BGP equilibria only emerge when η is sufficiently large, which is not likely to be the case in my quantitative analysis. In my quantitative practice below, I do not find any multiple BGP equilibria.

3 Calibration

3.1 Data used for Calibration

The quantitative practice of this paper focuses on the relative changes of BGP equilibrium with respect to exogenous trade and MP policy changes. It requires three sets of data: (i) bilateral MP sales in the BGP, (ii) bilateral trade flows in the BGP, and (iii) the countries' specialization in innovation. I consider a world with 21 major economies.[13]

Notably, the motivating facts about innovation specialization are derived from the data in 2015. Therefore, my quantitative analysis is based on the bilateral MP flows for the year 2011, which are

[13] I include Austria, Belgium, Canada, China, Germany, Denmark, Spain, Finland, France, United Kingdom, Greece, Ireland, Italy, Japan, Korea, Mexico, the Netherlands, Portugal, Sweden, Taiwan, the United States.

imputed from the latest available *bilateral* FDI stock data from UNCTAD.[14] Moreover, I obtain bilateral trade flows for the year 2011 from WIOD.

Finally, to calibrate parameters (δ, μ) that link the steady state innovation specialization with MP position, I need data measures for countries' specialization between product and process innovation across countries. The data comes from OECD Innovation Indicators in 2015 and has been described in details in Section 1.

3.2 Calibration Procedure

I calibrate the dispersion of core productivity $\theta = 3.058$ following the estimates of Lashkaripour and Lugovskyy (2017). Accordingly, I set the elasticity of substitution $\sigma = 3$ based on the firm's profit share. Moreover, β is the value-added share of production which is set to be 0.5.

η determines the external economies of scale in production since $-\frac{\partial \log P_\ell^m}{\partial \log N_\ell} = \eta$. A number of empirical and quantitative papers have estimated the external economies of scale using different identification strategies. Recent studies such as Bartelme et al. (2018) and Lashkaripour and Lugovskyy (2017) use trade data to estimate external economies of scale in production. Here, I follow Lashkaripour and Lugovskyy (2017) by setting $\eta = 0.27$, which is in line with the estimates in earlier studies (See, for example, Greenstone et al. (2010)). Notice that if $\eta = 0$ then production is of constant return to scale and there is no need for process innovation. As a result, the relationship between MP and process innovation shown in Figure 1 suggest that we must have $\eta > 0$. Moreover, the sufficient statistics of gains from openness in Proposition 6 show that when η is large, countries that further specialize in production gain more from openness.

ρ determines the correlation of productivity draws within multinationals. Wang (2017) estimate the elasticity of MP entry w.r.t. corporate tax rates to be -7.26. In the context of this paper, it implies that $\frac{\theta}{1-\rho} = 7.26$ and thereby $\rho = 0.58$.

Parameters (δ, μ) govern the growth and steady states of product and process innovation. Combining Equation (26) and (27), we have

$$\frac{r_i}{v_i} = \frac{\delta}{\mu} \frac{\Pi_i^f}{\Pi_i^m} + u_i, \tag{41}$$

[14] As discussed above, Ramondo et al. (2015) have shown that bilateral MP sales are strongly correlated with bilateral FDI stock.

where u_i is an exogenous measurement error. I regress $\frac{r_i}{v_i}$ on $\frac{\Pi_i^f}{\Pi_i^m}$ with zero intercept. This regression generates $\frac{\delta}{\mu}$. Since δ and μ cannot be identified separately through the lens of my model, I set $\mu = 1$ and calibrate δ accordingly. The regression suggests that $\frac{\delta}{\mu} = 0.68$ with s.e. 0.03.[15]

Finally, the "exact-hat" algebra requires trilateral trade flows $(X_{i\ell n})$, which are unobservable in the data. Through the lens of the model, I impute $(X_{i\ell n})$ from bilateral trade flows $X_{\ell n}^{TR}$ and bilateral MP flows $X_{i\ell}^{MP}$. Let $K_{i\ell} := \left(M_i T_i^f\right)^{-\frac{1}{\theta}} \gamma_{i\ell}$ and $\tilde{\tau}_{\ell n} = P_\ell^m \tau_{\ell n}$. Then trilateral trade flows can be computed by

$$X_{i\ell n} = \frac{K_{i\ell}^{-\frac{\theta}{1-\rho}} \tilde{\tau}_{\ell n}^{-\frac{\theta}{1-\rho}} \left[\sum_k K_{ik}^{-\frac{\theta}{1-\rho}} \tilde{\tau}_{kn}^{-\frac{\theta}{1-\rho}}\right]^{-\rho}}{\sum_h \sum_r K_{hr}^{-\frac{\theta}{1-\rho}} \tilde{\tau}_{rn}^{-\frac{\theta}{1-\rho}} \left[\sum_k K_{hk}^{-\frac{\theta}{1-\rho}} \tilde{\tau}_{kn}^{-\frac{\theta}{1-\rho}}\right]^{-\rho}} X_n. \tag{42}$$

I solve $(K_{i\ell}, \tilde{\tau}_{\ell n})$ by matching bilateral trade and MP flows generated by the model to their data counterparts. Then I compute $X_{i\ell n}$ from Equation (42).

3.3 Calibration Results

Table 2 summarizes the calibration of model parameters. Parameters (δ, μ) are recovered by Equation (41). The data and detailed regression results are presented in the appendix.

Table 2: Calibrated Parameters

Parameter	Value	Source
θ	3.058	Lashkaripour and Lugovskyy (2017)
σ	3	Profit share
β	0.5	Value-added share of production
η	0.27	Lashkaripour and Lugovskyy (2017)
ρ	0.58	Wang (2017)
μ	1	Equation (41)
δ	0.68	Equation (41)
$(X_{i\ell n})$	-	Equation (42)

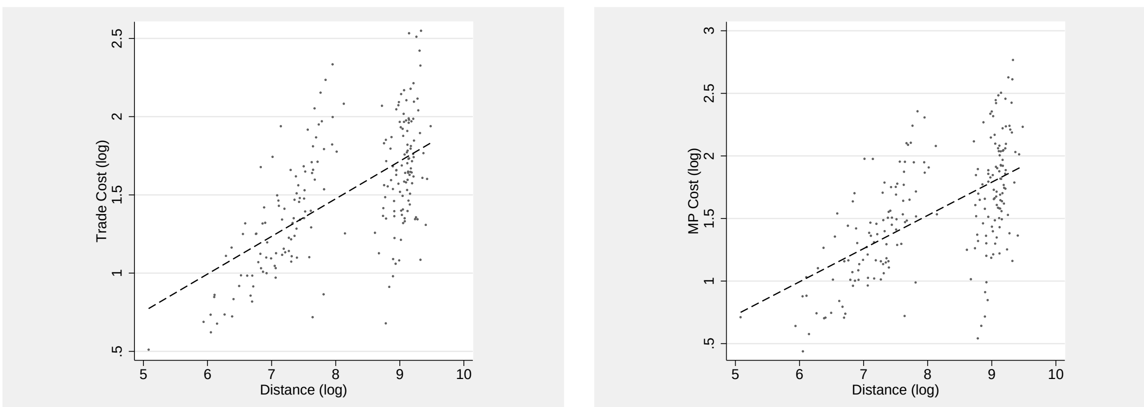
Trade and MP costs are identified from the calibrated trilateral trade flows if we assume sym-

[15] The details of this regression are presented in the appendix.

metry, i.e. $\tau_{\ell n} = \tau_{n\ell}$ for all (ℓ, n) and $\gamma_{i\ell} = \gamma_{\ell i}$ for all (i, ℓ). Under symmetry, we have

$$\tau_{\ell n} = \left(\sqrt{\frac{X_{\ell\ell n} X_{\ell n\ell}}{X_{\ell nn} X_{\ell\ell\ell}}} \right)^{-\frac{1-\rho}{\theta}}, \quad \gamma_{i\ell} = \left(\sqrt{\frac{X_{i\ell\ell} X_{\ell i\ell}}{X_{ii\ell} X_{\ell\ell\ell}}} \right)^{-\frac{1-\rho}{\theta}}. \tag{43}$$

Figure 5 links the imputed bilateral trade and MP costs to bilateral distances. It shows that both trade and MP costs are significantly increasing with respect to the distance. It also suggests that the bilateral distance account for a fraction of the variation of bilateral trade and MP costs. There are many other factors shaping global geography of trade and MP, which can be captured by the "exact-hat" algebra used in my quantitative exercises.



(a) Trade Cost

(b) MP Cost

Figure 5: Calibrated Trade and MP Costs

How do trade and MP costs change with respect to the observed trade and MP policies? To answer this question and guide my counterfactual experiments, I regress the calibrated trade and MP costs on measures for bilateral relationship, in particular whether two countries have free trade agreements. The results are presented in Table 3. It suggests that free trade agreements can substantially reduce bilateral trade and MP costs: they lower, ceteris paribus, bilateral trade cost by 21.4% and bilateral MP cost by 17%. In my counterfactual analysis in Section 4, I quantify the impacts of bilateral or multilateral trade and MP policies based on these estimates.

3.3.1 External Validity

I then assess the fit of the calibrated model by linking data moments that are not directly used in calibration. First, I link the data on innovation specialization, measured by the ratio of product-

Table 3: Calibrated Trade and MP costs w.r.t. Free Trade Agreement

Dependent Variable	$\log(\tau_{\ell n})$	$\log(\gamma_{i\ell})$
FTA	-.214	-.170
	(.040)	(.044)
D1	.0979	.0783
	(.042)	(.045)
D2	.232	.216
	(.046)	(.051)
D3	.497	.429
	(.051)	(.056)
Contiguity	-.174	-.162
	(.048)	(.057)
Common Language	-.0509	-.101
	(.036)	(.049)
Exporter f.e.	✓	✓
Importer f.e.	✓	✓
R-squared	.898	.899
N. of Obs.	420	420

(Note: FTA is a dummy equal to 1 if the exporting and importing countries have signed free trade agreements, based on the records of WTO. D1 is a dummy equal to 1 if bilateral distance is greater than 900 km but less than 1500 km. D2 is a dummy equal to 1 if bilateral distance is greater than 1500 km but less than 7000 km. And D3 is a dummy equal to 1 if bilateral distance is greater than 7000 km.)

innovative firms to process-innovative firms, to $\frac{r_i}{v_i}$ in the calibrated model.[16] The result is plotted in Panel (a) of Figure 6. The calibrated model generates innovation specialization that captures the data pattern in OCED innovation indicators.

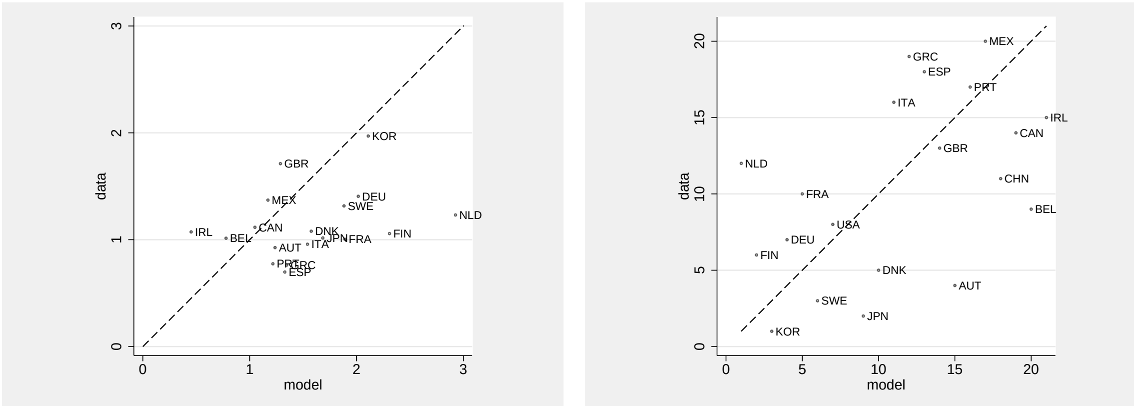
Second, I link the data on R&D expenditure as a share of GDP from the World Bank to total R&D expenditure share, $r_i + v_i$, in the calibrated model. This exercise is to test the model's capability in characterizing countries' comparative advantage in innovation and production. Panel (b) of Figure 6 reveals that the model captures the ranking of R&D shares across countries.

4 Counterfactual Analysis

4.1 Innovation Specialization under MP Liberalization

This paper aims at understanding how MP liberalization leads to innovation relocation and specialization across countries. To achieve this, we conduct two counterfactual exercises in this

[16]Although the data on innovation specialization has been used to calibrate δ/μ, $\frac{r_i}{v_i}$ generated by the model cannot fully replicate the observed innovation specialization due to the measurement error in Equation (41). So this validity analysis is to understand the magnitude of measurement errors.



(a) Innovation Specialization

(b) R&D Share: Rank

Figure 6: External Validities

(Note: innovation specialization in the data is measured by the number of product-innovation firms over the number of process-innovation firms. The data on R&D expenditure as a share of GDP comes from World Development Indicators collected by the World Bank. Panel (b) presents the country rank of R&D share in the model and data. The dash line is the 45-degree line.)

subsection. First, we consider a 5 percent reduction in $\gamma_{i\ell}$ for all $i \neq \ell$ based on the observed economy in 2011. This hypothetical MP liberalization is to further understand the model features shown in Proposition 4.

Figure 7 plots the changes in innovation specialization under MP liberalization against the initial net outward MP. It suggests that countries that initially have larger net outward MP tend to further specialize in product innovation under MP liberalization. Intuitively, the universal decline in the cost of MP allows multinationals in rich countries to offshore more of their production to foreign countries. This production relocation makes process innovation more profitable in host countries. The changes in innovation specialization illustrated by Figure 7 is qualitatively consistent with the data pattern shown in Figure 2.

Second, I quantify the impacts of *actual* MP liberalization over 2004-2015 on the *observed* changes in innovation specialization over the same period. Due to the data limitation, I impute MP liberalization over 2004-2015 from the bilateral trade and FDI stock data on 2001 and 2011. Specifically, I apply the imputation procedures described in Section 3.2 to data on 2001 and 2011 and impute the MP liberalization using Equation (43).[17]

Then I consider the counterfactual economy with the MP costs at the level before MP liberalization but all other parameters at the level after MP liberalization. The differences between

[17] This imputed MP liberalization is summarized in the appendix.

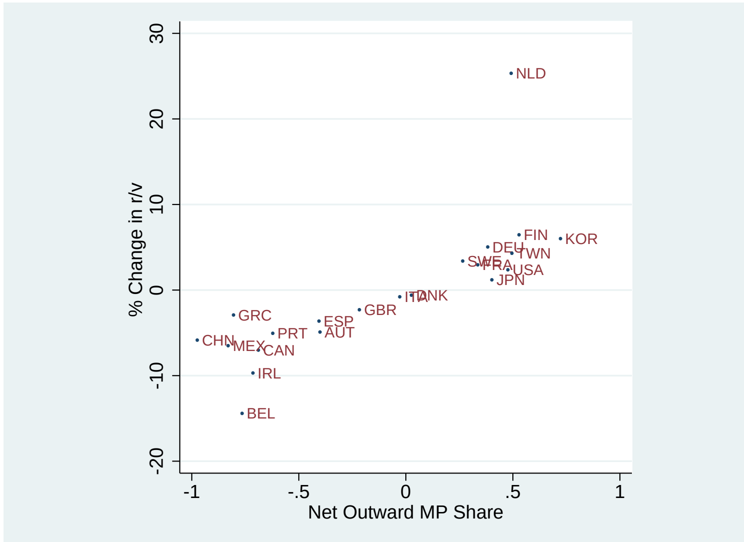


Figure 7: Changes in BGP $\frac{r_i}{v_i}$ under MP Liberalization

(Note: MP liberalization refers to 5 percent reduction in $\gamma_{i\ell}$ for all $i \neq \ell$ from the world economy in 2015.)

this counterfactual economy and the observed economy after MP liberalization characterize the implications of MP liberalization.

Table 4 compares the counterfactual changes in $\frac{v_i}{r_i}$ under MP liberalization with the observed changes in the data. The results show that MP liberalization over 2004-2015 does make three out of four European countries further specialize in product innovation. Changes in innovation specialization are heterogeneous across countries: $\frac{\hat{v}_i}{\hat{r}_i} = 0.92$ in Germany but $\frac{\hat{v}_i}{\hat{r}_i} = 1.04$ in France.[18] On average, MP liberalization over 2004-2015 accounts for about 35 percent of the relative decline in process innovation in these four large European countries. The rest of the decline is due to changes in trade costs and fundamental efficiencies of product and process innovation.

4.2 The Static and Dynamic Gains from MP

How would innovation relocation led by MP affect our quantification of the welfare consequences of globalization? To answer this question, I first quantify the welfare effects of MP using the baseline model in which product and process innovation can fully adjust to new steady-states after MP shocks. In particular, I compute changes from the counterfactual economy without MP

[18] This is mainly due to the heterogeneity of the imputed MP liberalization across countries.

Table 4: $\hat{v}_i/\hat{r}_i$ over 2004-2015

	Data	Counterfactual	Contribution
	(1)	(2)	(3)
Germany	0.85	0.92	0.57
France	0.76	1.04	-0.16
The U.K.	0.95	0.97	0.54
The Netherlands	0.87	0.94	0.45
Average	0.86	0.96	0.35

(Note: column (3) is computed by $(1-\text{column (2)})/(1-\text{column (1)})$. Average refers to the simple average over all countries. The innovation data comes from OECD Innovation indicators and OECD "Innovation in Firms" (2009). Counterfactual refers to moving from the counterfactual economy with the MP costs at the level before MP liberalization but all other parameters at the level after MP liberalization to the observed economy after MP liberalization.)

to the observed economy in 2011. The results are presented in Column (1)-(3) of Table 5. It can be seen that countries gain substantially from MP in the baseline model. Small open economies such as Ireland and Belgium realize highest gains from MP, which is consistent with previous quantification in the literature. Consistent with my theoretical characterization, the counterfactual exercise show that MP leads to substantial innovation relocation. Rich countries such as the U.S., Germany, Japan, and France are further specialized in product innovation, having their production as well as process innovation offshored to developing countries like China and Mexico.

To isolate the welfare consequences of innovation relocation, I compute the welfare gains from MP in the static model without product and process innovation. As shown in Table 1, this static model is isomorphic to Ramondo and Rodriguez-Clare (2013) (see Column (6) of Table 5). Analogously, I compute gains from MP in the product-innovation-only model which is isomorphic to ARRY (2018) and in the process-innovation-only model (Column (4)-(5) of Table 5).

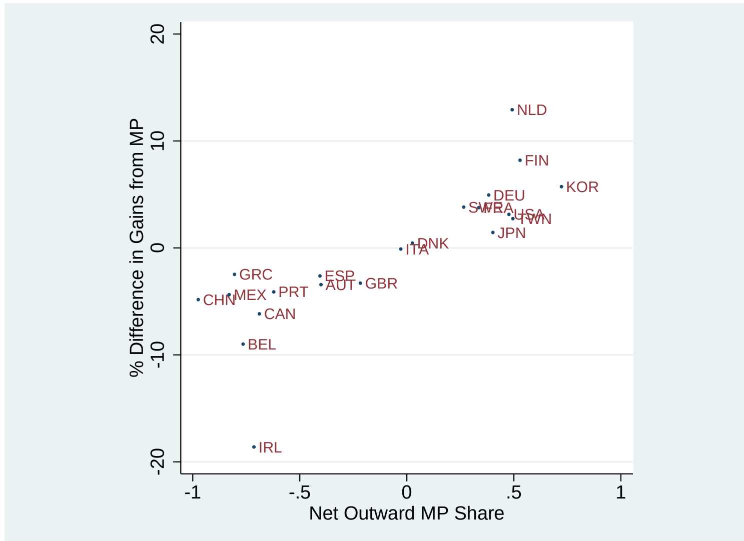
Comparing to the product-only-model isomorphic to ARRY (2018), innovation relocation considered in the baseline model shifts welfare gains from MP from source countries that have large net outward MP to host countries that have large net inward MP. This can be seen clearly in Panel (a) of Figure 8. Since process innovation relies on the feedback from local manufacturing, it is more likely to be offshored with manufacturing production to host countries. This "hollow-out" effect reduces the productivities of firms that still produce in source countries and thus hurts production workers in these countries. Notice that the source countries can still gain from production offshoring via the reduction in production costs and the improvements of product innovation. How-

Table 5: Gains from MP (GMP): Baseline Model vs. Static Model

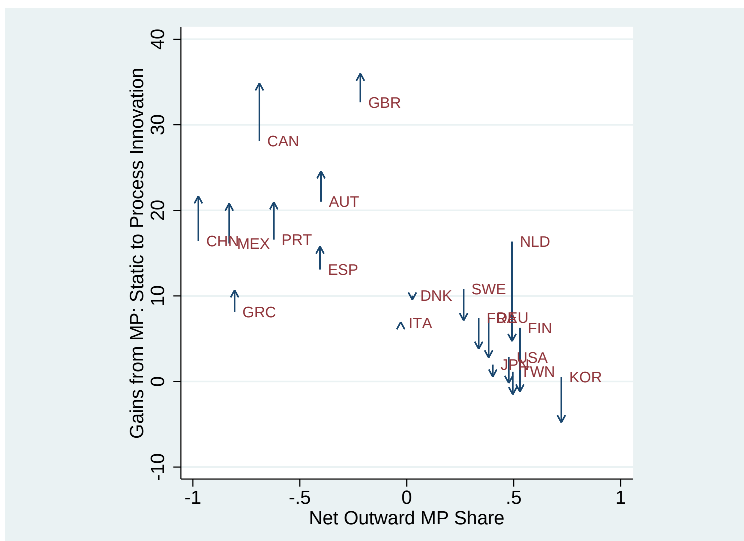
in % Change	Baseline Model r	v	w/P	GMP in Alternative Settings product inno.	process inno.	static
	(1)	(2)	(3)	(4)	(5)	(6)
AUT	-14.6	7.3	17.7	14.3	24.6	21.0
BEL	-39.9	20.1	37.1	28.1	61.4	51.2
CAN	-24.3	12.2	21.3	15.1	34.9	28.1
CHN	-18.4	9.2	11.7	6.9	21.7	16.4
DEU	17.9	-9.0	9.5	14.4	2.8	7.5
DNK	0.9	-0.4	10.2	10.6	9.6	10.0
ESP	-10.2	5.1	10.8	8.2	15.8	13.1
FIN	27.7	-13.9	9.0	17.2	-1.2	6.3
FRA	13.4	-6.7	9.2	12.9	3.8	7.4
GBR	-12.2	6.1	29.4	26.1	36.0	32.6
GRC	-9.4	4.7	6.1	3.6	10.7	8.1
IRL	-61.9	31.1	98.2	79.6	166.3	142.0
ITA	-0.6	0.3	6.7	6.6	6.9	6.9
JPN	5.4	-2.7	2.8	4.2	0.6	2.0
KOR	21.2	-10.7	2.8	8.6	-4.8	0.6
MEX	-17.9	9.0	11.8	7.5	20.8	16.1
NLD	45.3	-22.8	18.5	31.4	4.7	16.4
PRT	-15.6	7.8	12.7	8.6	21.0	16.6
SWE	13.1	-6.6	12.5	16.4	7.1	10.8
TWN	11.1	-5.6	2.5	5.2	-1.5	1.1
USA	11.7	-5.9	4.3	7.5	-0.2	2.8
Average	-2.7	1.4	16.4	15.9	21.0	19.9

(Note: Gains from MP refers to changes in welfare from the case with $\gamma_{i\ell} = \infty$ for all $i \neq \ell$ to the observed equilibrium.)

ever, these benefits are at least partially offset by the decline of process innovation.



(a) Product-Innovation-Only Model vs Baseline Model



(b) Static Model vs Process-Innovation-Only Model

Figure 8: Gains from MP and Net Outward MP

Panel (b) of Figure 8 compares gains from MP in the static model with ones in the process-innovation-only model. It is clear that in the static model, countries with large net inward MP gain more from MP. This is mainly due to the terms-of-trade effect discussed in Rodriguez-Clare (2011) and Ramondo and Rodriguez-Clare (2013). This effect becomes more pronounced when there is relocation of process innovation. In countries like the U.S. and Korea, the *static* terms-of-trade gains from MP are entirely canceled out by the decline in process innovation. In other words, these countries loses from MP in the process-innovation-only model.

Table 6: Gains from Openness

in % Change	Gains from Openness w/P	r	v	Gains from Trade w/P
	(1)	(2)	(3)	(4)
AUT	67.9	-14.6	7.3	10.1
BEL	182.4	-39.9	20.1	21.2
CAN	64.9	-24.3	12.2	8.4
CHN	22.4	-18.4	9.2	1.3
DEU	48.3	17.9	-9.0	9.2
DNK	49.7	0.9	-0.4	9.9
ESP	32.9	-10.2	5.1	4.6
FIN	44.1	27.7	-13.9	8.0
FRA	35.2	13.4	-6.7	6.3
GBR	81.6	-12.2	6.1	7.5
GRC	14.2	-9.4	4.7	1.0
IRL	483.2	-61.9	31.1	27.3
ITA	23.9	-0.6	0.3	5.1
JPN	9.9	5.4	-2.7	4.0
KOR	24.6	21.2	-10.7	12.2
MEX	42.8	-17.9	9.0	7.6
NLD	145.8	45.3	-22.8	9.0
PRT	37.8	-15.6	7.8	4.2
SWE	57.6	13.1	-6.6	9.3
TWN	39.1	11.1	-5.6	18.7
USA	16.3	11.7	-5.9	4.5
Average	72.6	-2.7	1.4	9.0

I also compute the welfare gains from openness and from trade in the baseline model. Column (1) of Table 6 shows that gains from openness tend to be much larger than gains from MP. In the baseline model, trade and MP are largely substitutes. So if MP is shut down, countries can still be connected by trade. However, when both MP and trade are shut down, countries would incur substantial welfare losses.

4.3 Welfare Consequences of (Anti-)Globalization

In this subsection, I use the baseline model to quantify the welfare consequences of important trade and MP shocks. I start by quantifying the welfare consequences of a set of policies that facilitate globalization: China's WTO accession, Trans-Pacific Partnership (TPP), and Transatlantic Trade and Investment Partnership (TTIP).

Through the lens of my model, I consider two views on China's WTO accession. First, I regard China's WTO accession as a trade liberalization between China and other countries. Based on the results shown in Table 3, I simulate this case by reducing trade costs between China and all other countries by 21.4%. The result is shown in Column (2) of Table 7. All countries gain from China's trade liberalization. Small open economies close to China such as Taiwan and Korea enjoy largest gains. Second, I regard China's WTO accession as both trade and MP liberalization between China and other countries. In addition to trade liberalization, I further reduce iceberg MP costs between China and all other countries by 17%. The result is shown in Column (1) of Table 7. Most countries gain much more from the combination of trade and MP liberalization than trade liberalization, raising a question how we should think about important policy shocks such as China's WTO accession. Notably, most of the recent trade agreements involve terms that reduce or remove barriers for FDI. Quantifying the effects of trade agreements on bilateral MP costs turns out to be crucial for us to fully understand the welfare consequences of these agreements.

Table 7: Welfare Consequences of Globalization and Anti-Globalization

	China Joined WTO		TPP		TTIP	Brexit	No NAFTA	US-China Trade Conflict	
in % Change	All	Trade	All	No US				two-sided	unilateral
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
AUT	0.97	0.48	-0.10	0.00	3.52	-0.86	0.08	0.03	0.04
BEL	1.07	0.50	0.02	-0.01	12.51	-1.62	-0.01	0.05	0.05
CAN	0.94	0.50	24.44	1.17	0.13	0.05	-11.39	0.12	0.13
CHN	8.00	1.02	-0.04	0.00	-0.03	0.00	0.00	-0.30	-0.21
DEU	1.08	0.74	-0.01	0.00	6.11	-1.29	0.01	0.09	0.11
DNK	0.79	0.43	-0.05	-0.01	5.10	-1.72	0.03	0.03	0.03
ESP	0.42	0.18	-0.05	-0.01	3.31	-0.81	0.04	0.04	0.05
FIN	0.66	0.46	-0.07	0.00	3.28	-1.01	0.04	0.02	0.02
FRA	0.71	0.34	-0.02	0.00	4.59	-0.91	0.02	0.04	0.05
GBR	0.95	0.33	0.11	0.00	13.86	-8.24	-0.05	0.06	0.06
GRC	0.32	0.18	-0.03	0.00	1.68	-0.47	0.02	0.02	0.03
IRL	1.13	0.46	0.57	-0.02	40.02	-3.31	-0.31	0.08	0.05
ITA	0.58	0.32	-0.03	0.00	3.00	-0.63	0.02	0.05	0.05
JPN	1.21	0.64	2.94	0.25	-0.01	0.01	0.00	0.04	0.04
KOR	3.04	1.91	-0.04	0.00	-0.06	0.01	0.01	0.07	0.08
MEX	0.86	0.51	17.91	1.60	0.00	0.01	-7.93	0.20	0.24
NLD	0.65	0.82	0.50	0.00	12.76	-1.89	-0.27	0.08	0.10
PRT	0.30	0.11	-0.04	0.00	2.40	-0.83	0.03	0.02	0.03
SWE	0.92	0.44	-0.03	0.00	4.69	-1.45	0.02	0.02	0.02
TWN	3.54	3.25	-0.03	0.00	-0.12	0.04	0.02	-0.02	-0.03
USA	0.78	0.43	2.82	-0.01	6.10	0.00	-1.01	-0.54	-0.48

I then quantify the welfare consequences of two proposed trade and investment agreements, TPP and TTIP, by reducing trade costs by 21.4% and MP costs by 17% among participation countries.[19] The results are shown in Column (3)-(5) of Table 7. The results suggest that these pro-

[19]In the sample of countries, Canada, Japan, Mexico, and the U.S. are involved in the negotiation of TPP. TTIP

posed regional trade and investment agreements substantially benefit the participation countries, especially small open economies, but have negative welfare impacts on outside countries. Moreover, whether the U.S. joins TPP has tremendous impacts on the welfare consequences of TPP, especially for Canada and Mexico.

Now I turn to quantify the welfare effects of recent anti-globalization shocks: Brexit, the renegotiation of NAFTA, and the US-China trade conflicts. Brexit, according to recent policy debates, potentially involves an increase in trade and MP costs between the United Kingdom and the rest of EU. I simulate this shock by increasing trade costs by 21.4% and MP costs by 17% between the U.K. and the rest of EU. The results are shown in Column (6) of Table 7. It suggests that Brexit could reduce the real income in the U.K. by 8.24% in the long run. Ireland, closely connected with the U.K. in trade and MP, incurs a decline in real income by 3.31%. The real income in other major EU countries such as Germany and France also decreases by about 1%. In contrast, the U.S. barely incurs any welfare losses and Canada even gains slightly from Brexit since Brexit tends to shift UK-EU trade and MP towards North America.

The welfare effects of the recent US-China trade conflicts are shown in Column (8) and (9) of Table 7. I consider two scenarios: first, the U.S. unilaterally raises the trade costs for Chinese imports by 21.4%; second, China and the U.S. raise the trade costs to each other by 21.4%. The two-sided trade war, which is likely to occur in reality, would reduce the real income in China by 0.3% and the real income in the U.S by 0.54%.

Notably, due to the profit flows of multinationals, my model allows for trade imbalances in the steady-state. Therefore, my model can also be used to understand the impacts of trade wars on global trade imbalances. Table 8 shows that changes in bilateral trade imbalances between China and the U.S. as well as changes in total trade surplus (deficit) in China (the U.S.). Interestingly, this counterfactual exercise shows that trade conflicts will decrease *bilateral* trade imbalances between the U.S. and China but increase the *total* trade deficit in the U.S. and the *total* trade surplus in China. Intuitively, the U.S. multinationals increase their production in China to avoid high tariffs, which increases the profits of U.S. multinationals from China and the total trade deficit in the U.S. Therefore, trade wars with China may not be able to address the U.S. trade deficits President Trump is worrying about.

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refers to a reduction in trade and MP costs between the U.S. and EU countries.

Table 8: US-China Trade Imbalance under Trade Conflicts

	$\frac{\text{China-US trade surplus}}{\text{Chinese total exports}}$	$\frac{\text{US-China trade deficit}}{\text{US total imports}}$	$\frac{\text{Chinese total trade surplus}}{\text{Chinese total exports}}$	$\frac{\text{US Total trade deficit}}{\text{US total imports}}$
Baseline	0.26	-0.22	0.66	-0.46
Two-sided	0.20	-0.16	0.72	-0.50
Unilateral	0.16	-0.13	0.70	-0.49

4.4 Optimal Innovation Policy

My model deviates from the first-best since local specialists do not internalize the benefits of process innovation in reducing the costs of final production. This inefficiency leaves room for government intervention. In this subsection, I characterize a country's incentives to intervene different types of innovation in the global economy. In particular, I am interested in the innovation policy in which a country i decides (r_i, v_i) to maximize its welfare W_i, given other countries do not intervene innovation.

Country i' chooses its innovation policy, $(\hat{r}_{i'}, \hat{v}_{i'})$, by solving the following problem:

$$\max_{\left(\hat{X}_\ell,\hat{P}_\ell,\hat{r}_\ell,\hat{v}_\ell,\hat{w}_\ell,\hat{w}_\ell^R,\hat{w}_\ell^S,\hat{\tilde{M}}_\ell,\hat{\tilde{N}}_\ell,\hat{\tilde{L}}_\ell^P\right)_{\ell=1}^I} \hat{W}_{i'} := \frac{1}{\hat{P}_{i'}}\left(\frac{\tilde{L}_{i'}^P}{\tilde{L}_{i'}}\hat{\tilde{L}}_{i'}^P\hat{w}_{i'} + r_{i'}\hat{r}_{i'}\hat{w}_{i'}^R + v_{i'}\hat{v}_{i'}\hat{w}_{i'}^S\right), \tag{44}$$

subject to

$$\begin{aligned}
&\hat{w}_\ell\hat{\tilde{L}}_\ell^P w_\ell L_\ell^P = \beta s^p \sum_{i,n}\hat{\pi}_{i\ell n}\hat{X}_n\pi_{i\ell n}X_n + s\hat{X}_\ell X_\ell, \quad \forall \ell\\
&\hat{\tilde{M}}_i = \hat{r}_i^\delta, \quad \hat{\tilde{N}}_i = \hat{v}_i^\mu, \quad \forall i\\
&\hat{X}_\ell X_\ell = \hat{w}_\ell\hat{\tilde{L}}_\ell^P w_\ell L_\ell^P + \hat{w}_\ell^R\hat{r}_\ell w_\ell r_\ell L_\ell + \hat{w}_\ell^S\hat{v}_\ell w_\ell v_\ell L_\ell + (1-\beta)s^p\sum_{i,n}\hat{\pi}_{i\ell n}\hat{X}_n\pi_{i\ell n}X_n, \quad \forall \ell\\
&\hat{P}_n^{-\theta} = \left(\frac{\hat{w}_n}{\hat{X}_n}\right)^{-\frac{\theta-(\sigma-1)}{\sigma-1}}\sum_h \lambda_{hn}\hat{\tilde{M}}_h\left[\sum_k \psi_{hkn}\hat{\xi}_{hkn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}, \quad \forall n\\
&\hat{r}_\ell = \frac{\hat{\Pi}_\ell^f}{\hat{w}_\ell^R}, \quad \hat{v}_\ell = \frac{\hat{\Pi}_\ell^m}{\hat{w}_\ell^S}, \quad \forall \ell\\
&r_i\hat{r}_i + v_i\hat{v}_i + \frac{\tilde{L}_i^P}{\tilde{L}_i}\hat{\tilde{L}}_i^P = 1, \quad \forall i\\
&\hat{w}_i = \hat{w}_i^R = \hat{w}_i^S, \quad \forall i \neq i'.
\end{aligned} \tag{45}$$

$\hat{\pi}_{i\ell n}$ is given by Equation (33) and $\hat{\Pi}_i^f$ and $\hat{\Pi}_i^m$ are given by Equation (37). Notably, the problem in Equation (44) is equivalent to the problem in which country i chooses subsidy rates for product and process innovation. The unilaterally optimal innovation policies for each country are shown in

Table 9.

Table 9: Unilaterally Optimal Innovation Policy

% change in:	Policy		Welfare			
	r	v	Self	Other	By US	By China
	(1)	(2)	(3)	(4)	(5)	(6)
AUT	-48.0	19.5	6.5	-0.0	0.1	0.3
BEL	-60.2	14.3	5.8	-0.1	-3.2	0.4
CAN	-46.5	16.2	5.3	-0.0	-6.0	0.2
CHN	-36.1	15.3	4.5	0.2	-0.9	4.5
DEU	-50.4	33.5	11.6	-1.0	-1.2	0.1
DNK	-45.6	23.9	7.9	-0.1	-0.4	0.2
ESP	-39.7	18.4	5.7	-0.1	-0.2	0.2
FIN	-51.1	38.9	13.4	-0.1	-0.1	-0.1
FRA	-46.6	29.6	10.2	-0.6	-0.7	0.2
GBR	-56.5	23.6	8.6	-0.6	-4.2	0.2
GRC	-34.9	17.2	5.2	0.0	-0.1	0.1
IRL	-80.8	10.6	5.7	-0.1	-15.1	0.5
ITA	-39.4	21.3	6.8	-0.1	-0.3	0.2
JPN	-37.9	22.9	7.8	-0.1	-0.6	0.3
KOR	-43.3	31.1	10.9	-0.0	-0.6	0.3
MEX	-38.8	15.7	4.7	0.0	-2.7	0.2
NLD	-72.1	66.5	23.4	-0.5	-8.1	-0.3
PRT	-39.4	16.6	5.0	-0.0	-0.1	0.1
SWE	-51.7	31.9	11.0	-0.2	-0.6	0.3
TWN	-42.2	26.0	8.7	-0.0	-0.8	-0.3
USA	-41.9	26.9	9.4	-2.3	9.4	0.2

Column (1) and (2) of Table 9 show that it is optimal for the government to shift labor from product innovation to process innovation. This is due to the positive externalities of process innovation: local specialists do not internalize the benefits of process innovation in reducing the costs of final producers. Or equivalently, when multinational firms offshore their production to foreign countries, they do not internalize the losses from the decline in process innovation in the home country. To correct this inefficiency, the government should subsidize process innovation, or equivalently, production. This result provides a rationale for the policies in some developed countries that aim at bringing offshored production back to home countries.

The welfare effects of optimal innovation policies are shown in Column (3) and (4) of Table 9. It suggests that most countries gain from their unilaterally optimal innovation policies at the expense of other countries. Notice that the outcomes of process innovation can only be used locally. Therefore, a country benefits from the economies of scale in production by subsidizing process innovation, whereas other countries suffer from the decline in process innovation. Column

(5) of Table 9 further shows that the optimal innovation policies in the U.S. substantially reduce the real incomes in other countries due to the relocation of production back to the U.S.

However, a country's optimal innovation policies do not necessarily harm other countries. Column (6) of Table 9 shows that the optimal innovation policies in China raises the real incomes in other countries. This is because that without intervention, China is specialized in production and process innovation in the global economy. The optimal innovation policies in China further strengthen the specialization between product and process innovation across countries and thereby benefit all countries.

5 Conclusion

The decline in the costs of MP has led to international innovation relocation and specialization since some innovative activities rely more on instant feedback from local plants than others. To quantify the welfare consequences of this phenomenon, I develop a multi-country general equilibrium model with MP and innovation. Production offshoring reduces the firms' production costs and thereby spurs product innovation in the source country. In contrast, process innovation tend to be offshored with production into the host country since it relies on feedback from production plants.

The model yields simple structural expressions for bilateral trade and MP flows and technology evolution that I use in the calibration to 21 countries. I use the calibrated model to perform counterfactual exercises to understand the innovation and welfare consequences of MP liberalization. I find that MP liberalization over 2004-2015 accounts for 35% of the relative decline in process innovation observed in four large European countries. In my model, countries with large net outward MP realize less gains from MP than implied by ARRY (2018) due to the decline in their process innovation. This resonates popular fears that production offshoring would undermine innovation in the source countries and damage their growth prospects. I also show the usefulness of my model in understanding the consequences of trade and MP shocks in the real world.

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Appendix A Theories

A.1 The Illustrative Three-Country Example

To save notations, I omit (t) in this section. By construction, the price index for intermediate goods in country ℓ is $P_\ell^m = N_\ell^{-\eta} w_\ell$. Due to free trade of final goods, the world final price index can be expressed as

$$P^{-\theta} = \sum_{i,\ell} M_i \left(\gamma_{i\ell} N_\ell^{-\eta} w_\ell \right)^{-\theta}. \tag{46}$$

Since $\rho = 0$, the tri-lateral trade share can be expressed as

$$\pi_{i\ell n} = \frac{M_i \left(\gamma_{i\ell} N_\ell^{-\eta} w_\ell \right)^{-\theta}}{\sum_{i',\ell'} M_{i'} \left(\gamma_{i'\ell'} N_{\ell'}^{-\eta} w_{\ell'} \right)^{-\theta}}. \tag{47}$$

Since $\gamma_{12} = \gamma \in [1, \infty]$ and $\gamma_{i\ell} = \infty$ for all $(i, \ell) \neq (1, 2)$ and $i \neq \ell$, we have $\pi_{21n} = \pi_{01n} = \pi_{10n} = \pi_{02n} = \pi_{20n} = 0$ for all n. Moreover, since $\beta = 1$, we have $X_i = w_i L_i$. The labor market clearing thus implies that

$$(1-s) w_\ell L_\ell = (s^p + s^m) \sum_{i,n} \pi_{i\ell n} w_n L_n + s^f \sum_{k,n} \pi_{\ell k n} w_n L_n. \tag{48}$$

Let $X = L_0 + w_1 + w_2$ be the world nominal income. By construction, we have $M_0 = s^f$ and $N_0 = s^m$. Since we have normalized $w_0 = 1$, labor market clearing in country 0 implies that

$$P = \left[\left(s^f \right)^{-\frac{1}{\theta}} (s^m)^{-\eta} \right] (L_0 + w_1 + w_2)^{-\frac{1}{\theta}}. \tag{49}$$

Labor market clearing in country 1 implies that

$$(1-s) w_1 = \frac{1-s}{s^f (s^m)^{\theta\eta}} M_1 N_1^{\theta\eta} w_1^{-\theta} + \frac{1}{(s^m)^{\theta\eta}} \gamma^{-\theta} M_1 N_2^{\theta\eta} w_2^{-\theta}. \tag{50}$$

Labor market clearing in country 2 implies that

$$(1-s) w_2 = \frac{1-s}{s^f (s^m)^{\theta\eta}} M_2 N_2^{\theta\eta} w_2^{-\theta} + \frac{s^p + s^m}{s^f (s^m)^{\theta\eta}} \gamma^{-\theta} M_1 N_2^{\theta\eta} w_2^{-\theta}. \tag{51}$$

The free entry of firms in country 1 gives that

$$w_1 = (s^m)^{-\theta\eta} \left(N_1^{\theta\eta} w_1^{-\theta} + \gamma^{-\theta} N_2^{\theta\eta} w_2^{-\theta} \right). \tag{52}$$

The free entry of intermediate suppliers in country 1 implies that

$$N_1^{1-\theta\eta} = \frac{(s^m)^{1-\theta\eta}}{s^f} M_1 w_1^{-(1+\theta)}. \tag{53}$$

Similarly, The free entry of firms in country 2 gives that

$$w_2^{1+\theta} = (s^m)^{-\theta\eta} N_2^{\theta\eta}. \tag{54}$$

The free entry of intermediate suppliers in country 1 implies that

$$N_2^{1-\theta\eta} = \frac{(s^m)^{1-\theta\eta}}{s^f} \left(\gamma^{-\theta} M_1 + M_2 \right) w_2^{-(1+\theta)}. \tag{55}$$

Then we have

$$M_1 = \frac{(1-s)s^f w_1}{(1-s)w_1 - [(1-s) - s^f]\,\gamma^{-\theta} w_2} = \frac{(1-s)s^f}{(1-s) - [(1-s) - s^f]\,\gamma^{-\theta} \frac{w_2}{w_1}}. \tag{56}$$

And

$$N_2 = s^m + \frac{(1-s) - (s^p + s^m)}{1-s} \frac{s^m}{s^f} \gamma^{-\theta} M_1. \tag{57}$$

Moreover,

$$N_1 = \frac{(1-s)w_1 - \gamma^{-\theta} M_1 w_2}{(1-s)w_1} s^m = \frac{(1-s) - \gamma^{-\theta} M_1 \frac{w_2}{w_1}}{(1-s)} s^m. \tag{58}$$

And

$$M_2 = \frac{(1-s) - \frac{s^p + s^m}{s^f} \gamma^{-\theta} M_1}{1-s} s^f. \tag{59}$$

Finally, we have

$$\left(\frac{w_2}{w_1} \right)^{1+\theta} = \frac{s^f}{s^m} \left(\frac{N_2}{N_1} \right)^{\theta\eta} \frac{N_1}{M_1}. \tag{60}$$

Now inserting $\theta\eta = 1$, we have

$$(1-s)\left(\frac{w_2}{w_1}\right)^{1+\theta} + \left[(1-s) - s^f\right]\gamma^{-\theta}\left(\frac{w_2}{w_1}\right) = (1-s) + s^f\gamma^{-\theta}. \tag{61}$$

Notice that M_1, M_2, N_1, N_2 can be expressed in terms of γ and $\frac{w_2}{w_1}$. Total differentiation of Equation (56) and (61) suggests that $-\frac{\partial M_1}{\partial \gamma} > 0$. So we have $-\frac{\partial r_1}{\partial \gamma} > 0$. Total differentiation of Equation (57), (58), and (59) then leads to $-\frac{\partial N_2}{\partial \gamma} > 0$, $-\frac{\partial N_1}{\partial \gamma} < 0$, and $-\frac{\partial M_2}{\partial \gamma} < 0$. These results have shown Proposition 7.

Now we study gains from MP. If $\gamma = \infty$, i.e. MP is eliminated, then $w_1 = w_2 = 1$, $M_1 = M_2 = s^f$, and $N_1 = N_2 = s^m$. If $\gamma = 1$, i.e. MP is frictionless from country 1 to country 2, then we have

$$(1-s)\left(\frac{w_2}{w_1}\right)^{1+\theta} + (s^p + s^m)\left(\frac{w_2}{w_1}\right) = (1-s) + s^f. \tag{62}$$

Inserting $s^f = s^m + s^p$, we have $\frac{w_2}{w_1} = 1$ in this case. From Equation (56) and (57), we have $w_1 = w_2 = 2^{\frac{1}{1+\theta}}$. $\text{GMP}_i^{\text{baseline}}$ can be computed accordingly.

Now we consider the product-innovation-only model in which $\mu = \eta = 0$. Notice that in this case $s^m = 0$. If $\gamma = \infty$, then we still have $w_1 = w_2 = 1$, $M_1 = M_2 = s^f$, and $N_1 = N_2 = s^m$. Interestingly, regardless of γ, the free entry of firms in country 2 implies that in the product-innovation-only model, $w_2 = 1$. Therefore, we have $\text{GMP}_2^{\text{baseline}} > \text{GMP}_2^{\text{product-innovation-only}} = \text{GMP}_0^{\text{product-innovation-only}}$. Moreover, if $\gamma = 1$, the wage in country 1 satisfies

$$w_1 = w_1^{-\theta} + 1, \tag{63}$$

based on which it is straightforward to show that $w_1 > 2^{\frac{1}{1+\theta}}$. Since $L_0 >> 1$, we have $\text{GMP}_1^{\text{product-innovation-only}} > \text{GMP}_1^{\text{baseline}}$. This completes the proof to Proposition 8.

A.2 “Exact-Hat" Algebra

A.2.1 Production Innovation Only

I shut down process innovation by letting $\mu = 0$. The production workers' labor market clearing condition implies that

$$\hat{w}_\ell \hat{L}_\ell^P w_\ell L_\ell^P = (\beta s^p + s^m) \sum_{i,n} \hat{\pi}_{i\ell n} \hat{X}_n \pi_{i\ell n} X_n + s \hat{X}_\ell X_\ell, \tag{64}$$

where

$$\hat{\pi}_{i\ell n} = \hat{\psi}_{i\ell n} \hat{\lambda}_{in}, \quad \hat{\psi}_{i\ell n} = \frac{\hat{\xi}_{i\ell n}^{-\frac{\theta}{1-\rho}}}{\sum_k \psi_{ikn} \hat{\xi}_{ikn}^{-\frac{\theta}{1-\rho}}}, \quad \hat{\lambda}_{in} = \frac{\hat{M}_i \left[\sum_k \psi_{ikn} \hat{\xi}_{ikn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}}{\sum_h \lambda_{hn} \hat{M}_h \left[\sum_k \psi_{hkn} \hat{\xi}_{hkn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}},$$
$$\hat{\xi}_{i\ell n} = \hat{\gamma}_{i\ell} \hat{P}_\ell^m \hat{\tau}_{\ell n}, \quad \hat{P}_\ell^m = \left(\hat{A}_\ell^S\right)^{-\eta} \hat{w}_\ell^\beta \hat{P}_\ell^{1-\beta}. \tag{65}$$

Changes in total expenditure can be given by

$$\hat{X}_\ell X_\ell = \hat{w}_\ell w_\ell L_\ell + (1-\beta) s^p \sum_{i,n} \hat{\pi}_{i\ell n} \hat{X}_n \pi_{i\ell n} X_n. \tag{66}$$

Changes in final price index can be given by

$$\hat{P}_n^{-\theta} = \left(\frac{\hat{w}_n}{\hat{X}_n}\right)^{-\frac{\theta-(\sigma-1)}{\sigma-1}} \sum_h \lambda_{hn} \hat{M}_h \left[\sum_k \psi_{hkn} \hat{\xi}_{hkn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}. \tag{67}$$

The share of researchers is changed according to

$$\hat{r}_\ell = \frac{\hat{\Pi}_\ell^f}{\hat{w}_\ell}, \tag{68}$$

where

$$\hat{\Pi}_i^f = \frac{\sum_{\ell,n} \hat{\pi}_{i\ell n} \hat{X}_n \pi_{i\ell n} X_n}{\sum_{\ell,n} \pi_{i\ell n} X_n}. \tag{69}$$

The changes in the mass of final varieties are given by

$$\hat{M}_i = \hat{A}_i^R \hat{r}_i^{\delta}. \tag{70}$$

Finally, labor market clearing implies that

$$r_i \hat{r}_i + \frac{L_\ell^P}{L_\ell}\hat{L}_\ell^P = 1. \tag{71}$$

Likewise, in the process-innovation-only model, I shut down product innovation by letting $\delta = 0$. Equilibrium conditions in relative changes are derived accordingly.

A.2.2 The Static Model

I shut down both product and process innovation by letting $\delta = \mu = 0$. The labor market clearing condition implies that

$$\hat{w}_\ell w_\ell L_\ell = (\beta s^p + s^m)\sum_{i,n}\hat{\pi}_{i\ell n}\hat{X}_n \pi_{i\ell n} X_n + s^f \sum_{k,n}\hat{\pi}_{\ell kn}\hat{X}_n \pi_{\ell kn} X_n + s\hat{X}_\ell X_\ell, \tag{72}$$

where

$$\hat{\pi}_{i\ell n} = \hat{\psi}_{i\ell n}\hat{\lambda}_{in}, \quad \hat{\psi}_{i\ell n} = \frac{\hat{\xi}_{i\ell n}^{-\frac{\theta}{1-\rho}}}{\sum_k \psi_{ikn}\hat{\xi}_{ikn}^{-\frac{\theta}{1-\rho}}}, \quad \hat{\lambda}_{in} = \frac{\hat{A}_i^R\left[\sum_k \psi_{ikn}\hat{\xi}_{ikn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}}{\sum_h \lambda_{hn}\hat{A}_h^R\left[\sum_k \psi_{hkn}\hat{\xi}_{hkn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}},$$
$$\hat{\xi}_{i\ell n} = \hat{\gamma}_{i\ell}\hat{P}_\ell^m \hat{\tau}_{\ell n}, \quad \hat{P}_\ell^m = \left(\hat{A}_\ell^S\right)^{-\eta}\hat{w}_\ell^{\beta}\hat{P}_\ell^{1-\beta}. \tag{73}$$

Changes in total expenditure can be given by

$$\hat{X}_\ell X_\ell = \hat{w}_\ell w_\ell L_\ell + (1-\beta)s^p \sum_{i,n}\hat{\pi}_{i\ell n}\hat{X}_n \pi_{i\ell n} X_n. \tag{74}$$

Changes in final price index can be given by

$$\hat{P}_n^{-\theta} = \left(\frac{\hat{w}_n}{\hat{X}_n}\right)^{-\frac{\theta-(\sigma-1)}{\sigma-1}} \sum_h \lambda_{hn}\hat{M}_h \left[\sum_k \psi_{hkn}\hat{\xi}_{hkn}^{-\frac{\theta}{1-\rho}}\right]^{1-\rho}. \tag{75}$$

A.3 The Proof to Proposition 9

Proof. Suppose that growth is always balanced. Notice that the Hamilton-Jacobian-Bellman equation for the value of final idea is

$$(\kappa - g_P(t))V_i^f(\omega,t) - \dot{V}_i^f(\omega,t) = \frac{\Pi_i^f(\omega,t)}{M_i(t)}.$$

In the BGP,

$$V_i^f(t) = \frac{1}{\kappa - g_P}\frac{\Pi_i^f(t)}{M_i(t)}. \tag{76}$$

The free entry condition for the researchers implies that,

$$V_i^f(t) = \frac{w_i}{\delta A_i^R r_i(t)^{\delta-1}}.$$

Since the growth is balanced for all t, I have

$$\frac{w_i}{\delta A_i^R r_i^{\delta-1}} = \frac{1}{\kappa - g_P}\frac{\Pi_i^f(t)}{M_i(t)}, \quad \forall t. \tag{77}$$

However, Equation (77) cannot hold for all t if $\frac{\Pi_i^f(0)}{M_i(0)}$ is not in the BGP. Similar arguments apply to the dynamics of intermediate ideas. ■

Appendix B Data and Calibration

B.1 Definitions of Innovation Types in the Data

OECD Innovation Indicators, based on the Oslo Manual, definite four types of innovation as follows:

1. Product innovation: the introduction of a good or service that is new or significantly improved with respect to its characteristics or intended uses. This includes significant improvements in technical specifications, components and materials, incorporated software, user friendliness or other functional characteristics.

2. Process innovation: the implementation of a new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software.

3. Marketing innovation: the implementation of a new marketing method involving significant changes in product design or packaging, product placement, product promotion or pricing.

4. Organisational innovation: the implementation of a new organisational method in the firmâĂŹs business practices, workplace organisation or external relations.

B.2 Calibration on (δ, μ)

Table 10 shows the results of the regression based on Equation (41). The result shows that MP is strongly correlated with innovation specialization. Moreover, Equation (41) implies that the coefficient of Π_ℓ^f/Π_ℓ^m identifies $\frac{\delta}{\mu}$.

Table 10: Innovation Specialization and FDI Stocks

Dependent variable: r_ℓ/v_ℓ	
Π_ℓ^f/Π_ℓ^m	.68
	(.03)
R-squared	.94
#Obs.	35

(Note: the coefficient is estimated by the OLS regression with zero intercept.)

B.3 The imputed MP liberalization over 2004-2015

As discussed in the main text, I impute $\{\gamma_{i\ell}\}$ by Equation (43) using trade and MP data in 2001 and 2011 and compute the implied changes in MP costs, $\{\hat{\gamma}_{i\ell}\}$. Figure 9 illustrates the median of $\hat{\gamma}_{i\ell}$ for each host country ℓ. The result suggests that the decline in MP costs concentrates in a small set of countries like China, Ireland, and Korea. Indeed, these countries are main host countries that multinational firms offshore their production to in recent years.

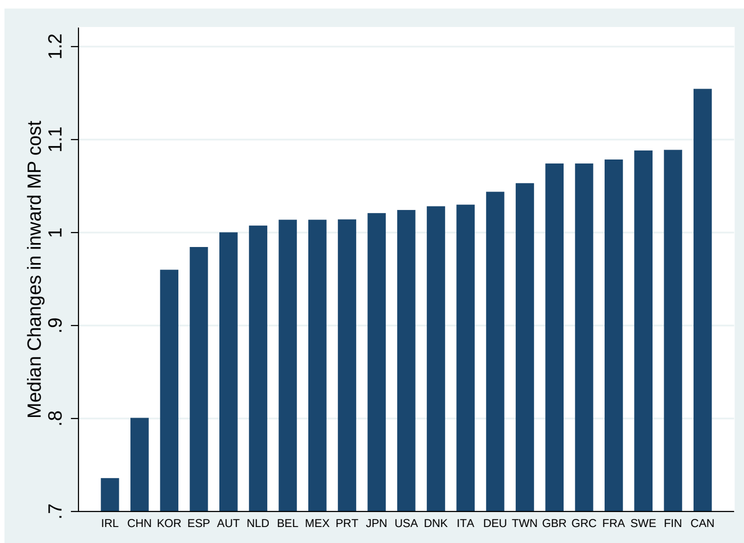

Figure 9: The Imputed Changes in Inward MP Costs over 2004-2015