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Abstract

The influence of domestic total factor productivity (TFP) growth on national welfare has been well-documented. Yet, the implications of global TFP growth on welfare through the lens of global value chains (GVCs) remains poorly understood. To bridge this gap, we developed a simple yet potent model to explore the TFP-welfare nexus based on growth accounting framework, streamlining the assumptions and parameters needed, facilitating the full integration of production networks. We measure the discrepancy between GDP growth and welfare growth of a nation, and further elucidate how this disparity, namely the terms of trade (TOT) effect, is influenced by global TFP growth. Integrating the concept of GVC TFP into the growth accounting framework enables us to break down the TOT effect into three primary components: global TFP growth, global wage growth, and global capital price growth; to further pinpoint the specific country origins of the three TOT effect components; and to differentiate between the direct and indirect TOT effects. Through the application of our model to the World Input-Output Database, we have gained novel insights into the complex interplay between global productivity and national welfare growth as well as trade policies.

Keywords: Welfare; Productivity; Global value chains; Terms of trade

JEL classification: D57, F10, O40

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Abstract: The influence of domestic total factor productivity (TFP) growth on national welfare has been well-documented. Yet, the implications of global TFP growth on welfare through the lens of global value chains (GVCs) remains poorly understood. To bridge this gap, we developed a simple yet potent model to explore the TFP-welfare nexus based on growth accounting framework, streamlining the assumptions and parameters needed, facilitating the full integration of production networks. We measure the discrepancy between GDP growth and welfare growth of a nation, and further elucidate how this disparity, namely the terms of trade (TOT) effect, is influenced by global TFP growth. Integrating the concept of GVC TFP into the growth accounting framework enables us to break down the TOT effect into three primary components: global TFP growth, global wage growth, and global capital price growth; to further pinpoint the specific country origins of the three TOT effect components; and to differentiate between the direct and indirect TOT effects. Through the application of our model to the World Input-Output Database, we have gained novel insights into the complex interplay between global productivity and national welfare growth as well as trade policies.

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1. Introduction

The impact of domestic total factor productivity (TFP) growth on national welfare has been widely recognized. However, the welfare consequence of global TFP growth through global value chains (GVCs) remains poorly understood. On one hand, foreign TFP can influence the prices of imported intermediate and final goods, thereby affecting the terms of trade (TOT), which stands as a crucial determinant of welfare (Feenstra et al., 2015). On the other hand, domestic TFP may impact the prices of goods that are exported and then re-imported within GVCs, also significantly influencing TOT effects. In light of the rise of GVCs since the early 1990s (Feenstra, 1998), the prices of goods are more significantly influenced by global TFP through input-output relationships rather than solely by domestic TFP (Gu & Yan, 2017). In light of the increasing prevalence of international production fragmentation, as indicated by the proportion of foreign value added in domestic final products, it becomes imperative to provide a precise assessment of the sources of national welfare growth with a complete incorporation of GVCs.

In this article, we formulate a streamlined yet powerful model to capture the intricate interplay between global productivity and national welfare growth. We introduce a model to measure the discrepancy between GDP growth and welfare growth of a nation, and further elucidate how this disparity, namely the TOT effect, is influenced by global TFP growth through the mechanisms of GVCs. By incorporating the concept of GVC TFP into the growth accounting framework, we can break down the TOT effect into three primary elements: global TFP growth, global wage growth, and global capital price growth. Additionally, we pinpoint the specific country origins of each TOT effect component. This approach enables us to determine the exact sources of welfare gains or losses, thereby aiding in the creation of targeted policy recommendations concerning bilateral or multilateral relations. Acknowledging the greater resilience of indirect trade relationships over direct ones (Alfaro & Chor 2023; World Bank, 2024), we proceed to dissect the TOT effect into its direct and indirect components. This detailed analysis provides crucial insights for informing and crafting effective trade policies. Through the application of our model to the WIOD, we have uncovered some novel findings on selected economies: the U.S., Japan, Germany, China, India, as well as the rest of the world.

Our contribution to the literature is manifold and can be delineated in four primary aspects. Firstly, we delve into the effects of global TFP growth on national welfare, a topic that has traditionally been explored through the lens of domestic TFP growth's contribution to national welfare. Several studies explore the welfare implications of TFP by employing the concept of revenue TFP which incorporates prices into the model, as opposed to the traditional metric of physical TFP. This approach is exemplified in the works of Basu & Fernald (2002), Petrin & Levinsohn (2012), and Basu et al. (2009, 2022). Revenue TFP, in contrast to physical TFP, is adept at capturing market distortions in both factors of production and outputs, which could influence welfare. Nonetheless, these studies fail to consider the critical role of international production fragmentation.

Secondly, unlike quantitative trade models, our model streamlines the assumptions and parameters needed, facilitating the comprehensive integration of production networks. Kleinman et al. (2023) attempt to quantify the impact of both domestic and foreign TFP growth on national welfare growth based on the pioneer work of Caliendo & Parro (2015). However, their approach, rooted in quantitative trade models, does not adequately capture the complexities of production networks due to the assumption that elasticities of substitution across different country origins are uniform. This overlook simplifies the intricate dynamics of global production and its influence on national welfare. In fact, assuming a constant trade elasticity could lead to significantly biased estimates of welfare effects when the true elasticity varies (Melitz & Redding, 2015). This issue persists despite trade economists' endeavors to estimate elasticities of substitution in detailed dimensions. As pointed out by Arkolakis et al. (2012), the foundational assumptions that are necessary for the prominent quantitative trade models, including those proposed by Armington (1969), Krugman (1980), Eaton & Kortum (2002), and Melitz (2003), among others, are notably restrictive. However, our model is grounded in growth accounting, thereby necessitating minimal assumptions and foregoing the need for parameters, including the elasticity of substitution, which is critical to quantitative trade models. Moreover, with the increasing availability of disaggregated input-output tables, encompassing those with ownership dimensions and even firm-level input-output tables, our methodology would enable the identification of more and more specific sources of welfare growth, and also the consideration of firm heterogeneity and micro structure, which are crucial for accurately assessing the welfare effects in an open economy, as demonstrated by Melitz & Redding (2015).

Thirdly, our research advances the understanding of the TOT effect by elucidating its multi-dimensional origins. Prior investigations into TOT typically culminate in its measurement without investigating its nuts and bolts (Diewert & Morrison 1986; Diewert & Lawrence, 2006; Reinsdorf, 2010; Ossa, 2014; Feenstra et al., 2015; Harchaoui & Willemsen, 2017). However, TOT itself is endogenous, necessitating a deeper exploration to identify its determinants. In addition, certain studies have utilized TOT as an explanatory factor for TFP growth, as demonstrated by Kehoe & Ruhl (2008) and Feenstra et al. (2013). While there is a mutual influence between TOT and TFP, our model suggests that the causal relationship may largely be reversed; it is TFP that impacts TOT, rather than the other way around. This insight reshapes our understanding of the dynamic interplay between TOT and global TFP growth.

Fourthly, our framework enables us to directly assess the global impact of both supply-side policies, such as technology and labor policies, and demand-side policies, especially monetary policies. For instance, numerous studies, such as Addison & Hirsch (1989) and Lingens (2007), have examined the effects of labor unions on wage increases and economic growth. Yet, these analyses are limited to a closed economy framework, and have not explored the indirect impact of labor unions on the domestic economic growth through GVCs. Furthermore, the effect of labor unions on foreign economic growth is also an interesting topic that is worth investigating. Lee (2023) finds that TOT volatility results in growth loss in sectors that are subject to stricter credit constraints and consequently face higher capital costs. However, this conclusion is drawn using regression models, without delving into the theoretical transmission mechanism behind. Our model can facilitate understanding of the intricate channels through which supply- or demand-side policies affect economic growth within the context of an open economy.

The remainder of this paper is structured as follows. Section 2 presents the theoretical model based on growth accounting framework. Initially, we introduce the model grounded on the trade balance assumption, a prevalent premise in the class of quantitative trade models. Subsequently, we expand our model to accommodate trade imbalances. Section 3 introduces the World Input-Output Database utilized in this paper and the empirical model that is derived from our theoretical framework. In Section 4, we carry out the empirical analysis. We juxtapose our estimates against the results from the Penn World Table (PWT) and proceed to dissect the TOT effect in three distinct dimensions: identifying fundamental components (the growth of TFP, capital price and wage), tracing country origins, and differentiating between direct and indirect TOT effects. Section 5 provides conclusions and discussions, and outlines avenues for future research.

2. Theoretical Model

2.1 Setup

We assume an H country and I sector world IO framework. Countries are indexed by h, s, and sectors are indexed by i, j.

p is the $1 \times HI$ row vector of p_{hi}, which denotes the price of commodity i produced by country h. $(h = 1,2, \dots, H; i = 1,2, \dots, I)$.

r is the $1 \times HI$ row vector of r_{hi}, which denotes the capital price of sector i in country h.

w is the $1 \times HI$ row vector of w_{hi}, which denotes the wage of sector i in country h.

c_h is a $HI \times 1$ column vector of country h, with the element c_{hi} representing the real final demand for commodity i in country h.

y_h is the $SJ \times 1$ column vector of $y_{sj,h}$, which denotes the real value added (gross output minus intermediate input) by country h.

x_h is the $HI \times 1$ column vector of x_{hi}, which denotes the real gross output of commodity i by country h, with $x_{si} = 0$ if $s \neq h$.

$\boldsymbol{A}$ denotes $HI * HI$ Leontief matrix of the world economy.

2.2 Welfare growth

Changes in country h's welfare can be expressed as

$$\frac{p\Delta c_h}{pc_h} \tag{1}$$

To simplify our analysis, we assume that each country's international trade is balanced. We will relax our assumption on zero international trade surplus of each country in section 2.5. Then we have

$$pc_h = py_h \tag{2}$$

The value added is defined as follows, which is elaborated in Appendix I.

$$py_h \equiv p(\boldsymbol{I} - \boldsymbol{A})x_h \tag{3}$$

We analyze how domestic TFP growth and changes in TOT affect welfare growth of a country. The GDP effect is centered on domestic factors and encompasses domestic TFP growth, labor force expansion, and capital accumulation. On the other hand, the TOT effect examines the influence of global TFP growth on national welfare through GVCs. By differentiating equation (2) over time, we have

$$\frac{p\Delta c_h}{pc_h} = \frac{p\Delta y_h}{py_h} + \frac{\Delta p(y_h - c_h)}{py_h} \tag{4}$$

The term on the left-hand side (LHS) refers to the weighted expenditure side GDP growth. The first term on the right-hand side (RHS) is the GDP effect, which refers to the weighted production side GDP growth. The second term on the RHS is the TOT effect. Higher export prices or lower import prices would bring stronger TOT effect. The two effects have been defined in existing literature, such as Feenstra et al. (2015).

2.3 GVC TFP and sectoral TFP

The country-sector of a GVC is identified by the final stage of production. GVC TFP growth measures the residual growth of final goods not accounted for by the growth of primary inputs in the final stage and all previous production stages within the GVC. In comparison, the traditional sectoral TFP growth measures the residual growth of total output not accounted for by the growth of primary and intermediate inputs within a sector, which fails to capture the input-output linkages across countries and sectors. Therefore, GVC TFP provides distinct advantages over sectoral TFP in capturing the impact of TFP on the price of final goods.

In a GVC, all intermediate inputs are netted out. Consequently, a condition of zero profit implies that the aggregate value of the final demand is equivalent to the total value of primary inputs. This relationship can be articulated as follows:

$$p_{hi} = \sum_{s=1}^{H}\sum_{j=1}^{I} r_{sj}\gamma_{sj,hi} + \sum_{s=1}^{H}\sum_{j=1}^{I} w_{sj}\lambda_{sj,hi}$$

$$\Rightarrow p = r\boldsymbol{\gamma} + w\boldsymbol{\lambda} \tag{5}$$

$\boldsymbol{\gamma} = \hat{\kappa}\boldsymbol{B}$ and $\boldsymbol{\lambda} = \hat{\ell}\boldsymbol{B}$ denotes the $HI \times HI$ matrix with element $\gamma_{sj,hi} = \kappa_{sj}b_{sj,hi}$ and $\lambda_{sj,hi} = \ell_{sj}b_{sj,hi}$ representing the capital and labor service of sector j in country s directly and indirectly resulting from one unit of final demand of commodity i in country h. $\kappa_{sj} = k_{sj}/x_{sj}$ and $\ell_{sj} = l_{sj}/x_{sj}$. k_{ij} and l_{sj} are the capital and labor service of sector i in country j. $\boldsymbol{B} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the $HI * HI$ Leontief inverse matrix in real terms. Then the Leontief inverse matrix in nominal terms can be expressed as $\hat{p}\boldsymbol{B}\hat{p}^{-1}$, which is articulated in the derivation of Equation (A-6) in Appendix II.

By differentiating Equation (5) over time, we have

$$\Delta p = (r\Delta\boldsymbol{\gamma} + w\Delta\boldsymbol{\lambda}) + \Delta r\boldsymbol{\gamma} + \Delta w\boldsymbol{\lambda} \tag{6}$$

Based on the abovementioned definition, GVC TFP growth rate $\frac{\Delta\pi_{hi}^{G}}{\pi_{hi}^{G}}$ can be expressed as follows:

$$\frac{\Delta\pi_{hi}^{G}}{\pi_{hi}^{G}} = \frac{\Delta y_{hi}}{y_{hi}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{r_{sj}}{p_{hi}y_{hi}}\Delta\left(\gamma_{sj,hi}y_{hi}\right) - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{w_{sj}}{p_{hi}y_{hi}}\Delta\left(\lambda_{sj,hi}y_{hi}\right) \tag{7}$$

Drawing from the dual measure of GVC TFP, as elaborated in Appendix II, we establish the following:

$$\frac{\Delta\pi_{hi}^{G}}{\pi_{hi}^{G}} = -\left(\sum_{s=1}^{H}\sum_{j=1}^{I} r_{sj}\Delta\gamma_{sj,hi} + \sum_{s=1}^{H}\sum_{j=1}^{I} w_{sj}\Delta\lambda_{sj,hi}\right)/p_{hi}$$

$$\Rightarrow \frac{\Delta\pi^{G}}{\pi^{G}} = -(r\Delta\boldsymbol{\gamma} + w\Delta\boldsymbol{\lambda})\hat{p}^{-1} \tag{8}$$

With Equation (8), Equation (6) can be rewritten as

$$\Delta p = -\frac{\Delta\pi^{G}}{\pi^{G}}\hat{p} + \Delta r\boldsymbol{\gamma} + \Delta w\boldsymbol{\lambda} \tag{9}$$

$\frac{\Delta\pi^{G}}{\pi^{G}}$ is a $1 \times HI$ row vector, with element $\frac{\Delta\pi_{hi}^{G}}{\pi_{hi}^{G}}$ representing the GVC TFP growth rate of sector i in country h. The underlying economic intuition here is that: Growth in GVC TFP is inversely related to the prices of final goods, whereas the prices of primary factors within the GVCs are positively correlated with the prices of final goods. GVC TFP growth rate can be further expressed as a function of world-wide sectoral TFP growth rates.

$$\begin{aligned}\frac{\Delta\pi^{G}}{\pi^{G}} &= -(rd\boldsymbol{\gamma} + wd\boldsymbol{\lambda})\hat{p}^{-1} \\ &= -\left(rd\hat{\kappa}\boldsymbol{B} + wd\hat{\ell}\boldsymbol{B}\right)\hat{p}^{-1} \\ &= -\left[\left(r\hat{\kappa} + w\hat{\ell}\right)d\boldsymbol{B} + \left(rd\hat{\kappa} + wd\hat{\ell}\right)\boldsymbol{B}\right]\hat{p}^{-1} \\ &= -\left[p(\boldsymbol{I}-\boldsymbol{A})d\boldsymbol{B} + \left(rd\hat{\kappa} + wd\hat{\ell}\right)\boldsymbol{B}\right]\hat{p}^{-1}\end{aligned}$$

Since $(\boldsymbol{I}-\boldsymbol{A})d\boldsymbol{B} + [d(\boldsymbol{I}-\boldsymbol{A})]\boldsymbol{B} = d[(\boldsymbol{I}-\boldsymbol{A})\boldsymbol{B}] = d\boldsymbol{I} = \boldsymbol{0}$, we have

$$\frac{\Delta\pi^{G}}{\pi^{G}} = -\left[pd\boldsymbol{A} + rd\hat{\kappa} + wd\hat{\ell}\right]\boldsymbol{B}\hat{p}^{-1} = \frac{\Delta\pi}{\pi}\hat{p}\boldsymbol{B}\hat{p}^{-1} \tag{10}$$

where $\frac{\Delta\pi}{\pi}$ is the $1 \times HI$ row vector of sectoral (gross output based) TFP growth rate $\frac{\Delta\pi_{hi}}{\pi_{hi}}$, which can be expressed as follows:

$$\frac{\Delta\pi_{hi}}{\pi_{hi}} = \frac{\Delta x_{hi}}{x_{hi}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}}{p_{hi}x_{hi}}\Delta\left(a_{sj,hi}x_{hi}\right) - \frac{w_{hi}}{p_{hi}x_{hi}}\Delta(\ell_{hi}x_{hi}) - \frac{r_{hi}}{p_{hi}x_{hi}}\Delta(\kappa_{hi}x_{hi}) \tag{11}$$

2.4 GDP growth and TOT effect

Reformulating Equation (11) yields:

$$\frac{p_{hi}\Delta x_{hi}}{py_{h}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}}{py_{h}}\Delta\left(a_{sj,hi}x_{hi}\right) = \frac{p_{hi}x_{hi}}{py_{h}}\frac{\Delta\pi_{hi}}{\pi_{hi}} + \frac{w_{hi}}{py_{h}}\Delta(\ell_{hi}x_{hi}) + \frac{r_{hi}}{py_{h}}\Delta(\kappa_{hi}x_{hi}) \tag{12}$$

By combining Equation (4) with (12), we arrive at the following standard growth accounting relationship

$$\frac{p\Delta y_{h}}{py_{h}} \equiv \frac{p\Delta[(\boldsymbol{I}-\boldsymbol{A})x_{h}]}{py_{h}}$$

$$= \sum_{i=1}^{I} \left\{ \frac{p_{hi} \Delta x_{hi}}{py_h} - \sum_{s=1}^{H} \sum_{j=1}^{I} \frac{p_{sj}}{py_h} \Delta\left(a_{sj,hi} x_{hi}\right) \right\}$$

$$= \sum_{i=1}^{I} \left(\frac{p_{hi} x_{hi}}{py_h} \frac{\Delta \pi_{hi}}{\pi_{hi}} \right) + \sum_{i=1}^{I} \left(\frac{w_{hi}}{py_h} \Delta l_{hi} \right) + \sum_{i=1}^{I} \left(\frac{r_{hi}}{py_h} \Delta k_{hi} \right) \quad (13)$$

The left-hand side of the first equation denotes production-side GDP growth of country h. The first term on the right-hand side of the second equation denotes Domar weighted TFP growth in country h.

It follows directly from Equation (4), (9), (10), and (13) that

$$\frac{p\Delta c_h}{pc_h} = \left[\sum_{i=1}^{I} \left(\frac{p_{hi} x_{hi}}{py_h} \frac{\Delta \pi_{hi}}{\pi_{hi}} \right) + \sum_{i=1}^{I} \left(\frac{w_{hi}}{py_h} \Delta l_{hi} \right) + \sum_{i=1}^{I} \left(\frac{r_{hi}}{py_h} \Delta k_{hi} \right) \right]$$

$$+ \frac{-\frac{\Delta \pi}{\pi} \hat{p} \boldsymbol{B}(y_h - c_h)}{py_h} + \frac{\Delta r \hat{\kappa} \boldsymbol{B}(y_h - c_h)}{py_h} + \frac{\Delta w \hat{\ell} \boldsymbol{B}(y_h - c_h)}{py_h} \quad (14)$$

The above equation shows that intertemporal changes in country h's national welfare consists of four components: 1) ordinary GDP growth caused by Domar weighted TFP growth plus increases in primary factors. An increase in domestic TFP and primary inputs contributes to the enhancement of welfare growth. 2) TOT effects caused by world-wide TFP growth. 3) TOT effects caused by world-wide changes in wage rates; and 4) TOT effects caused by world-wide changes in capital service prices.

Multiplying both sides of Equation (14) by each country's nominal GDP, py_h, summing up across all the countries, and dividing both sides by the world GDP, py, we have

$$\frac{p\Delta c}{pc} = \sum_{h=1}^{H} \frac{py_h}{py} \left[\sum_{i=1}^{I} \left(\frac{p_{hi} x_{hi}}{py_h} \frac{\Delta \pi_{hi}}{\pi_{hi}} \right) + \sum_{i=1}^{I} \left(\frac{w_{hi}}{py_h} \Delta l_{hi} \right) + \sum_{i=1}^{I} \left(\frac{r_{hi}}{py_h} \Delta k_{hi} \right) \right] \quad (15)$$

Changes in world-wide welfare is driven by Domar weighted TFP growth of the world, in addition to primary input growth. Since $y = c$ for the whole world, each of the three TOT effects disappears. In this case, TOT effect across countries can be regarded as a result of a zero-sum game.

2.5 Trade Imbalance

2.5.1 Decomposition framework

Since international trade might not be a zero-sum game, we are now relaxing our assumption of balanced trade for each country. In cases where international trade of each country is not in balance, the measurement of welfare involves incorporating the real trade surplus or deficit into the real final expenditure. We use country h's real GDP on the expenditure side, GDP_h^e, as the measure of this country's welfare. GDP_h^e is defined by①

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① Our definition here is similar with the definition of real GDP on the expenditure side in the Penn World Table (equation 16 of Feenstra, Inklaar, and Timmer 2015, AER) except the fact that we do not take account of PPP factor here.

$$GDP_h^e = \frac{py_h}{P_h} \tag{16}$$

where P_h denotes deflator for country h's final expenditure c_h. It should be noted that P_h represents a scalar, while p denotes a vector. P_h is defined by

$$\frac{\Delta P_h}{P_h} = \frac{\Delta pc_h}{pc_h} \tag{17}$$

By differentiating both sides of Equation (16) and using (17), we can derive the following equation on the growth rate of country h's real GDP on the expenditure side:

$$\frac{\Delta GDP_h^e}{GDP_h^e} = \frac{\Delta\frac{py_h}{P_h}}{\frac{py_h}{P_h}} = \frac{\Delta(py_h)}{py_h} - \frac{\Delta P_h}{P_h} = \frac{p\Delta y_h}{py_h} + \left(\frac{\Delta py_h}{py_h} - \frac{\Delta pc_h}{pc_h}\right) \tag{18}$$

The first term on the righthand side denotes growth rate of country h's real GDP on the production side. The second term denotes TOT effect, which is equal to growth rate of this country's GDP deflator minus growth rate of deflator for country h's final expenditure. When the growth rate of GDP deflator is larger than the growth rate of final expenditure deflator, then the country enjoys positive TOT effect. When trade is balanced, $py_h = pc_h$, Equation (18) will become identical with Equation (4).

By substituting Equation (9), (10), and (13) into Equation (18), we obtain:

$$\begin{aligned}
\frac{\Delta GDP_h^e}{GDP_h^e} &= \left[\sum_{i=1}^{I}\left(\frac{p_{hi}x_{hi}}{py_h}\frac{\Delta\pi_{hi}}{\pi_{hi}}\right) + \sum_{i=1}^{I}\left(\frac{w_{hi}l_{hi}}{py_h}\frac{\Delta l_{hi}}{l_{hi}}\right) + \sum_{i=1}^{I}\left(\frac{r_{hi}k_{hi}}{py_h}\frac{\Delta k_{hi}}{k_{hi}}\right)\right] \\
&\quad - \frac{\Delta\pi}{\pi}\hat{p}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right) + \Delta r\hat{\kappa}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right) + \Delta w\hat{\ell}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right) \\
&= \left[\sum_{i=1}^{I}\left(\frac{p_{hi}x_{hi}}{py_h}\frac{\Delta\pi_{hi}}{\pi_{hi}}\right) + \sum_{i=1}^{I}\left(\frac{w_{hi}l_{hi}}{py_h}\frac{\Delta l_{hi}}{l_{hi}}\right) + \sum_{i=1}^{I}\left(\frac{r_{hi}k_{hi}}{py_h}\frac{\Delta k_{hi}}{k_{hi}}\right)\right] \\
&\quad - \frac{\Delta\pi}{\pi}\hat{p}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right) + \frac{\Delta r}{r}r\hat{\kappa}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right) + \frac{\Delta w}{w}w\hat{\ell}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right) \\
&= \left[\sum_{i=1}^{I}\left(\frac{p_{hi}x_{hi}}{py_h}\frac{\Delta\pi_{hi}}{\pi_{hi}}\right) + \sum_{i=1}^{I}\left(\frac{w_{hi}l_{hi}}{py_h}\frac{\Delta l_{hi}}{l_{hi}}\right) + \sum_{i=1}^{I}\left(\frac{r_{hi}k_{hi}}{py_h}\frac{\Delta k_{hi}}{k_{hi}}\right)\right] \\
&\quad - \frac{\Delta\pi}{\pi}\hat{p}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right) + \frac{\Delta r}{r}\hat{\alpha}\hat{p}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right) + \frac{\Delta w}{w}\hat{\beta}\hat{p}\boldsymbol{B}\left(\frac{y_h}{py_h} - \frac{c_h}{pc_h}\right)
\end{aligned} \tag{19}$$

where α and β is the column vector of $\alpha_{hi} = \frac{r_{hi}\kappa_{hi}}{p_{hi}}$ and $\beta_{hi} = \frac{w_{hi}\ell_{hi}}{p_{hi}}$ respectively. When trade is balanced for each country $(py_h - pc_h = 0)$, Equation (19) becomes equivalent to Equation (14).

2.5.2 Non-zero-sum game

We further approximate the growth rate of the world standard of living by weighed average of each country's growth rate of real GDP on the expenditure side and use each country's share of nominal GDP as the weight:

$$\sum_{h=1}^{H}\frac{py_h}{\sum_{h=1}^{H}py_h}\frac{\Delta GDP_h^e}{GDP_h^e}$$

$$=\sum_{h=1}^{H}\frac{py_h}{\sum_{h=1}^{H}py_h}\frac{p\Delta y_h}{py_h}+\sum_{h=1}^{H}\frac{py_h}{\sum_{h=1}^{H}py_h}\frac{\Delta py_h-\Delta pc_h}{py_h}-\sum_{h=1}^{H}\frac{py_h}{\sum_{h=1}^{H}py_h}\left(\frac{\Delta pc_h}{pc_h}-\frac{\Delta pc_h}{py_h}\right)$$

$$=\sum_{h=1}^{H}\frac{p\Delta y_h}{\sum_{h=1}^{H}py_h}+\sum_{h=1}^{H}\frac{\Delta py_h-\Delta pc_h}{\sum_{h=1}^{H}py_h}-\sum_{h=1}^{H}\left(\frac{py_h-pc_h}{pc_h}\right)\frac{\Delta pc_h}{\sum_{h=1}^{H}py_h}$$

$$=\sum_{h=1}^{H}\frac{p\Delta y_h}{\sum_{h=1}^{H}py_h}+\left(\frac{1}{\sum_{h=1}^{H}py_h}\right)\Delta p\sum_{h=1}^{H}(y_h-c_h)-\left(\frac{1}{\sum_{h=1}^{H}py_h}\right)\sum_{h=1}^{H}\frac{\Delta pc_h}{pc_h}(py_h-pc_h)$$

$$=\sum_{h=1}^{H}\frac{p\Delta y_h}{\sum_{h=1}^{H}py_h}-\left(\frac{1}{\sum_{h=1}^{H}py_h}\right)\sum_{h=1}^{H}\frac{\Delta P_h}{P_h}(py_h-pc_h) \qquad (20)$$

On the righthand side of the first equation, the first term denotes the world real GDP growth on the production side. For the entire world, the total value added is equivalent to the total final demand ($y = c$), thereby rendering the second term null. However, in contrast to Equation (15), the third term in Equation (20), does not inherently reduce to zero. This means that the TOT effects will not fully disappear, even when considering the global scope. In this case, TOT effect across countries is not a zero-sum game. Specifically, when countries with trade surplus ($py_h - pc_h > 0$) tend to encounter declining TOT ($\frac{\Delta P_h}{P_h} > 0$), our measure of the growth rate of the world standard of living will be lower than the global real GDP growth on the production side.

2.5.3 Direct and Indirect effect

Direct and indirect trade linkages exhibit distinct behaviors, particularly in the context of the growing trade restrictions and fragmentation observed in recent years. Direct trade is more vulnerable to trade restrictions, such as the increase in tariffs, whereas indirect trade, facilitated through GVCs, demonstrates greater resilience. (Alfaro & Chor 2023; World Bank, 2024). To formulate more accurate trade policies, it is imperative to examine the magnitude of both direct and indirect TOT effects separately.

Taking the direct and indirect TOT effect into consideration, Equation (19) can be re-written as:

$$\frac{\Delta GDP_h^e}{GDP_h^e}=\left[\sum_{i=1}^{I}\left(\frac{p_{hi}x_{hi}}{py_h}\frac{\Delta\pi_{hi}}{\pi_{hi}}\right)+\sum_{i=1}^{I}\left(\frac{w_{hi}l_{hi}}{py_h}\frac{\Delta l_{hi}}{l_{hi}}\right)+\sum_{i=1}^{I}\left(\frac{r_{hi}k_{hi}}{py_h}\frac{\Delta k_{hi}}{k_{hi}}\right)\right]$$

$$-\frac{\Delta\pi}{\pi}\hat{p}\boldsymbol{A}\left(\frac{y_h}{py_h}-\frac{c_h}{pc_h}\right)+\frac{\Delta r}{r}\hat{\alpha}\hat{p}\boldsymbol{A}\left(\frac{y_h}{py_h}-\frac{c_h}{pc_h}\right)+\frac{\Delta w}{w}\hat{\beta}\hat{p}\boldsymbol{A}\left(\frac{y_h}{py_h}-\frac{c_h}{pc_h}\right)$$

$$-\frac{\Delta\pi}{\pi}\hat{p}(\boldsymbol{B}-\boldsymbol{A})\left(\frac{y_h}{py_h}-\frac{c_h}{pc_h}\right)+\frac{\Delta r}{r}\hat{\alpha}\hat{p}(\boldsymbol{B}-\boldsymbol{A})\left(\frac{y_h}{py_h}-\frac{c_h}{pc_h}\right)+\frac{\Delta w}{w}\hat{\beta}\hat{p}(\boldsymbol{B}-\boldsymbol{A})\left(\frac{y_h}{py_h}-\frac{c_h}{pc_h}\right) \tag{21}$$

3. Data and Empirical Model

3.1 Data

We used the WIOD, which covers 56 sectors in 44 countries ranging from 2000 to 2014. It includes the world input–output tables (WIOTs)① and social economic accounts (SEAs)②, which provide abundant information on output, value-added, intermediate input, labor input, capital input, and price indices at the country-sector level, and thus allows the calculation of both GVC and TFP. The output, value added, and intermediate input from the WIOT and those from the SEA are basically equal.

Whereas the WIOT contains information on the output and intermediate input of the rest of the world (ROW), the SEA dataset does not. Thus, we estimate the primary inputs of ROW by assuming that the average ratio between primary inputs and output of all the middle-income countries equals to that of ROW. 10 out of 44 countries in the WIOT are middle-income countries.

We converted the local currency in the SEA to USD based on the exchange rate data provided by the WIOD and transformed all the nominal values into real values using the price index with 2010 as the basic year. The unit of all values was USD, and the unit of labor was a person.

The number of employees (EMPE) and total hours worked by employees (H_EMPE) were missing for China; thus, we used the number of persons engaged (EMP) to measure labor input. The number of abnormal values for compensation of employees (COMP), which is larger than value-added (VA), was 483, whereas that for labor compensation (LAB) was 1,827. Therefore, we used COMP rather than LAB to measure labor compensation, and if COMP was greater than VA, we set them equal. We used the difference between VA and COMP to measure capital compensation (CAP)③, which is in line with the assumption of constant returns to scale.

3.2 Empirical model

Here we provide the empirical evidence from our theoretical model, that is Equation (19). To apply the model to data, we have to use Törnqvist approximation. In other words, we re-write (19) as follows:

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① Source: http://www.wiod.org/database/wiots16

② Source: http://www.wiod.org/database/seas16

③ The CAP directly provided by WIOD-SEA is calculated by subtracting LAB from VA, resulting in 1,819 instances of negative values, out of a total of 36,120 samples.

$$\frac{\Delta GDP_h^e}{GDP_h^e}$$

$$= \sum_i \frac{1}{2}\left(\frac{p_{hi}^{t+1}x_{hi}^{t+1}}{\sum_{sj} p_{sj}^{t+1}y_{sj,h}^{t+1}} + \frac{p_{hi}^{t}x_{hi}^{t}}{\sum_{sj} p_{sj}^{t}y_{sj,h}^{t}}\right)(ln\pi_{hi}^{t+1} - ln\pi_{hi}^{t})$$

$$+ \sum_i \frac{1}{2}\left(\frac{w_{hi}^{t+1}l_{hi}^{t+1}}{\sum_{sj} p_{sj}^{t+1}y_{sj,h}^{t+1}} + \frac{w_{hi}^{t}l_{hi}^{t}}{\sum_{sj} p_{sj}^{t}y_{sj,h}^{t}}\right)(lnl_{hi}^{t+1} - lnl_{hi}^{t})$$

$$+ \sum_i \frac{1}{2}\left(\frac{r_{hi}^{t+1}k_{hi}^{t+1}}{\sum_{sj} p_{sj}^{t+1}y_{sj,h}^{t+1}} + \frac{r_{hi}^{t}k_{hi}^{t}}{\sum_{sj} p_{sj}^{t}y_{sj,h}^{t}}\right)(lnk_{hi}^{t+1} - lnk_{hi}^{t})$$

$$- \sum_{sj}\left\{\left(ln\pi_{sj}^{t+1} - ln\pi_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar\imath} p_{sj}^{t+1}b_{sj,\hbar\imath}^{t+1}\left(\frac{y_{\hbar\imath,h}^{t+1}}{\sum_{\hbar\imath} p_{\hbar\imath}^{t+1}y_{\hbar\imath,h}^{t+1}} - \frac{c_{\hbar\imath,h}^{t+1}}{\sum_{\hbar\imath} p_{\hbar\imath}^{t+1}c_{\hbar\imath,h}^{t+1}}\right) +\right.\right.$$

$$\left.\left.\sum_{\hbar\imath} p_{sj}^{t}b_{sj,\hbar\imath}^{t}\left(\frac{y_{\hbar\imath,h}^{t}}{\sum_{sj} p_{\hbar\imath}^{t}y_{\hbar\imath,h}^{t}} - \frac{c_{\hbar\imath,h}^{t}}{\sum_{sj} p_{\hbar\imath}^{t}c_{\hbar\imath,h}^{t}}\right)\right]\right\}$$

$$+ \sum_{sj}\left\{\left(lnr_{sj}^{t+1} - lnr_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar\imath} \frac{r_{sj}^{t+1}k_{sj}^{t+1}}{p_{sj}^{t+1}x_{sj}^{t+1}} p_{sj}^{t+1}b_{sj,\hbar\imath}^{t+1}\left(\frac{y_{\hbar\imath,h}^{t+1}}{\sum_{sj} p_{\hbar\imath}^{t+1}y_{\hbar\imath,h}^{t+1}} - \frac{c_{\hbar\imath,h}^{t+1}}{\sum_{\hbar\imath} p_{\hbar\imath}^{t+1}c_{\hbar\imath,h}^{t+1}}\right) +\right.\right.$$

$$\left.\left.\sum_{\hbar\imath} \frac{r_{sj}^{t}k_{sj}^{t}}{p_{sj}^{t}x_{sj}^{t}} p_{sj}^{t}b_{sj,\hbar\imath}^{t}\left(\frac{y_{\hbar\imath,h}^{t}}{\sum_{sj} p_{\hbar\imath}^{t}y_{\hbar\imath,h}^{t}} - \frac{c_{\hbar\imath,h}^{t}}{\sum_{sj} p_{\hbar\imath}^{t}c_{\hbar\imath,h}^{t}}\right)\right]\right\}$$

$$+ \sum_{sj}\left\{\left(lnw_{sj}^{t+1} - lnw_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar\imath} \frac{w_{sj}^{t+1}l_{sj}^{t+1}}{p_{sj}^{t+1}x_{sj}^{t+1}} p_{sj}^{t+1}b_{sj,\hbar\imath}^{t+1}\left(\frac{y_{\hbar\imath,h}^{t+1}}{\sum_{sj} p_{\hbar\imath}^{t+1}y_{\hbar\imath,h}^{t+1}} - \frac{c_{\hbar\imath,h}^{t+1}}{\sum_{sj} p_{\hbar\imath}^{t+1}c_{\hbar\imath,h}^{t+1}}\right) +\right.\right.$$

$$\left.\left.\sum_{i} \frac{w_{sj}^{t}l_{sj}^{t}}{p_{sj}^{t}x_{sj}^{t}} p_{sj}^{t}b_{sj,\hbar\imath}^{t}\left(\frac{y_{\hbar\imath,h}^{t}}{\sum_{sj} p_{\hbar\imath}^{t}y_{\hbar\imath,h}^{t}} - \frac{c_{\hbar\imath,h}^{t}}{\sum_{sj} p_{\hbar\imath}^{t}c_{\hbar\imath,h}^{t}}\right)\right]\right\} \tag{22}$$

The TFP growth can be calculated as follows:

$$ln\pi_{hi}^{t+1} - ln\pi_{hi}^{t} = (lnx_{hi}^{t+1} - lnx_{hi}^{t})$$

$$- \frac{1}{2}\left(\frac{\sum_{sj} P_{sj}^{t+1}x_{sj,hi}^{t+1}}{p_{hi}^{t+1}x_{hi}^{t+1}} + \frac{\sum_{sj} P_{sj}^{t}x_{sj,hi}^{t}}{p_{hi}^{t}x_{hi}^{t}}\right)\sum_{sj}\frac{1}{2}\left(\frac{P_{sj}^{t+1}x_{sj,hi}^{t+1}}{\sum_{sj} P_{sj}^{t+1}x_{sj,hi}^{t+1}} + \frac{P_{sj}^{t}x_{sj,hi}^{t}}{\sum_{sj} P_{sj}^{t}x_{sj,hi}^{t}}\right)\left(lnx_{sj,hi}^{t+1} - lnx_{sj,hi}^{t}\right)$$

$$- \frac{1}{2}\left(\frac{w_{hi}^{t+1}l_{hi}^{t+1}}{p_{hi}^{t+1}x_{hi}^{t+1}} + \frac{w_{hi}^{t}l_{hi}^{t}}{p_{hi}^{t}x_{hi}^{t}}\right)(lnl_{hi}^{t+1} - lnl_{hi}^{t}) - \frac{1}{2}\left(\frac{r_{hi}^{t+1}k_{hi}^{t+1}}{p_{hi}^{t+1}x_{hi}^{t+1}} + \frac{r_{hi}^{t}k_{hi}^{t}}{p_{hi}^{t}x_{hi}^{t}}\right)(lnk_{hi}^{t+1} - lnk_{hi}^{t}) \tag{23}$$

Considering the difference between direct and indirect, the corresponding empirical model (22) can be re-written as:

$$\frac{\Delta GDP_h^e}{GDP_h^e}$$

$$= \sum_i \frac{1}{2}\left(\frac{p_{hi}^{t+1}x_{hi}^{t+1}}{\sum_{sj} p_{sj}^{t+1}y_{sj,h}^{t+1}} + \frac{p_{hi}^{t}x_{hi}^{t}}{\sum_{sj} p_{sj}^{t}y_{sj,h}^{t}}\right)(ln\pi_{hi}^{t+1} - ln\pi_{hi}^{t})$$

$$+\sum_{i}\frac{1}{2}\left(\frac{w_{hi}^{t+1}l_{hi}^{t+1}}{\sum_{sj}p_{sj}^{t+1}y_{sj,h}^{t+1}}+\frac{w_{hi}^{t}l_{hi}^{t}}{\sum_{sj}p_{sj}^{t}y_{sj,h}^{t}}\right)(lnl_{hi}^{t+1}-lnl_{hi}^{t})$$

$$+\sum_{i}\frac{1}{2}\left(\frac{r_{hi}^{t+1}k_{hi}^{t+1}}{\sum_{sj}p_{sj}^{t+1}y_{sj,h}^{t+1}}+\frac{r_{hi}^{t}k_{hi}^{t}}{\sum_{sj}p_{sj}^{t}y_{sj,h}^{t}}\right)(lnk_{hi}^{t+1}-lnk_{hi}^{t})$$

$$-\sum_{sj}\left\{\left(ln\pi_{sj}^{t+1}-ln\pi_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar1}p_{sj}^{t+1}a_{sj,\hbar1}^{t+1}\left(\frac{y_{\hbar1,h}^{t+1}}{\sum_{\hbar1}p_{\hbar1}^{t+1}y_{\hbar1,h}^{t+1}}-\frac{c_{\hbar1,h}^{t+1}}{\sum_{\hbar1}p_{\hbar1}^{t+1}c_{\hbar1,h}^{t+1}}\right)+\right.\right.$$

$$\left.\left.\sum_{\hbar1}p_{sj}^{t}a_{sj,\hbar1}^{t}\left(\frac{y_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}y_{\hbar1,h}^{t}}-\frac{c_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}c_{\hbar1,h}^{t}}\right)\right]\right\}$$

$$+\sum_{sj}\left\{\left(lnr_{sj}^{t+1}-lnr_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar1}\frac{r_{sj}^{t+1}k_{sj}^{t+1}}{p_{sj}^{t+1}x_{sj}^{t+1}}p_{sj}^{t+1}a_{sj,\hbar1}^{t+1}\left(\frac{y_{\hbar1,h}^{t+1}}{\sum_{sj}p_{\hbar1}^{t+1}y_{\hbar1,h}^{t+1}}-\frac{c_{\hbar1,h}^{t+1}}{\sum_{\hbar1}p_{\hbar1}^{t+1}c_{\hbar1,h}^{t+1}}\right)+\right.\right.$$

$$\left.\left.\sum_{\hbar1}\frac{r_{sj}^{t}k_{sj}^{t}}{p_{sj}^{t}x_{sj}^{t}}p_{sj}^{t}a_{sj,\hbar1}^{t+1}\left(\frac{y_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}y_{\hbar1,h}^{t}}-\frac{c_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}c_{\hbar1,h}^{t}}\right)\right]\right\}$$

$$+\sum_{sj}\left\{\left(lnw_{sj}^{t+1}-lnw_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar1}\frac{w_{sj}^{t+1}l_{sj}^{t+1}}{p_{sj}^{t+1}x_{sj}^{t+1}}p_{sj}^{t+1}a_{sj,\hbar1}^{t+1}\left(\frac{y_{\hbar1,h}^{t+1}}{\sum_{sj}p_{\hbar1}^{t+1}y_{\hbar1,h}^{t+1}}-\frac{c_{\hbar1,h}^{t+1}}{\sum_{sj}p_{\hbar1}^{t+1}c_{\hbar1,h}^{t+1}}\right)+\right.\right.$$

$$\left.\left.\sum_{i}\frac{w_{sj}^{t}l_{sj}^{t}}{p_{sj}^{t}x_{sj}^{t}}p_{sj}^{t}a_{sj,\hbar1}^{t+1}\left(\frac{y_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}y_{\hbar1,h}^{t}}-\frac{c_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}c_{\hbar1,h}^{t}}\right)\right]\right\}$$

$$-\sum_{sj}\left\{\left(ln\pi_{sj}^{t+1}-ln\pi_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar1}p_{sj}^{t+1}\left(b_{sj,\hbar1}^{t+1}-a_{sj,\hbar1}^{t+1}\right)\left(\frac{y_{\hbar1,h}^{t+1}}{\sum_{\hbar1}p_{\hbar1}^{t+1}y_{\hbar1,h}^{t+1}}-\frac{c_{\hbar1,h}^{t+1}}{\sum_{\hbar1}p_{\hbar1}^{t+1}c_{\hbar1,h}^{t+1}}\right)+\right.\right.$$

$$\left.\left.\sum_{\hbar1}p_{sj}^{t}\left(b_{sj,\hbar1}^{t+1}-a_{sj,\hbar1}^{t+1}\right)\left(\frac{y_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}y_{\hbar1,h}^{t}}-\frac{c_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}c_{\hbar1,h}^{t}}\right)\right]\right\}$$

$$+\sum_{sj}\left\{\left(lnr_{sj}^{t+1}-lnr_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar1}\frac{r_{sj}^{t+1}k_{sj}^{t+1}}{p_{sj}^{t+1}x_{sj}^{t+1}}p_{sj}^{t+1}\left(b_{sj,\hbar1}^{t+1}-a_{sj,\hbar1}^{t+1}\right)\left(\frac{y_{\hbar1,h}^{t+1}}{\sum_{sj}p_{\hbar1}^{t+1}y_{\hbar1,h}^{t+1}}-\frac{c_{\hbar1,h}^{t+1}}{\sum_{\hbar1}p_{\hbar1}^{t+1}c_{\hbar1,h}^{t+1}}\right)+\right.\right.$$

$$\left.\left.\sum_{\hbar1}\frac{r_{sj}^{t}k_{sj}^{t}}{p_{sj}^{t}x_{sj}^{t}}p_{sj}^{t}\left(b_{sj,\hbar1}^{t+1}-a_{sj,\hbar1}^{t+1}\right)\left(\frac{y_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}y_{\hbar1,h}^{t}}-\frac{c_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}c_{\hbar1,h}^{t}}\right)\right]\right\}$$

$$+\sum_{sj}\left\{\left(lnw_{sj}^{t+1}-lnw_{sj}^{t}\right)\frac{1}{2}\left[\sum_{\hbar1}\frac{w_{sj}^{t+1}l_{sj}^{t+1}}{p_{sj}^{t+1}x_{sj}^{t+1}}p_{sj}^{t+1}\left(b_{sj,\hbar1}^{t+1}-a_{sj,\hbar1}^{t+1}\right)\left(\frac{y_{\hbar1,h}^{t+1}}{\sum_{sj}p_{\hbar1}^{t+1}y_{\hbar1,h}^{t+1}}-\right.\right.\right.$$

$$\left.\left.\left.\frac{c_{\hbar1,h}^{t+1}}{\sum_{sj}p_{\hbar1}^{t+1}c_{\hbar1,h}^{t+1}}\right)+\sum_{i}\frac{w_{sj}^{t}l_{sj}^{t}}{p_{sj}^{t}x_{sj}^{t}}p_{sj}^{t}\left(b_{sj,\hbar1}^{t+1}-a_{sj,\hbar1}^{t+1}\right)\left(\frac{y_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}y_{\hbar1,h}^{t}}-\frac{c_{\hbar1,h}^{t}}{\sum_{sj}p_{\hbar1}^{t}c_{\hbar1,h}^{t}}\right)\right]\right\} \tag{24}$$

4. Empirical Evidence

4.1 Comparison with PWT

To enhance the credibility of the empirical results. We first compare our GDP effect with the GDP growth rate reported in both the PWT ① and the World Development Indicators (WDI) ②, as depicted in Figure 1. For computing the GDP growth rate, we utilized the output-side real GDP ($RGDP^o$) from PWT, and the annual percentage GDP growth at market prices, calculated using a constant local currency from WDI. When estimating the GDP growth rate for the rest of the world (ROW) in WDI, we adopted the proportion of each economy's GDP (expressed in constant 2015 US dollars) within the ROW as a weighting factor to aggregate the GDP growth rate.

Figure 1 illustrates that our measured GDP effect closely mirrors the GDP growth rates derived from both PWT and WDI. Our GDP effect demonstrates superior performance in aligning with the GDP growth rate from the WDI compared to that from the PWT.

Next, we contrast our evaluation of the TOT effect with the corresponding data from the PWT, as shown in Figure 2. Feenstra et al. (2015) provides only the level of TOT effect using the gap between $RGDP^e$ and $RGDP^o$, rather than the growth rate of TOT effect. In order to maintain consistency with this paper, we measure TOT effect in PWT as the discrepancy between the growth rates of expenditure-side real GDP ($RGDP^e$) and the output-side real GDP ($RGDP^o$).

Figure 2 indicates that our estimated TOT effect exhibits substantial similarity to the TOT effect calculated using the PWT. However, it's important to note that the variance between PWT and WIOD is more pronounced in the case of the TOT effect than it is for the GDP effect. This discrepancy primarily arises from the reliance of the TOT effect on import and export prices, data that are not available in WIOD.

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① PWT (version 10.01) encompasses 183 economies, https://www.rug.nl/ggdc/productivity/pwt/?lang=en

② WDI includes 227 economies, https://data.worldbank.org/

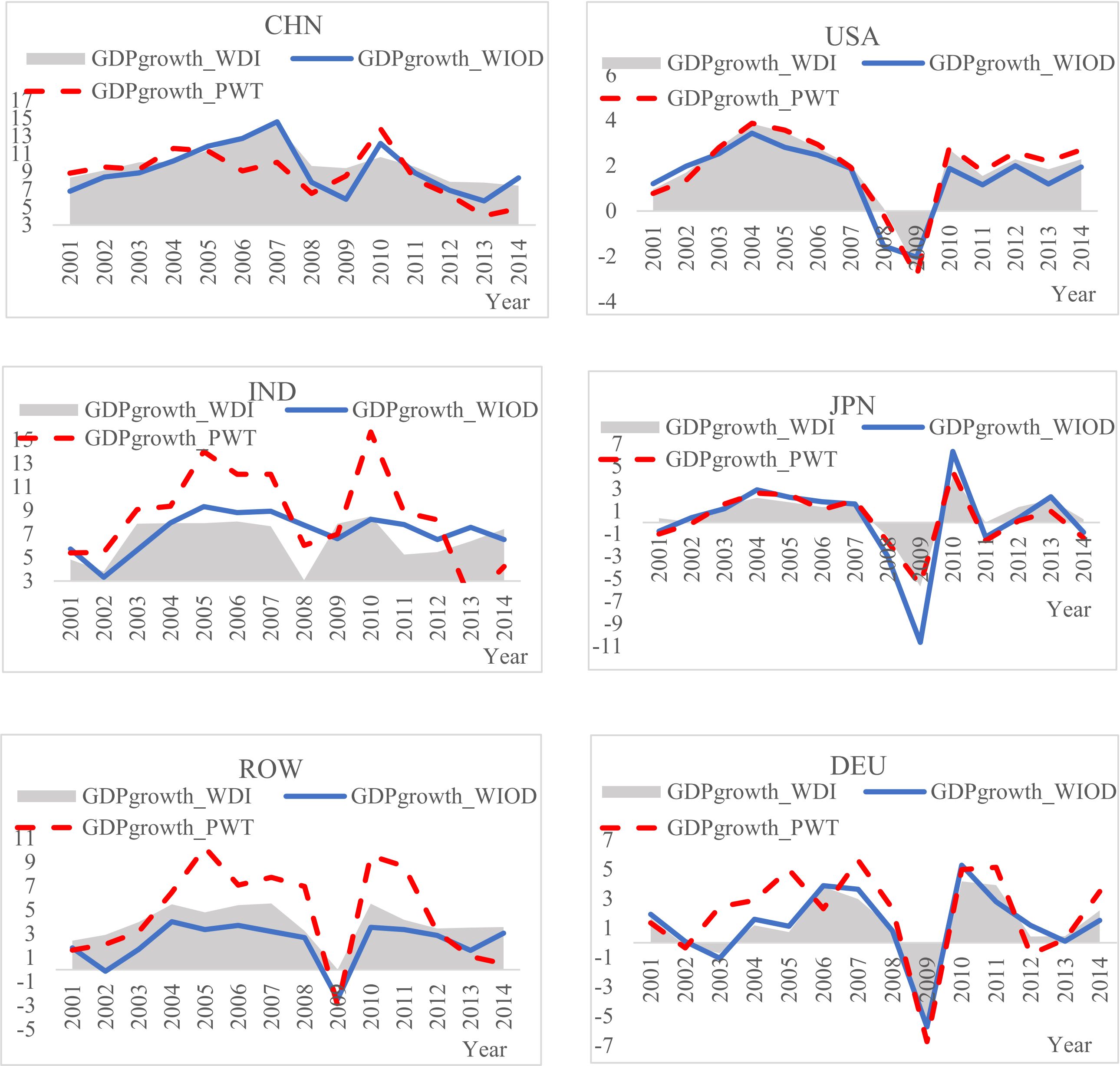

Figure 1: Comparison of GDP effect between WIOD, PWT and WDI (2001-2014)

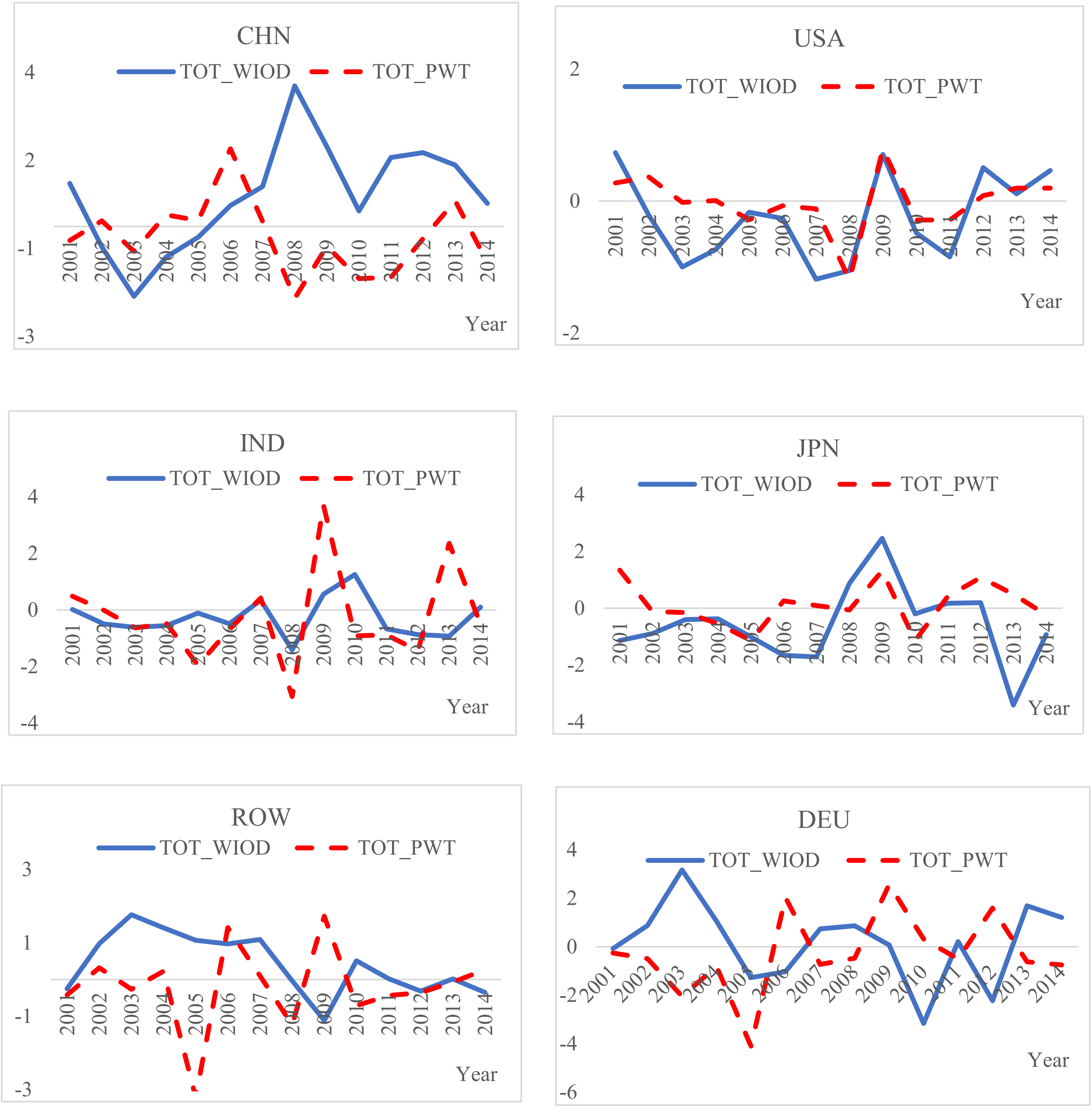

Figure 2: Comparison of TOT effect between WIOD and PWT (%, 2001-2014)

4.2 Welfare growth and TOT effect

Figure 3 shows that China and India witnessed substantial welfare growth from 2001 to 2014, and surpassing that of three developed countries. However, the welfare growth in developing countries declined following the financial crisis, whereas the developed countries demonstrated resilience in their welfare growth.

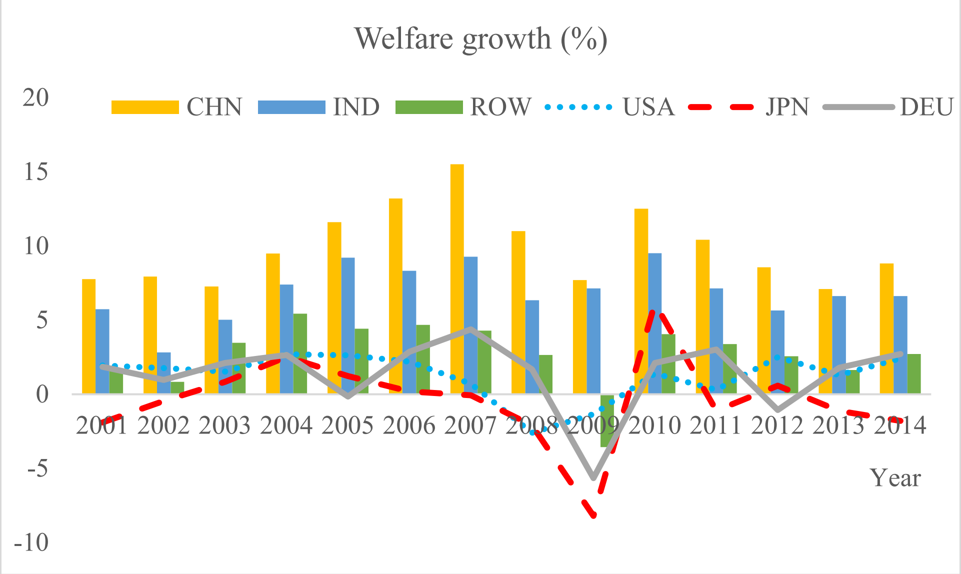

Figure 3: Welfare growth of selected economies (2001-2014)

By decomposing the welfare growth into GDP effect and TOT effect, we find the results derived from WIOD in Figures 1 and 2 that the GDP effect is the predominant driver of welfare growth, while TOT effect plays a substantial role as well. Notably, China reaped significant benefits from both the TOT effect and the GDP effect. However, these benefits began to wane in the aftermath of the 2008 financial crisis. Conversely, the TOT effect in the U.S. exhibited significant improvements following the global financial crisis of 2008. However, Japan's resilience in withstanding the crisis appears inadequate, and resulting in a significant decline in TOT effect following the financial crisis. In contrast, Germany seems to be more resilient in weathering the crisis, maintaining a robust TOT effect.

4.3 Components of TOT effect

Figure 2 illustrates the progression of the three components comprising the TOT effect in both China and the U.S.①: changes in TFP, capital prices, and wages. Notably, the U.S. consistently gains substantial benefits from global TFP growth each year, while China does not enjoy as significant an advantage in this regard. The TOT effect in China and the U.S. resulting from increases in TFP growth display contrasting outcomes. In addition, while China consistently derives substantial benefits from global wage growth, the U.S., on the

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① For the sake of simplicity, the outcomes related to other countries are not listed.

other hand, is adversely affected by the rise in global wages. The underlying cause of these differences remains elusive until we conduct a deeper analysis into the country-specific origins of the TFP growth and wage growth. Therefore, it is essential to develop a model that facilitates the decomposition of effects by country-sector origins.

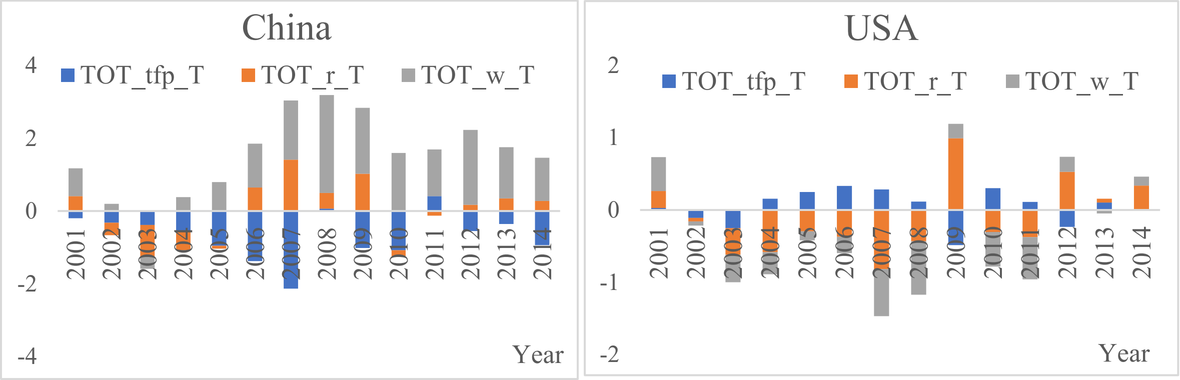

Figure 4: Three components of TOT effect in China and the U.S. (2001-2014)

4.4 Country origins of TOT effect

Table 1a and 1b illustrate the country origins of the TOT effect in the U.S. and China, respectively. In both cases, these nations experience positive TOT effects from their own country, but a predominantly negative TOT effect to the other country during the sample period. Without further examination of the individual components of the TOT effects, it is not easy to understand these outcomes.

Table 2a and 2b present a detailed analysis of the country origins of each component of the TOT effect in the U.S. and China, respectively. Both nations have benefited from the TFP growth experienced in each other's economies, because the TFP growth in a partner country leads to a reduction in the price of imported goods. However, this positive TOT effect from TFP growth is surpassed by the negative TOT effects driven by the rise in factor prices, particularly wage growth, in each other, which increases the prices of imported goods.

Conversely, while each country reaps the benefits of a positive TOT effect stemming from the increase in their own factor prices, with wage growth being a significant contributor, they simultaneously face a negative TOT effect, primarily due to its own TFP growth. This occurs because the rise in factor prices contributes to an increase in the price of exports, whereas the growth in domestic TFP leads to a decrease in export prices.

Upon conducting a more in-depth investigation into the country origins①, it now becomes evident that the adverse TOT effect observed in China due to global TFP changes

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① To simplify our analysis, we consolidate the sectors within each country. The origins of country-sector specificities can be identified using a similar approach.

is primarily attributed to China's own TFP growth during the sample period. This TFP growth in China results in reduced costs for U.S. imports from China, thereby contributing to an increase in welfare growth in the U.S. In addition, the positive TOT effect in China resulting from global wage change primarily stems from China's wage growth during the sample period. This wage growth in China leads to increased costs for U.S. imports from China, consequently diminishing the welfare growth in the U.S.

Table 1a: Country origins of TOT effect in the U.S (%)

Year	USA	JPN	DEU	CHN	IND	ROW
2001	0.45	0.12	0.01	-0.01	0.00	0.16
2002	0.22	0.04	-0.04	0.00	0.00	-0.43
2003	0.30	-0.06	-0.13	-0.02	-0.01	-1.08
2004	0.39	-0.04	-0.08	-0.04	-0.01	-0.95
2005	0.49	0.02	0.00	-0.03	-0.01	-0.64
2006	0.40	0.06	-0.01	-0.06	-0.01	-0.65
2007	0.24	0.01	-0.08	-0.13	-0.02	-1.21
2008	0.24	-0.11	-0.07	-0.24	0.00	-0.87
2009	-0.01	-0.09	0.03	-0.05	0.01	0.82
2010	0.14	-0.02	0.03	-0.08	-0.02	-0.54
2011	0.28	-0.06	-0.05	-0.21	-0.01	-0.80
2012	0.26	0.00	0.05	-0.10	0.02	0.27
2013	0.22	0.16	-0.04	-0.12	0.01	-0.12
2014	0.23	0.05	-0.01	-0.02	0.00	0.21

Table 1b: Country origins of TOT effect in China (%)

Year	USA	JPN	DEU	CHN	IND	ROW
2001	-0.02	0.26	0.02	0.49	0.00	0.23
2002	-0.02	0.09	-0.07	0.17	0.00	-0.65
2003	-0.03	-0.16	-0.24	0.66	-0.02	-1.80
2004	-0.04	-0.15	-0.16	1.39	-0.03	-1.71
2005	-0.06	0.08	0.00	0.91	-0.03	-1.14
2006	-0.05	0.17	-0.02	1.49	-0.02	-1.10
2007	-0.04	0.04	-0.14	2.99	-0.06	-1.87
2008	-0.05	-0.28	-0.12	4.85	-0.01	-1.20
2009	0.00	-0.22	0.06	0.86	0.01	1.11
2010	-0.03	-0.05	0.07	1.18	-0.04	-0.78
2011	-0.03	-0.16	-0.09	3.00	-0.02	-1.14
2012	-0.03	0.00	0.09	1.22	0.02	0.38
2013	-0.02	0.26	-0.06	1.38	0.01	-0.17
2014	-0.02	0.08	-0.02	0.21	0.00	0.28

Table 2a: Country origins of each component of the U.S.'s TOT effect (%)

	USA from USA			USA from CHN		
Year	TOT_tfp	TOT_r	TOT_w	TOT_tfp	TOT_r	TOT_w
2001	-0.01	0.04	0.42	0.01	0.00	-0.01
2002	-0.17	0.16	0.23	0.01	0.00	-0.02
2003	-0.29	0.29	0.30	0.01	-0.01	-0.02
2004	-0.03	0.09	0.33	0.03	-0.02	-0.05
2005	0.04	0.17	0.27	0.04	-0.03	-0.05
2006	0.07	0.08	0.25	0.07	-0.05	-0.07
2007	-0.10	0.09	0.25	0.11	-0.12	-0.12
2008	0.07	0.06	0.11	0.00	-0.06	-0.19
2009	-0.03	-0.01	0.03	0.02	0.02	-0.09
2010	-0.19	0.20	0.13	0.11	-0.04	-0.15
2011	-0.05	0.16	0.17	-0.01	-0.05	-0.16
2012	-0.02	0.13	0.15	0.02	0.03	-0.14
2013	0.11	0.04	0.07	0.03	-0.02	-0.12
2014	-0.01	0.08	0.16	0.08	0.00	-0.10

Table 2b: Country origins of each component of China's TOT effect (%)

	CHN from USA			CHN from CHN		
Year	TOT_tfp	TOT_r	TOT_w	TOT_tfp	TOT_r	TOT_w
2001	0.00	0.00	-0.02	-0.22	0.08	0.63
2002	0.01	-0.01	-0.02	-0.39	-0.04	0.60
2003	0.03	-0.03	-0.03	-0.45	0.26	0.85
2004	0.00	-0.01	-0.04	-0.86	0.72	1.53
2005	0.00	-0.02	-0.03	-1.28	0.73	1.45
2006	-0.01	-0.01	-0.03	-1.72	1.30	1.91
2007	0.02	-0.02	-0.04	-2.59	2.71	2.87
2008	-0.01	-0.01	-0.02	0.02	1.11	3.71
2009	0.01	0.00	-0.01	-0.28	-0.35	1.49
2010	0.03	-0.04	-0.02	-1.72	0.59	2.31
2011	0.01	-0.02	-0.02	0.17	0.63	2.20
2012	0.00	-0.01	-0.01	-0.23	-0.34	1.79
2013	-0.01	0.00	-0.01	-0.30	0.28	1.40
2014	0.00	-0.01	-0.02	-0.87	-0.03	1.10

4.5 Direct and Indirect TOT effect

Table 3 presents the share of the indirect TOT effect within the overall TOT effect. The signs of both direct and indirect TOT effects are consistent, with the indirect TOT effect accounting for roughly 75% of the overall TOT impact. This suggests that overlooking the indirect TOT effect would significantly understate the magnitude of the TOT effect. This also suggests that the detrimental impact on the indirect TOT effect resulting from the host country's imposition of higher tariffs significantly exceeds the direct TOT effect. Given that the indirect TOT effect demonstrates greater resilience compared to its direct counterpart, it is crucial to assess the potential welfare gains and losses prior to enacting trade restrictions.

Table 3: The proportion of indirect TOT effect (%)

Year	USA	JPN	DEU	CHN	IND	ROW
2001	75.94	75.33	76.32	75.16	70.34	75.27
2002	75.75	75.41	75.68	74.51	75.74	75.16
2003	75.51	75.51	76.01	74.36	75.47	74.89
2004	75.38	75.72	75.44	72.76	75.65	75.05
2005	74.75	75.58	76.97	69.43	75.76	75.39
2006	75.17	75.56	77.28	79.65	76.02	75.36
2007	75.46	75.66	74.02	80.44	76.54	74.99
2008	75.39	75.02	75.37	76.95	75.80	95.20
2009	75.41	75.55	97.34	74.90	76.01	75.52
2010	75.45	76.51	76.59	82.02	75.79	75.38
2011	75.61	74.03	71.38	78.49	76.00	45.32
2012	75.86	74.88	76.27	75.75	76.10	75.31
2013	75.78	75.79	76.30	76.76	76.31	50.24
2014	76.01	75.77	77.06	75.10	76.54	76.04

5. Concluding Remarks

With the growing trade restrictions and the restructuring of GVCs in recent years, including the shift from globalization to "slowbalization", the welfare consequence of global TFP growth have gained increasing significance in shaping the trade and technology policies. This paper has developed a concise yet potent model to investigate the influence of global TFP growth on national welfare growth through GVCs. Our model is grounded in a growth accounting framework, which minimizes the number of assumptions required. Initially, we decompose national welfare growth into two key components: the GDP effect and the TOT effect.

Leveraging the concept of GVC TFP, we gain the ability to dissect the TOT effect into its fundamental components, particularly highlighting the contributions arising from the growth of TFP, capital prices, and wages. This approach enables us to further pinpoint the origins of these contributions, whether at the country level or within specific country-sector segments. Additionally, it facilitates an exploration of the role of direct and indirect involvement in GVCs in influencing TOT effect. This approach allows us to gain valuable insights into the complex interplay between global productivity and national welfare growth in the context of modern globalized production networks. By applying the model to data, we obtained five important findings:

(1) From 2001 to 2014, China and India experienced remarkable welfare growth, surpassing that of three developed countries (the U.S., Japan, Germany). However, post-financial crisis, welfare growth in developing countries saw a decline, in contrast to the resilience shown by developed countries, except Japan. The primary drivers of welfare changes were found to be GDP growth, as opposed to the TOT effect. Our estimates of the GDP effect and the TOT effect, derived from the WIOD, closely correspond with the results obtained from the PWT.

(2) The TOT effect in China significantly surpasses that in the U.S during the period from 2001 to 2014. However, the trend in China exhibits an inverted U shape, while the U.S. trend demonstrates a U shape, with both patterns pivoting around the 2008 financial crisis as a turning point.

(3) Through delving deep into the components of the TOT effect, we can reveal some novel insights. Both China and the U.S. experience negative TOT effects towards each other. After further investigating the components of TOT effect, we revealed some interesting stories behind the general TOT effect. The negative TOT effects towards each other primarily results from increasing factor prices, notably wages, in the other economy. However, both nations benefit from positive TOT effects stemming from TFP growth within each other's economies. This underscores the importance of foreign TFP growth in enhancing welfare. The contribution of foreign TFP can only be fully understood by

dissecting the components of TOT effect. Hence, foreign TFP influences national welfare not just by promoting real GDP growth but by improving the TOT of a country.

(4) By investigating the country-specific origins of the TOT effect, we can thoroughly comprehend findings that are initially challenging to understand. The TOT effect resulting from global TFP changes is positive for the U.S., but negative for China. In contrast, the TOT effect resulting from global wage growth is positive for China, but negative for the U.S.. It is essential to further identify the country origins of these TOT components before fully grasping these findings. Indeed, the adverse TOT effect observed in China due to global TFP changes is primarily attributed to China's own TFP growth during the sample period. This TFP growth in China results in reduced costs for U.S. imports from China, thereby contributing to an increase in welfare growth in the U.S. In addition, the positive TOT effect in China resulting from global wage change primarily stems from China's wage growth during the sample period. This wage growth in China leads to increased costs for U.S. imports from China, consequently diminishing the welfare growth in the U.S.

(5) The distinction between direct and indirect input-output relationships plays a significant role in shaping trade policies and, therefore, must be taken into account when analyzing the TOT effect. The signs of both direct and indirect TOT effects align, with the indirect TOT effect contributing to approximately 75% of the total TOT impact. The substantial contribution, along with the possible stronger resilience, of indirect input-output relationships underscores the necessity of assessing potential welfare gains and losses, with a particular focus on the indirect TOT effect, before proceeding with the implementation of trade restrictions, such as the introduction of higher tariffs.

It's important to recognize that the TOT effect does not encompass the entire spectrum of welfare effects arising from trade. In reality, a portion of the trade's impact on welfare is already accounted for in the GDP effect. In addition, we should approach the interpretation of our empirical findings with caution, given the limitations inherent in the data we have employed. We are uncertain about the extent to which the price data within the WIOD accurately captures quality change of output.

We plan to extend our model in the following ways in future research: (1) Addressing the endogeneity of factor prices by introducing general equilibrium model. (2) Considering the quality of factors and products, such as working hours and education levels; (3) Transitioning from a static framework to a dynamic analysis by including the capital accumulation. In terms of the empirical analysis, we will investigate the impact of increasing imports from countries with lower labor costs on national welfare growth, such as the U.S.' increased imports from China; and also, we will take into consideration the significant role of FDI by utilizing Input-Output tables that differentiate between domestic and foreign-owned firms. These enhancements will contribute to a more comprehensive and refined analysis welfare growth.

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Appendix

Appendix I. Illustration of Identity (3)

We use an input-output table with two countries (H=2) and two sectors (I =2) to help understand the definition of value added and identity (3):

	H1 I1	H2 I1	H1 I2	H2 I2	C1	C2	x
H1 I1	$x_{11,11}$	$x_{11,12}$	$x_{11,21}$	$x_{11,22}$	$c_{11,1}$	$c_{11,2}$	x_{11}
H1 I2	$x_{12,11}$	$x_{12,12}$	$x_{12,21}$	$x_{12,22}$	$c_{12,1}$	$c_{12,2}$	x_{12}
H2 I1	$x_{21,11}$	$x_{21,12}$	$x_{21,21}$	$x_{21,22}$	$c_{21,1}$	$c_{21,2}$	x_{21}
H2 I2	$x_{22,11}$	$x_{22,12}$	$x_{22,21}$	$x_{22,22}$	$c_{22,1}$	$c_{22,2}$	x_{22}
v	v_{11}	v_{12}	v_{21}	v_{22}			
x	x_{11}	x_{12}	x_{21}	x_{22}			

$$p = (p_{11}, p_{12}, p_{21}, p_{22});\ py_1 \equiv pv_1;\ v_1 = (v_{11}, v_{12}, 0,0)'$$

$$c_1 = \left(c_{11,1}, c_{12,1}, c_{21,1}, c_{22,1}\right)'\ ; c_2 = \left(c_{11,2}, c_{12,2}, c_{21,2}, c_{22,2}\right)'$$

If trade is balanced, then we have $py_1 \equiv pv_1 = pc_1;\ py_2 \equiv pv_2 = pc_2$. Then we have

$$p(\boldsymbol{I} - \boldsymbol{A})x_1 = p\begin{bmatrix} 1 - a_{11,11} & -a_{11,12} & -a_{11,21} & -a_{11,22} \\ -a_{12,11} & 1 - a_{12,12} & -a_{12,21} & -a_{12,22} \\ -a_{21,11} & -a_{21,12} & 1 - a_{21,21} & -a_{21,22} \\ -a_{22,11} & -a_{22,12} & -a_{22,21} & 1 - a_{22,22} \end{bmatrix}\begin{bmatrix} x_{11} \\ x_{12} \\ 0 \\ 0 \end{bmatrix} \equiv p\begin{bmatrix} y_{11,1} \\ y_{12,1} \\ y_{21,1} \\ y_{22,1} \end{bmatrix}$$
$$= py_1$$

where $x_{21,11} = a_{21,11} * x_{11}$, which represents the intermediate goods of country 2 and sector 1 delivered to country 1 and sector 1. y_1 refers to country 1's value added in a closed economy. Specifically, $y_{11,1} = x_{11} - x_{11,11} - x_{11,12}$ represents country 1's value added produced in country 1 and sector 1, including the final demand by country 1 and export of final goods and intermediate goods to country 2; $y_{21,1} = -x_{21,11} - x_{21,12}$ represents country 1's import of intermediate goods produced in country 2 and sector 1.

In other words, the value added of country 1 equals to its total output minus the intermediate goods supplied by country 1 and country 2. Then production-side GDP growth of country 1 can be expressed as

$$\frac{p\Delta y_1}{py_1}=\frac{p\Delta[(\boldsymbol{I}-\boldsymbol{A})x_1]}{py_1}$$
$$=\frac{1}{py_1}\begin{pmatrix}p_{11}\Delta x_{11}+p_{12}\Delta x_{12}-p_{11}\Delta x_{11,11}-p_{12}\Delta x_{12,11}-p_{21}\Delta x_{21,11}-p_{22}\Delta x_{22,11}\\ -p_{11}\Delta x_{11,12}-p_{12}\Delta x_{12,12}-p_{21}\Delta x_{21,12}-p_{22}\Delta x_{22,12}\end{pmatrix} \tag{A-1}$$

Appendix II. Proof of Equation (8)

II.1 Dual measure of sectoral TFP

The output-based sectoral production function is

$$x_{hi}=\pi_{hi}(k_{hi})^{\alpha_{hi}}(l_{hi})^{\beta_{hi}}\prod\nolimits_{sj}\left(a_{sj,hi}x_{hi}\right)^{\theta_{sj,hi}} \tag{A-2}$$

The two neoclassical assumptions (perfect competition and constant returns to scale) suggest that:

$$\alpha_{hi}=\frac{r_{hi}\kappa_{hi}}{p_{hi}};\ \beta_{hi}=\frac{w_{hi}\ell_{hi}}{p_{hi}};\ \theta_{sj,hi}=\frac{p_{sj}a_{sj,hi}}{p_{hi}}$$

$$\sum_{s=1}^{S}\sum_{j=1}^{J}\theta_{sj,hi}+\alpha_{hi}+\beta_{hi}=1$$

Then we have sectoral TFP growth rate:

$$\frac{\Delta\pi_{hi}}{\pi_{hi}}=\frac{\Delta x_{hi}}{x_{hi}}-\sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}}{p_{hi}x_{hi}}\Delta\left(a_{sj,hi}x_{hi}\right)-\frac{r_{hi}}{p_{hi}x_{hi}}\Delta(\kappa_{hi}x_{hi})-\frac{w_{hi}}{p_{hi}x_{hi}}\Delta(\ell_{hi}x_{hi})$$

$$=\frac{\Delta x_{hi}}{x_{hi}}-\sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}}{p_{hi}x_{hi}}\left(\Delta a_{sj,hi}x_{hi}+a_{sj,hi}\Delta x_{hi}\right)-\frac{r_{hi}}{p_{hi}x_{hi}}(\Delta\kappa_{hi}x_{hi}+\kappa_{hi}\Delta x_{hi})$$
$$-\frac{w_{hi}}{p_{hi}x_{hi}}(\Delta\ell_{hi}x_{hi}+\ell_{hi}\Delta x_{hi})$$

$$=\frac{\Delta x_{hi}}{x_{hi}}-\left(\sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}a_{sj,hi}}{p_{hi}}+\frac{r_{hi}\kappa_{hi}}{p_{hi}}+\frac{w_{hi}\ell_{hi}}{p_{hi}}\right)\frac{\Delta x_{hi}}{x_{hi}}-\sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}}{p_{hi}x_{hi}}\Delta a_{sj,hi}x_{hi}$$
$$-\frac{r_{hi}}{p_{hi}x_{hi}}\Delta\kappa_{hi}x_{hi}-\frac{w_{hi}}{p_{hi}x_{hi}}\Delta\ell_{hi}x_{hi}$$

$$=\frac{\Delta x_{hi}}{x_{hi}}-\left(\sum_{s=1}^{S}\sum_{j=1}^{J}\theta_{sj,hi}+\alpha_{hi}+\beta_{hi}\right)\frac{\Delta x_{hi}}{x_{hi}}-\sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}}{p_{hi}x_{hi}}\Delta a_{sj,hi}x_{hi}-\frac{r_{hi}}{p_{hi}x_{hi}}\Delta\kappa_{hi}x_{hi}$$
$$-\frac{w_{hi}}{p_{hi}x_{hi}}\Delta\ell_{hi}x_{hi}$$

$$= -\sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}}{p_{hi}x_{hi}}\Delta a_{sj,hi}x_{hi} - \frac{r_{hi}}{p_{hi}x_{hi}}\Delta\kappa_{hi}x_{hi} - \frac{w_{hi}}{p_{hi}x_{hi}}\Delta\ell_{hi}x_{hi}$$

$$= -\left(\sum_{s=1}^{H}\sum_{j=1}^{I}p_{sj}\Delta a_{sj,hi} + r_{hi}\Delta\kappa_{hi} + w_{hi}\Delta\ell_{hi}\right)/p_{hi} \tag{A-3}$$

Equation (A-3) includes physical variables. To enhance our understanding of the dual measures, we proceed to articulate TFP growth exclusively utilizing the relevant price variables. Zero profit of each country-sector implies that

$$p_{hi} = r_{hi}\kappa_{hi} + w_{hi}\ell_{hi} + \sum_{s=1}^{H}\sum_{j=1}^{I}p_{sj}a_{sj,hi}$$

$$\Rightarrow \Delta p_{hi} = \left(r_{hi}\Delta\kappa_{hi} + w_{hi}\Delta\ell_{hi} + \sum_{s=1}^{H}\sum_{j=1}^{I}p_{sj}\Delta a_{sj,hi}\right) + \Delta r_{hi}\kappa_{hi} + \Delta w_{hi}\ell_{hi} + \sum_{s=1}^{H}\sum_{j=1}^{I}\Delta p_{sj}a_{sj,hi} \tag{A-4}$$

Substitute (A-3) into (A-4), we have

$$\Delta p_{hi} = -p_{hi}\frac{\Delta\pi_{hi}}{\pi_{hi}} + \Delta r_{hi}\kappa_{hi} + \Delta w_{hi}\ell_{hi} + \sum_{s=1}^{H}\sum_{j=1}^{I}\Delta p_{sj}a_{sj,hi}$$

$$\Rightarrow \frac{\Delta p_{hi}}{p_{hi}} = -\frac{\Delta\pi_{hi}}{\pi_{hi}} + \frac{r_{hi}\kappa_{hi}}{p_{hi}}\frac{\Delta r_{hi}}{r_{hi}} + \frac{w_{hi}\ell_{hi}}{p_{hi}}\frac{\Delta w_{hi}}{w_{hi}} + \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{p_{sj}a_{sj,hi}}{p_{hi}}\frac{\Delta p_{sj}}{p_{sj}} \tag{A-5}$$

In matrix form, Equation (A-5) can be expressed as follows:

$$\frac{\Delta p}{p} = -\frac{\Delta\pi}{\pi} + \frac{\Delta r}{r}\hat{\alpha} + \frac{\Delta w}{w}\hat{\beta} + \frac{\Delta p}{p}\hat{p}\boldsymbol{A}\hat{p}^{-1}$$

$$\Rightarrow \frac{\Delta p}{p}(\boldsymbol{I} - \hat{p}\boldsymbol{A}\hat{p}^{-1}) = -\frac{\Delta\pi}{\pi} + \frac{\Delta r}{r}\hat{\alpha} + \frac{\Delta w}{w}\hat{\beta}$$

$$\Rightarrow \frac{\Delta p}{p}\hat{p}(\boldsymbol{I} - \boldsymbol{A})\hat{p}^{-1} = -\frac{\Delta\pi}{\pi} + \frac{\Delta r}{r}\hat{\alpha} + \frac{\Delta w}{w}\hat{\beta}$$

$$\Rightarrow \frac{\Delta p}{p} = \left(-\frac{\Delta\pi}{\pi} + \frac{\Delta r}{r}\hat{\alpha} + \frac{\Delta w}{w}\hat{\beta}\right)\hat{p}\boldsymbol{B}\hat{p}^{-1} \tag{A-6}$$

Equation (A-5) also suggests that the price of output can be expressed as a function of factor prices and TFP, which is the dual of production function (A-2).

$$p_{hi} = \frac{(r_{hi})^{\alpha_{hi}}(w_{hi})^{\beta_{hi}}\prod_{sj}(p_{sj})^{\theta_{sj,hi}}}{\pi_{hi}} \tag{A-7}$$

II.2 Dual measure of GVC TFP

We assume a GVC production function as follows:

$$y_{hi} = \pi_{hi}^{G}\prod_{sj}(\gamma_{sj,hi}y_{hi})^{\alpha_{sj,hi}}(\lambda_{sj,hi}y_{hi})^{\beta_{sj,hi}} \tag{A-8}$$

The two neoclassical assumptions (perfect competition and constant returns to scale) suggest that:

$$\alpha_{sj,hi} = \frac{r_{sj}(\gamma_{sj,hi}y_{hi})}{p_{hi}y_{hi}} = \frac{r_{sj}\gamma_{sj,hi}}{p_{hi}};\ \beta_{sj,hi} = \frac{w_{sj}(\lambda_{sj,hi}y_{hi})}{p_{hi}y_{hi}} = \frac{w_{sj}\lambda_{sj,hi}}{p_{hi}}$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N}(\alpha_{sj,hi} + \beta_{sj,hi}) = 1$$

Then we have GVC TFP growth rate:

$$\frac{\Delta\pi_{hi}^{G}}{\pi_{hi}^{G}} = \frac{\Delta y_{hi}}{y_{hi}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{r_{sj}(\gamma_{sj,hi}y_{hi})}{p_{hi}y_{hi}}\frac{\Delta(\gamma_{sj,hi}y_{hi})}{(\gamma_{sj,hi}y_{hi})} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{w_{sj}(\lambda_{sj,hi}y_{hi})}{p_{hi}y_{hi}}\frac{\Delta(\lambda_{sj,hi}y_{hi})}{(\lambda_{sj,hi}y_{hi})}$$

$$= \frac{\Delta y_{hi}}{y_{hi}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{r_{sj}}{p_{hi}y_{hi}}\Delta(\gamma_{sj,hi}y_{hi}) - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{w_{sj}}{p_{hi}y_{hi}}\Delta(\lambda_{sj,hi}y_{hi})$$

$$= \frac{\Delta y_{hi}}{y_{hi}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{r_{sj}}{p_{hi}y_{hi}}(\Delta\gamma_{sj,hi}y_{hi} + \gamma_{sj,hi}\Delta y_{hi})$$
$$- \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{w_{sj}}{p_{hi}y_{hi}}(\Delta\lambda_{sj,hi}y_{hi} + \lambda_{sj,hi}\Delta y_{hi})$$

$$= \frac{\Delta y_{hi}}{y_{hi}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{r_{sj}}{p_{hi}y_{hi}}(\Delta\gamma_{sj,hi}y_{hi} + \gamma_{sj,hi}\Delta y_{hi})$$
$$- \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{w_{sj}}{p_{hi}y_{hi}}(\Delta\lambda_{sj,hi}y_{hi} + \lambda_{sj,hi}\Delta y_{hi})$$

$$= \frac{\Delta y_{hi}}{y_{hi}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{r_{sj}\gamma_{sj,hi}}{p_{hi}}\frac{\Delta y_{hi}}{y_{hi}} - \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{w_{sj}\lambda_{sj,hi}}{p_{hi}}\frac{\Delta y_{hi}}{y_{hi}}$$

$$- \left(\sum_{s=1}^{H}\sum_{j=1}^{I}\frac{r_{sj}\Delta\gamma_{sj,hi}}{p_{hi}} + \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{w_{sj}\Delta\lambda_{sj,hi}}{p_{hi}}\right)$$

$$= -\left(\sum_{s=1}^{H}\sum_{j=1}^{I} r_{sj}\Delta\gamma_{sj,hi} + \sum_{s=1}^{H}\sum_{j=1}^{I} w_{sj}\Delta\lambda_{sj,hi}\right)/p_{hi} \qquad \text{(A-9)}$$

Thus far, Equation (8) has been proved. To gain a deeper comprehension of the dual measures, we further articulate GVC TFP growth exclusively using the pertinent price variables.

Zero profit of each GVC means that

$$p_{hi} = \sum_{s=1}^{H}\sum_{j=1}^{I} r_{sj}\gamma_{sj,hi} + \sum_{i=1}^{H}\sum_{j=1}^{I} w_{sj}\lambda_{ij,hi}$$

$$\Rightarrow \Delta p_{hi} = \left(\sum_{s=1}^{H}\sum_{j=1}^{I} r_{sj}\Delta\gamma_{sj,hi} + \sum_{s=1}^{H}\sum_{j=1}^{I} w_{sj}\Delta\lambda_{sj,hi}\right)$$

$$+ \left(\sum_{s=1}^{H}\sum_{j=1}^{I} \Delta r_{sj}\gamma_{sj,hi} + \sum_{s=1}^{H}\sum_{j=1}^{I} \Delta w_{sj}\lambda_{sj,hi}\right)$$

(A-10)

Substitute (A-9) into (A-10), we have

$$\Delta p_{hi} = -p_{hi}\frac{\Delta\pi_{hi}^{G}}{\pi_{hi}^{G}} + \left(\sum_{s=1}^{H}\sum_{j=1}^{I} \Delta r_{sj}\gamma_{sj,hi} + \sum_{s=1}^{H}\sum_{j=1}^{I} \Delta w_{sj}\lambda_{sj,hi}\right)$$

$$\Rightarrow \frac{\Delta p_{hi}}{p_{hi}} = -\frac{\Delta\pi_{hi}^{G}}{\pi_{hi}^{G}} + \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{r_{sj}\gamma_{sj,hi}}{p_{hi}}\frac{\Delta r_{sj}}{r_{sj}} + \sum_{s=1}^{H}\sum_{j=1}^{I}\frac{w_{sj}\lambda_{sj,hi}}{p_{hi}}\frac{\Delta w_{sj}}{w_{sj}}$$

(A-11)

In matrix form, the equation (A-11) can be expressed as follows

$$\Rightarrow \frac{\Delta p}{p} = -\frac{\Delta\pi^{G}}{\pi^{G}} + \frac{\Delta r}{r}\hat{r}\boldsymbol{\gamma}\hat{p}^{-1} + \frac{\Delta w}{w}\widehat{w}\boldsymbol{\lambda}\hat{p}^{-1}$$

$$= -\frac{\Delta\pi^{G}}{\pi^{G}} + \frac{\Delta r}{r}\hat{r}\hat{\kappa}\boldsymbol{B}\hat{p}^{-1} + \frac{\Delta w}{w}\widehat{w}\hat{\ell}\boldsymbol{B}\hat{p}^{-1}$$

$$= -\frac{\Delta\pi^G}{\pi^G} + \left(\frac{\Delta r}{r}\hat{r}\hat{\kappa} + \frac{\Delta w}{w}\widehat{w}\widehat{\ell}\right)\boldsymbol{B}\hat{p}^{-1} \tag{A-12}$$

Equation (A-11) also suggests that the price of output in the final stage of production can be expressed as a function of primary factor prices and TFP, which is the dual of GVC production function (A-8).

$$p_{hi} = \frac{\prod_{sj}(r_{sj})^{\alpha_{sj,hi}}(w_{sj})^{\beta_{sj,hi}}}{\pi_{hi}^G} \tag{A-13}$$