Winners and losers in global supply chain trade: embedding GSC in CGE

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Who are the winners and losers from Global Supply Chain trade?
Embedding GSC in CGE

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Abstract

A major question in contemporary economic discussions is who wins and who loses from global supply chain (GSC) trade. In trying to answer this question policy makers are not well served by existing economic models. GSC models lack adequate representation of labour markets and other aspects of the economy outside the GSC sector. Global computable general equilibrium (CGE) models have an economy-wide perspective but lack essential GSC features. We integrate GSC with CGE. Results from the integrated model can differ sharply from standalone results. A stylized application of the integrated model shows that GSC trade can accelerate the transfer of labour in developing countries out of low-marginal-productivity agriculture into higher-marginal-productivity manufacturing. At the same time, GSC trade can leave high-income countries with a difficult structural-adjustment problem and little if any long-run gain.

JEL:* *F12; C68; C63

Key words:* *Global supply chain trade; computable general equilibrium; GSC-CGE integration; benefits/costs of GSCs; surplus labour

1. Introduction

Global supply chain (GSC) trade has developed over the last 30 years. It is trade resulting from decisions by firms producing final goods (such as Apple iPhones) to allocate underlying tasks (such as design, component production and assembly) to dedicated facilities in different countries. These decisions create cross-border flows of products at various stages of completion (e.g. iPhone components produced in Thailand and Vietnam sent to China for assembly). GSCs now account for more than half the world's trade in manufactured products (Athukorala and Talgaswatta, 2016).

As set out by Athukorala *et al.* (2018), the essential characteristics of global markets in which GSC trade predominates are:

(i) fragmentation of production processes;
(ii) economies of scale within each process;
(iii) intermediate inputs that are tradable across national borders multiple times embodied in products at different stages of completion; and
(iv) decision-making by economic actors with a global rather than national perspective (multi-national corporations).

Although computable general equilibrium (CGE) modelling is the most popular tool for analysing the effects of trade policy, CGE models do not include these characteristics. This paper demonstrates how GSC can be integrated into a CGE framework.

A stylized application of our method suggests that developing countries are winners from GSC trade and high-income countries may be losers. In our integrated GSC-CGE model we find that by providing low-skilled jobs in developing countries, GSC trade can accelerate the transfer of labour out of low-marginal-productivity agriculture into higher-marginal-productivity manufacturing. At the same time, GSC trade can leave high-income countries having to transfer considerable fractions of their workforce out of manufacturing and into services. After potentially expensive structural adjustment, high-income countries may be left in the long run with no more than a small welfare gain or even a loss.

The paper is organized as follows.

Section 2 is a selective review of the GSC literature. We focus on a theoretical paper by Antràs and de Gortari (2020). This paper is important for our work for two reasons. First, we draw from their mathematical specification of GSC trade. Second, their paper sets the agenda in theoretical studies of GSC trade. This agenda can be contrasted with the more policy-oriented focus of CGE modelling.

Section 3 describes a 1-sector GSC model and a multi-sector multi-country CGE model, and shows how the two models can be integrated. Section 3 is non-technical and intuitive. Technical specifications are in the appendix.

Section 4 is the main part of the paper. It provides a numerical example of GSC-CGE integration. We compute standalone CGE results and standalone GSC results. Then we compute integrated GSC-CGE results. Integration has profound effects on results from both models. We show that the introduction of GSC trade to the CGE model can produce a situation in which there is a hole in the CGE demand curve for labour in the developing country. At high wage rates the developing country cannot support participation in GSCs and experiences a low level of productive employment. At a critical lower-wage-rate point, participation in GSCs becomes viable and productive employment jumps to a higher level. This jump is an ingredient in our argument that developing countries are GSC winners.

Concluding remarks are in section 5.

2. Economic studies of GSC trade

Economists have responded to the challenge of understanding GSC trade with studies that can be classified loosely as descriptive, input-output and theoretical/econometric. Many papers have elements from more than one of these categories. This paper is firmly in the third category, mainly theoretical but with illustrative numbers and policy implications. In subsections 2.1 to 2.3 we briefly review papers from the three categories to give a balanced view of the state of GSC research. In subsection 2.4 we describe how CGE modellers have tackled GSC trade. This motivates the rest of the paper.

2.1. Descriptive GSC studies

An early prominent contribution to the descriptive literature was Stan Shih's (1996) "smiling curve". Shih produced a smile by drawing a curve that relates aspects of value added such as wage rates and profitability to stage in the supply chain. The smile comes about because high value added occurs at early stages (design and planning) and at late stages (advertising and sales), while the middle stages (manufacturing and assembly) consist of a large number of separate processes all with low value added characteristics. Firms that undertake activities at the two ends of the supply chain are mainly in developed countries while the middle-chain activities are mainly in developing countries. Consistent with the smiling curve, Shen and Zheng (2020) show that participation in GSC trade can bias technological progress in developing countries towards low-skilled industries, reducing opportunities to make full use of available skilled labour. The smiling curve may explain why some developing countries are pursuing plans that emphasize early-stage activities, especially research, see for example Fang and Walsh's (2018) description of China's MIC2025 plan. Follow-up studies using the smiling curve include Hallward-Driemeier & Nayyar (2017), Chen (2004) and Shin *et al.* (2012).

The case-study approach is also prominent in descriptive GSC literature. Examples of such studies are Grapper's (2007) description of production sharing arrangements for Boeing's 787 Dreamliner, Dedrik *et al.*'s (2010) study of profit sharing in global production of iPod and notebook PCs, and the studies of the global semiconductor industry by Grunwald & Flamm (1985) and Brown & Linden (2005).

Another strand of the descriptive literature on GSC trade provides statistics on its prevalence, see for example Athukorala (2011), Yeats (2001) and Athukorala & Talgaswatta (2016).

2.2. Input-output GSC studies

GSCs create situations in which value added generated in one country makes multiple border crossings, including returning to the country from which it originated (e.g. Vietnamese labour embodied in Apple iPhone components exported to China and then returned to Vietnam embodied in assembled iPhones purchased by Vietnamese households). Input-output models can be used to estimate the value-added contributions from different countries embedded in each trade flow. Politically significant recalculations of bilateral trade balances can then be made in value-added terms. GSC input-output studies include Amador and Cabral (2017), Dean *et al.* (2011), Koopman, *et al.* (2014), Mattoo *et al.* (2013), Johnson and Noguera (2012), Productivity Commission (2015) and Fan and Liu (2021).

2.3. Theoretical/econometric GSC studies

Theorists and econometricians have studied inter-country differences in participation in GSC trade and the nature of the tasks in GSCs that are allocated to countries at different stages of development. These studies often adopt a gravity framework, see for example, Athukorala (2009) and Athukorala & Yamashita (2006 & 2009). Hanson *et al.* (2005), Golub *et al.*

(2007), Baldwin & Taglioni (2011) and Okubo *et al.* (2014) show how econometric equations can be formulated to explain trade in the presence of GSCs. Other authors have investigated, theoretically and econometrically, factors underlying the growth of GSC trade such as changes in the relative costs of *inter*-firm transactions versus *intra*-firm coordination [see, for example, Antràs & Chor (2013), Grossman & Rossi-Hansberg (2008 & 2013) and Fally & Hillberry (2018)]. Yi (2003) quantifies the role of GSC trade in the overall growth in trade. Lu *et al.* (2018) describe econometrically the factors that determine differences between firms in their participation in GSCs.

The most relevant paper for our study is Antràs & de Gortari (2020, hereafter A&deG). [1] They develop an algebraic model and illustrate its properties via numerical simulations. In their model there is one final good produced in N stages. The final good is consumed in J countries, with the level of consumption in each country set exogenously. The stage-1 good can be produced in any country under constant returns to scale using only labour supplied by residents of that country. The stage-n good, n>1, can be produced in any country using a Cobb-Douglas constant-returns-to-scale combination of the country's own labour and an intermediate input consisting of the stage-(n-1) good supplied by any of the J countries. A&deG assume that markets are purely competitive at each production stage. Thus, prices equal costs. Accordingly, the purchaser's price of a stage-n good supplied to country j from country k is a combination of: the stage-n unit labour cost in k; the purchaser's price in k of the (n-1) good; and the trade cost applying to a k-to-j flow of the stage-n good. A&deG assume that demanders of the stage-n good in country j always buy at what to them is the lowest price. Using this assumption, they design an algorithm to solve the model for the prices and production volumes of goods at each stage in each country, and the shipments between countries.

A&deG examined a large number of solutions of their model in a stylized 4-country, 4-stage setup with values of unit-labour costs and other key parameters drawn from probability distributions. They used these solutions to build up pictures of how the global supply chain satisfying the demand for the final good in any country depends on trade costs.

A conclusion from A&deG's model is that their specification of GSC trade is likely to lead to models that produce welfare results that are similar to those from models without GSC trade. By contrast, the model we develop in this paper (see subsection 4.7) suggests that recognition of GSC trade can have profound effects on welfare results.

While A&deG and other GSC modellers provide impressive treatments of GSC sectors, their specifications of other aspects of the economy are rudimentary. For example, in the A&deG model there is no investment or capital accumulation, no governments or taxes except those embedded in trade costs, no non-traded services, no land or other natural resources, no balance of payments accounting or treatment of foreign assets and liabilities, and no occupational or regional barriers to labour mobility between different employment activities. All of these phenomena have been included in CGE models.

2.4. Next step: embedding GSC in CGE

CGE modellers have captured elements of GSC trade by introducing additional detail on import flows. Walmsley and Minor (2017 & 2020) and OECD (2020a&b) add a user dimension to the flow of imports of commodity c from region r to region d. This is an improvement on the standard CGE practice adopted in GTAP (Corong *et al.*, 2017) in which the source composition of imported commodity c to region d is identical for all users in d.

[1] Here we give an overview of the A&deG model. A more detailed review of A&deG with explanations of technical aspects and a comparison with Fally and Hillberry (2018) is in Dixon and Rimmer (2019).

With users in d distinguished, global CGE models can recognize that U.S. imports of Motor vehicles from Canada are used mainly as inputs to the U.S. Motor vehicle industry whereas U.S. imports of Motor vehicles from Europe are purchased mainly by households as finished goods. With this feature, the CGE model shows that a Motor vehicle tariff against Canada would disrupt the supply chain to the U.S. Motor vehicle industry whereas a Motor vehicle tariff against Europe would protect the U.S. Motor vehicle industry. Dixon *et al.* (2020) take a more direct approach. They disaggregate Motor vehicle output in each region and inter-regional trade flows into 9 sub-commodities, thereby sharply identifying the trade flows that form part of the global supply chain.

However, none of the CGE modellers to date have captured what we consider the essence of GSC trade: fragmentation of production processes; economies of scale within processes; intermediate inputs that cross national borders multiple times; and decision-making by economic global actors. What is needed is an integrated GSC-CGE model.

An integrated GSC-CGE model would provide simulations of adjustment paths recognizing investment-capital links and connections between current account balances and the accumulation of financial assets and liabilities. In view of contemporary political discussions of GSC trade, perhaps the most important potential contribution of an integrated GSC-CGE model would be to throw light on the effects of GSC trade taking account of labour markets that work differently in different parts of the world. How does GSC trade affect the occupational and regional composition of employment in each country? How does GSC trade affect wage rates by occupation and by educational level? Within each country, does GSC trade lead to reductions or increases in inequality? Do free trade agreements help or hinder GSC trade? What are the implications of anti-trade policies by the U.S. for participation by China and other developing countries in global production sharing? In broad terms, what factors determine the international allocation of welfare benefits and adjustment costs from GSC trade?

In this paper we can't answer all these questions. But we make a start by setting out a methodology for integrating GSC and CGE, and applying it in a stylized setting.

3. Integrating a GSC model and a global CGE model: general approach

Subsection 3.1 describes a standard global multi-region CGE model, focusing on the form of the database.[2] Subsection 3.2 describes a GSC model. Then subsection 3.3 describes in general terms how the two models can be integrated.

3.1. Global CGE models

Global CGE models are built around input-output databases. Table 3.1 is illustrative for a simple N-region global CGE model in which labour is the only primary factor input and tariffs on intermediate flows are the only wedges between factory door prices and purchasers' prices.

In Table 3.1, V(r,d) is a C by C matrix where C is the number of commodities or industries. The h,k component of V(r,d) is the pre-tariff value of commodity h produced in region r used in industry k in region d. VTI(r,d) is the C by C matrix of tariff collections associated with V(r,d). FD(r,d) is a C by 1 vector in which the h component is the value of commodity h from country r used in final demand in country d. For simplicity we assume no tariffs on final goods. LAB(r) is a 1 by C vector in which the k component is the value of labour input to industry k in region r. Z(r) is the C by 1 vector of sales values of commodities produced in

[2] The best known and most widely used global CGE model is GTAP, originally documented in Hertel (1997) and regularly updated, see for example Corong *et al.* (2017)

Table 3.1. Input-output database for a simple global CGE model

V(1,1)		…	V(1,N)	FD(1,1)	…	FD(1,N)	Z(1)
V(2,1)		…	…	…	…	…	…
…							
V(N,1)		…	V(N,N)	FD(N,1)	…	FD(N,N)	Z(N)
0		…	VTI(1,N)				
VTI(2,1)	0						
…		…0	…				
VTI(N,1)		…	0				
LAB(1)		…	LAB(N)				
Z′(1)			Z′(N)				

region r, calculated by adding across V(r,1), …, FD(r,N).. Its transpose, Z′(r) , is the 1 by C vector of total costs incurred by industries in region r. A fundamental balance condition in CGE models is that the value of sales of each commodity produced in each region is equal to costs in the producing industry. In Table 3.1, these costs are the value of labour plus intermediate goods including tariffs on intermediates.

One interpretation of a CGE model is that it is a system of equations which drive the components of an input-output database. The variables in the CGE model that combine to determine the value of each input-output flow are factory prices and quantities. Factory prices are determined by technology (input requirements per unit of output) and by wages. Technology is usually treated as exogenous. Wages depend on demand and supply for labour. Demand for labour depends on wages and productivity while supply is either exogenous or modelled via demographic variables. Quantities in the input-output table are determined in cost-minimizing and utility-maximizing problems in which industries and households take account of purchasers' prices. Purchasers' prices reflect factory prices (costs) and tariffs. In this stylized example, we leave out sales taxes and transport costs. Total final demand in each region depends on incomes, which depend on wages.

In a CGE model, the effects of changes in tariffs, technologies and other exogenous variables are computed by comparing solutions of the model's equation system generated with different settings of these variables.

3.2. GSC models

A GSC model is a mathematical system describing world-wide output and trade for a particular sector. We have in mind sectors such as Motor vehicles, Electronic equipment and Textiles. However, in what follows we avoid unintended specificity by referring only to a hypothetical GSC sector that produces Widgets.

An essential characteristic of a GSC model is optimizing behaviour by one or more agents who take a global perspective in deciding which activities within the sector to locate in different countries and which sectoral products to trade between countries. In solving their optimizing problems, global agents treat wage rates, consumer incomes and other economy-wide variables as exogenous (beyond their control). In the simple GSC model described in section 4 and set out mathematically in the appendix, there is a single global agent whose objective is to minimize the cost of satisfying world-wide consumer demands for Widgets. These costs include production costs of Widget sub-commodities in each region and tariffs on Widget trade. The global Widget agent is constrained by production technologies in each region. In our simple model, these technologies are specified along the lines of A&deG. However, unlike A&deG we introduce economies of scale in the production of Widget sub-commodities and assume Leontief rather than Cobb-Douglas in substitution between labour and intermediate inputs.

In a GSC model, the effects of changes in tariffs, technologies and other exogenous variables are computed by comparing solutions of the global agent's constrained optimization problem generated with different settings of these variables.

3.3. Integrating a GSC model and a global CGE model

In a global CGE model we assume that the GSC sector, Widgets, is represented as a single commodity and industry in each region. The Widget row of the input-output data for region r shows Widget sales to the Widget industry and other parts of region r's economy as well as Widget sales to export. The Widget column for region r shows inputs to Widget production in region r and associated tariffs.

What we cannot see in the input-output data is the underlying nature of the Widget flows. In the input-output data, Widget exports from region r and intermediate inputs to region r's Widget industry are aggregations of Widget sub-commodities (includes services) such as Design, Components, etc. Region r's domestic Widget sales outside the Widget sector are likely to consist predominantly of the final Widget good. But these features are not revealed by the input-output data: we simply see undifferentiated flows of Widgets.

In essence, our approach to integrating GSC and CGE models is to drive undifferentiated Widget flows and other inputs to the Widget industry in each region in the CGE model in a way that takes account of the underlying changes in activities in the GSC model. At the same time, we must drive economy-wide variables in the GSC model to be consistent with the CGE model.

If, as in the A&deG model, Widget production at each stage requires only labour and Widget inputs from earlier stages, then the variables in the CGE model that need to be set exogenously in each region to reflect outcomes from the GSC model are:

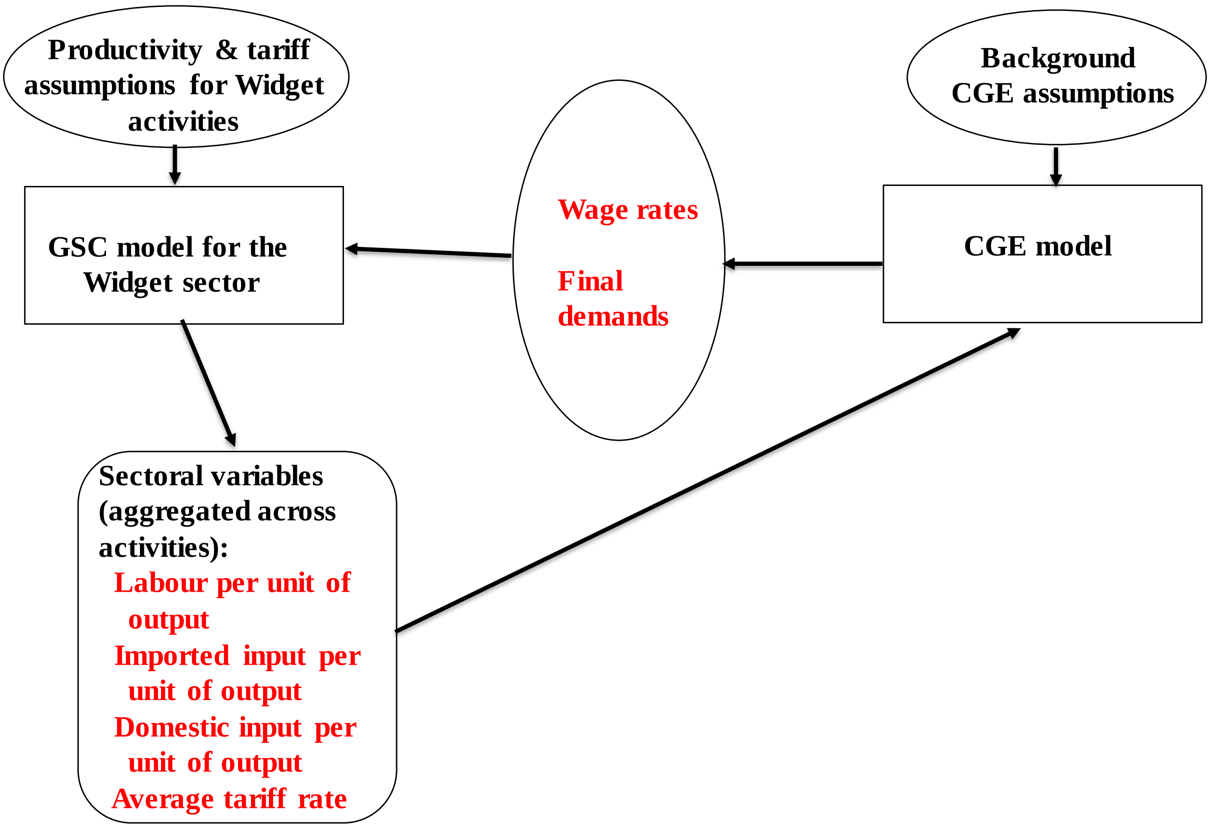
(a) demands for domestic and imported inputs per unit of output in the Widget sector;
(b) demands for labour per unit of output in the Widget sector; and
(c) average tariff rates in each region on imports of Widget commodities taking account of the composition of these imports and the tariff rates on each of the Widget sub-commodities.

Variables in the GSC model that need to be set exogenously in each region to reflect outcomes from the CGE model are:

(d) wage rates; and
(e) Widget demand by final users.

Figure 3.1 illustrates an algorithm for implementing integration of a GSC model for Widgets and a CGE model. The GSC model receives shocks describing changes in productivity and tariff variables applying to production and trade in the Widget sector's activities in each region. Then on the basis of assumed values for wage rates and final demands for Widgets, the GSC model produces results for Widget activities. From these, movements for each region in inputs per unit of output and average tariff rates at the aggregated sectoral level for Widgets can be calculated. As shown in the figure, these can be passed to the CGE model.

Figure 3.1. An algorithm for integrating GSC and CGE models



The CGE model can also receive shocks to the myriad of technology, tariff and other exogenous CGE variables outside the Widget sector (shown in Figure 3.1 as background CGE assumptions). The CGE model then produces results for wage rates and final demands for Widgets in each region. Starting with a CGE solution incorporating initial guesses for Widget sectoral variables or with a GSC solution incorporating initial guesses for wage rates and final demands for Widgets, we can follow the arrows around Figure 3.1 looking for a converged solution. A converged solution occurs when wage rates and final demands being passed to the GSC model are unchanged between successive iterations or equivalently when the Widget sectoral variables being passed to the CGE model are unchanged between successive iterations.

By computing converged solutions we hope to reveal (1) the economy-wide (CGE) effects of shocks to productivity and tariffs applying to GSC activities, and (2) the intra-widget (GSC) effects of shocks to exogenous CGE variables such as changes in productivity in sectors apart from Widgets.

But will the algorithm in Figure 3.1 produce converged solutions? And if it does, will these solutions reveal insights that go beyond those from CGE models without explicit recognition of GSC behaviour? We answer these questions in section 4 through a numerical example.

4. Numerical example: a GSC sector in a CGE model

We develop our numerical example in seven parts. Subsection 4.1 specifies a simple numerical GSC model for the world Widget sector. Subsection 4.2 shows what this Widget sector would look like with its underlying sub-commodity detail suppressed in a CGE database. Subsection 4.3 uses the CGE database from subsection 4.2 in a CGE simulation with the Widget sector treated as any other sector, that is without recognition of underlying GSC activities. Subsection 4.4 sets out results from a stand-alone simulation with the GSC Widget model from subsection 4.1. In this standalone simulation, final demands for Widgets and economy-wide wage rates are set exogenously: there is no input from the CGE model. Shocks are applied to technological variables and tariffs for each Widget activity in each region. Aggregated across Widget activities these shocks are the same as those adopted for the Widget sector in the CGE simulation in subsection 4.3. Subsection 4.5 describes an initial attempt to rework the CGE simulation from subsection 4.3 with GSC results from subsection 4.4 introduced via the algorithm illustrated in Figure 3.1. This attempt failed, but for instructive reasons. After modifying the CGE model, we obtain a converged CGE-GSC solution in subsection 4.6. Subsection 4.7 compares this converged solution with the standard CGE solution in subsection 4.3.

4.1. The GSC model and its solution for 1990[3]

We assume that there are two regions, R1 and R2, which we think of as the U.S. and Asia, and two industries, Ind1 and Ind2. Ind1 is a potential GSC industry producing Widgets while Ind2 is the rest of the economy consisting mainly of services but also including tradable goods such as agriculture and mining.

Within the Widget industry, there are four activities: Design; Components; Assembly; and SalesDist. Similar to A&deG, we assume that the four activities are undertaken in a one-directional sequence. Data for these four activities are given in Table 4.1, part A. For concreteness, we think of these data as referring to 1990.

Panel (a) in Table 4.1A shows that: production of Design requires no intermediate inputs; production of a unit of Components requires 1 unit of Design; production of a unit of Assembly requires 1 unit of Components; and production of a unit of SalesDist requires 1 unit of Assembly. Panel (b) gives the values for labour productivity (denoted by PROD) in each Widget activity at standard scale. As explained in the appendix, we introduce economies of scale by assuming that labour productivity in activity j in region r is 5 per cent greater than PROD if r undertakes all of the output of j required for both regions. Panel (c) gives the powers of the tariffs (T) and panel (e) gives wage rates (W). SalesDist is the non-traded final Widget commodity. Quantities of this commodity (Y) used in each region are given in panel (d).

Panel (f) in Table 4.1A shows wage rates divided by PROD, that is labour costs per unit of output at standard scale for each Widget activity in the two regions. Even though wage rates are much lower in R2 than in R1, wage costs per unit of output in all traded Widget activities are higher in R2 than in R1. This reflects the very low productivity levels assumed for R2 in panel (b) relative to those for R1.

Part B of Table 4.1 shows the GSC Widget solution. As set out in subsection A.1 of the appendix, the GSC model was solved as a constrained optimization problem. We chose output levels for each Widget sub-commodity in each region and sub-commodity trade flows between regions to minimize aggregate world-wide Widget costs (including tariff payments) subject to satisfying exogenous final demands for Widgets [demands for SalesDist, Y(R1) = 1 and Y(R2) = 0.5]. In this cost minimizing problem, technology variables, tariffs and wage rates were set at the levels indicated in Table 4.1A.

[3] The GCS Widget model that we describe here is the same as that in Athukorala *et al.* (2018), but we take the analysis and application of it in a different direction. Whereas the earlier paper focused on the properties of the GSC model, this paper is about integrating the GSC model with a CGE model.

Table 4.1. World Widget sector in 1990

A. Technology assumptions and data for 1990

	Design	Components	Assembly	SalesDist
(a) Intermediate inputs for producing 1 unit of output of each activity in both regions				
Design	0	1	0	0
Components	0	0	1	0
Assembly	0	0	0	1
SalesDist	0	0	0	0
(b) Output per unit of labour input, standard scale (Productivity, PROD)				
R1(US)	1	1	1	1
R2 (Asia)	0.0833	0.1667	0.125	0.25
(c) Powers of tariffs (T) on imports by importing region				
R1 (US)	1.1	1.2	1.2	1
R2 (Asia)	1.1	1.2	1.2	1
(d) Demand for final product:				
R1 (US)				Y(R1) = 1
R2 (Asia)				Y(R2) = 0.5
	(e) Wage rate (W)			
	R1 (US)	1.0		
	R2 (Asia)	0.25		
(f) Labour costs per unit of output at standard scale, that is W/PROD				
R1 (US)	1	1	1	1
R2 (Asia)	3	1.5	2	1

B. Output, employment, trade and prices in 1990: solution from GSC model

	Price[#]	Output	Employment	Exports, qty	Exports, value
R1					
Design	0.950	1.5	1.425	0.0	0.0
Components	1.900	1.5	1.425	0.0	0.0
Assembly	2.850	1.5	1.425	0.5	1.425
SalesDist	3.850	1.0	1.000	0.0	0.0
Total			5.275		1.425
			VA=5.275		
R2					
Design	3.000	0.0	0.0	0.0	0.0
Components	2.545	0.0	0.0	0.0	0.0
Assembly	4.280	0.0	0.0	0.0	0.0
SalesDist	4.420	0.5	2.0	0.0	0.0
Total			2.0		0.0
			VA=0.5		

[#] Except for a minor role in determining tariff costs, Widget prices don't enter the cost optimization problem. They are computed post-optimization in accordance with revealed production costs. The price of Design in R1 is the unit labour cost in R1 for Design including the 5 per cent scale adjustment allowed for producing the entire global output. The price of Components in R1 (1.900) is the price of Design (0.950) *plus* the unit labour cost for Components including the 5 per cent scale adjustment (0.950). Details are in the appendix.

In view of the high labour costs per unit of output applying to Design, Components and Assembly in R2, it is not surprising that R1 is dominant in world production of these three traded Widget commodities. The only non-zero Widget activity in R2 is production of the non-traded commodity (service), SalesDist. Despite a tariff of 20 per cent, R2 satisfies all of its requirement for Assembly by importing from R1. Imported Assembly goes to R2's

SalesDist activity. Because R2 does not produce either Components or Assembly, it does not import either Design or Components.

4.2. The Widget industry in a CGE database for 1990

The shaded parts of Table 4.2A depict the Widget industry of Tables 4.1A&B in a world input-output database of the form used in CGE modelling. In this database, the Widgets industry (Ind1) is represented as producing a single composite commodity (C1). The underlying details of Design, Components, Assembly and SalesDist are suppressed.

Exports of Widgets (C1) from R1 to R2 are shown in Table 4.2A with a cif value of 1.425. This consists of 0.5 units of Assembly priced at 2.850 per unit (see Table 4.1B) purchased as an intermediate input by Ind1 in R2.

The flow of C1 to Ind1 in R1 in Table 4.2A is 7.125. This is the value of output of Design, Components and Assembly produced in R1 less exports of Assembly, that is: 0.95*1.5 + 1.9*1.5 + 2.85*1.5 – 1.425 = 7.125 (see Table 4.1B).

The only tax collection on Widgets is the tariff on R2's imports of Widgets. These imports consist of Assembly with a tariff rate of 20 per cent (Table 4.1A). With the cif value of imports being 1.425, the tariff collection is, as shown in Table 4.2A, 0.285 (=0.2*1.425).

The values in Table 4.2A of labour input to Ind1 in the two regions (5.275 and 0.5) are simply the value added (VA) numbers in Table 4.1B. These numbers are the wage rates in the two regions (1.0 and 0.25, Table 4.1A) multiplied by the Widget employment levels (5.275 and 2.0, Table 4.1B).

The value of Widget consumption shown in Table 4.2A for each region is the value of output *plus* imports *less* exports *less* intermediate use. For R1 this gives consumption of Widgets at 3.85 (= 12.4 +0 – 1.425 – 7.125). For R2, consumption of Widgets is 2.21 (= 2.21 +1.425 – 0 – 1.425). These consumption values can be checked from Table 4.1. They are the consumption (or output) quantities of SalesDist (1 and 0.5, Table 4.1A) *times* the prices of SalesDist (3.850 and 4.420, Table 4.1B).

For simplicity we assume that Ind2 in each region uses only labour as an input and sells only to final demand. We also assume there are no tariffs on trade in Ind2's product (C2). In both regions, Ind2 is much larger than Ind1. As shown in Table 4.2A, Ind2 accounts for 83.33 per cent of employment in R1 [=100*26.375/(5.265+26.375)] and 95.24 per cent in R2 [=100*10/(0.5+10)].

We assume that trade in 1990 is balanced. Reflecting its specialization in Widgets, R1 has a Widget trade surplus of 1.425 while R2 has a surplus of 1.425 in C2 trade (= 4.275 – 2.85)

Before it can be used in a CGE model, the database in Table 4.2A needs to be slightly modified. The problem is zero flows. In CGE modelling it is difficult to project non-zero flows from a zero starting point. In Table 4.2A there are zero flows of C1 from R2 to Ind1 in both countries. In subsection 4.5 and 4.6 we project to situations in which these flows are non-zero. To make this possible, we adjust the database in Table 4.2A by adding tiny amounts (0.01) to the flows of C1 from R2 to Ind1 in R1 and to Ind1 in R2. We then rebalance the table, by reducing labour input to Ind1 in R1 by 0.01 and reducing consumption of C1 in R2 by 0.01, to arrive at Table 4.2B. In rebalancing, we preserve the original trade balances, zero for each region.

Table 4.2A. World input-output table for 1990 ($)

		R1	R1	R2	R2	R1	R2	Totals
		Ind1	Ind2	Ind1	Ind2	Consumption		
R1	C1	7.125		1.425		3.85		12.400
R1	C2					23.525	2.85	26.375
R2	C1						2.210	2.210
R2	C2					4.275	5.725	10.000
Tax R1	C1			0.285				
Tax R1	C2							
Tax R2	C1							
Tax R2	C2							
Labour		5.275	26.375	0.5	10			
Totals		12.400	26.375	2.210	10.000	31.650	10.785	

The numbers in the shaded rows and columns are for flows of commodity 1 (C1) and inputs to industry 1 (Ind1) that produces C1. These numbers are obtained from the Widget data in Table 4.1. The numbers for C2 and Ind2 were set so that the Widget industry (manufacturing) contributes about 17 per cent of GDP in region 1 (R1) and 5 per cent of GDP in region 2 (R2).

Table 4.2B. World input-output table for 1990 ($) modified for use in CGE model

		R1	R1	R2	R2	R1	R2	Totals
		Ind1	Ind2	Ind1	Ind2	Consumption		
R1	C1	7.125		1.425		3.85		12.400
R1	C2					23.525	2.85	26.375
R2	C1	0.01		0.01			2.200	2.220
R2	C2					4.265	5.735	10.000
Tax R1	C1			0.285				
Tax R1	C2							
Tax R2	C1							
Tax R2	C2							
Labour		5.265	26.375	0.5	10			
Totals		12.400	26.375	2.220	10.000	31.640	10.785	

4.3. Applying a standard CGE model: producing a baseline forecast for 1990 to 2000

Imagine that we are standing in 1990 trying to project forward to 2000. We have the input-output database set out in Table 4.2B and decide to build a standard CGE model calibrated to this database. In the model, we assume that: production functions for the two industries in each of the two regions are Leontief in intermediate inputs of C1 and C2 and the single primary factor labour; household preferences are Cobb-Douglas between C1 and C2; and Armington elasticities set at 3.8 (a typical value in widely used CGE models such as GTAP, Corong *et al.*, 2017) determine substitution by industries and households between imported and domestic varieties of the same commodity. In modelling each intermediate and labour input, we allow for technical change by introducing an exogenous variable that affects the use of the input per unit of output.

Shocks

In applying this CGE model to the task of projecting from 1990 to 2000, we introduce three ideas. First, R2 (Asia) is rapidly catching up to R1 (U.S.) in terms of productivity and wages. Second, productivity growth is rapid in Ind1 (think manufacturing) relative to Ind2 (dominated by services). Third, tariffs are being dismantled. Looking at these ideas through CGE eyes, we project from 1990 to 2000 by applying the following shocks:

(1) labour-saving technical progress in Ind1, R1 = 15%
(2) labour-saving technical progress in Ind2, R1 = 0%
(3) labour-saving technical progress in Ind1, R2 = 27.75%
(4) labour-saving technical progress in Ind2, R2 = 15%
(5) reduction in the power of the tariff on R2's imports of C1 = 12.5%

Shocks (1) and (2) give R1 a background rate of labour-saving technical change of 0% with 15% extra for Ind1. Shocks (3) and (4) give R2 a background rate of labour-saving technical change of 15% with 15% extra for Ind1. The 15% extra means that instead of falling from 1 to 0.85, the index of labour requirements per unit of output in R2's Widget industry falls from 1 to 0.7225 (= 0.85*0.85). Shock (5) introduces a reduction in the rate of the tariff imposed by R2 on imports of C1 from 20% to 5% [-12.5= 100*(1.05/1.20 - 1)].

We assume no change in both regions in employment measured in people. In generating standard CGE forecasts, we also assume no growth in aggregate labour input (row 22, Table 4.3), implying that labour input is adequately measured by number of people employed. In subsections 4.6 and 4.7, describing results from the integrated GSC-CGE model, we allow for changes in labour input (with no change in the number of people employed) associated with movement of surplus but employed labour from Ind2 to Ind1 in R2.

We could add other shocks to (1) - (5). For example, we could include shocks to the number of people employed in each region to account for demographic developments and to the trade balance to account for capital flows. These variables are exogenous in our projections. However, including shocks to employment and the trade balance is unnecessary for our current illustrative purposes.

Results

Table 4.3 shows the projections for R1 and R2 derived by applying shocks (1) to (5) in our stylized CGE model. With no capital in this simple model and with no growth in labour input, the projected increases in real GDP (row 1) can be explained purely from our technology assumptions and items in the input-output data in Table 4.2B. R1 is projected to have labour-saving technical progress of 15 per cent [shock (1)] in 16.6 per cent of its economy (Ind1's share of R1's labour input) giving it a GDP increase of about 2.6 per cent, close to the number shown in Table 4.3 (2.72, row 1, col 1). R2 is projected to have labour-saving technical progress of 27.75 per cent [shock (3)] in about 4.8 per cent (Ind1) of its economy and 15 per cent [shock (4)] in the other 95.2 per cent (Ind2). For a given level of output this technical progress frees up about 15.6 per cent of the labour force. Re-employing this labour enables R2 to increase its GDP by about 18.5 per cent [= 100*0.156/(1-0.156)], which is close to the result in Table 4.3 (18.76, row 1, col 2).

Rapid technical progress in R2 relative to R1 gives workers in R2 a wage increase of 13.82 per cent relative to workers in R1 (row 3 in Table 4.3).[4] In real terms the wage increase in R2 is nearly 20 percentage points greater than that in R1 (row 4). The wage differential is accentuated in real terms by the improvement in R2's terms of trade (discussed below) and by the cut in its tariffs on its imports of C1 [shock (5)].[5]

[4] The wage rate in R1 is the numeraire. Consequently, it is shown in Table 4.3 with zero change.
[5] A cut in tariffs, as with a cut in any indirect tax, allows a given level of employment to be maintained with a higher pre-tax real wage rate. In post-tax terms workers may not be better off if lost tariff revenue is replaced by an income tax.

Table 4.3. Projection from 1990 to 2000 using a standard CGE model

		R1	R2
1	Real GDP (% change from 1990 to 2000)	2.72	18.76
2	Real consumption, welfare (% change)	2.41	19.76
3	Wage rate	0.00	13.82
4	Real wage rate, CPI delated (% change)	2.41	22.19
5	Factory price of C1 (% change)	-15.01	-23.85
6	Factory price of C2 (% change)	0.00	-3.25
7	Purchasers' price to consumers of C1 (% change)	-15.01	-23.85
8	Purchasers' price to consumers of C2 (% change)	-0.53	-2.22
9	Consumption of C1, quantity (% change)	9.77	32.46
10	Consumption of C2, quantity (% change)	1.47	16.89
11	Value of exports (% change)	9.11	9.11
12	Value of imports (% change)	9.11	9.11
13	Quantity of exports (% change)	15.28	12.84
14	Quantity of imports (% change)	12.84	15.28
15	Terms of trade (% change)	-2.12	2.17
16	Labour input in Ind1	-1.51	-4.49
17	Labour input in Ind2	0.30	0.21
18	Exports C1 (100 times change in value at initial prices as share of initial GDP) #	1.47	0.04
19	Exports C2 (100 times change in value at initial prices as share of initial GDP) #	0.66	5.05
20	Imports C1 (100 times change in value at initial prices as share of initial GDP) #	0.01	4.30
21	Imports C2 (100 times change in value at initial prices as share of initial GDP) #	1.72	1.94
22	Aggregate labour input (no. of employed persons in the standard CGE projection)	0	0

100*(Quantity in final year times price in initial year – Value in initial year)/GDP in initial year

Reflecting the 1990 situation of balanced trade and the assumption of no-change in the trade balance, real consumption (row 2, Table 4.3) in the two regions increases broadly in line with GDP. Small GDP-consumption discrepancies arise from terms-of-trade movements. R2 benefits from a terms-of-trade improvement (row 15) which increases the amount of consumption that it can undertake per unit of output (or GDP). The reverse is true for R1. R2 experiences a terms-of-trade improvement because it is a net exporter of C2 and it imports C1: rapid technical progress in the production of C1 relative to C2 causes prices for C1 to fall relative to those for C2 (rows 5 to 8).

With balanced trade and strong growth in R2 relative to R1, R2's trade falls as a share of GDP [real export growth of 12.84 per cent (row 13) compared with GDP growth of 18.76 per cent]. The explanation is that the export market for R2 (namely R1) is shrinking relative to the size of R2's domestic market. The opposite is true for R1.

Rows 16 to 21 show developments at the industry/commodity level. In both regions, labour input in industry 1 declines relative to that in industry 2 (rows 16 and 17). These declines are brought about by rapid technical progress in Ind1 relative to Ind2. They can be accommodated by small switches between industries in labour input. In R1, labour input in Ind1, which accounts for 16.6 per cent of R1's total labour input in 1990 (Table 4.2B), falls by 1.51 per cent. With no change in aggregate labour input this implies a reallocation between 1990 and 2000 of 0.25 per cent of R1's workforce from Ind1 to Ind2 (= 1.51*0.166). The workforce-switch percentage is even smaller for R2, 0.21 per cent.

Rows 18 to 21 show changes in the commodity composition of each region's trade. In these rows, it is convenient to report changes in volume flows as percentage-point changes in shares of initial GDP. For example, the entry in the R1 column of row 18 means that between 1990 and 2000 R1's exports of C1 valued at 1990 prices increase as a share of initial GDP by 1.47 percentage points, that is, from 4.50 per cent of GDP in the 1990 database in Table 4.2B to 5.97 per cent. In this case, the volume increase is finite and interpretable, 32.6 per cent [=100*(5.97/4.50-1)]. However, as we will see in subsection 4.7, our integrated GSC-CGE model can generate substantial trade flows for 2000 from an arbitrarily small starting point in 1990, making percentage change results uninformative. By reporting percentage-point share changes in GDP, we not only avoid this problem but we also highlight changes in the commodity structure of trade.

The trade projections in Table 4.3 can be described as "business as usual". In 1990, R2 specialized in the export of C2 (4.265 out of total exports of 4.275, see Table 4.2B). This specialization continues in 2000 with the expansion of R2's exports accounted for almost entirely by C2 (5.05 in row 19 compared with 0.04 in row 18). In 1990, R1 exported both commodities (1.425 for C1 and 2.85 for C2, see Table 4.2B). This mixed pattern continues for R1 with substantial increases in exports of both commodities (rows 18 & 19, col 1). Technical progress is 15 per cent faster in each industry in R2 than in R1. Thus, R1's comparative advantage in the production of C1 is preserved. Given the relative weakness of R2 in the production of C1, R2's consumers draw strongly on R1 to satisfy their rapidly growing demand for C1. This explains the growth in R1's exports of C1 (row 18) relative to its exports of C2 (row 19).

The import results in rows 20 and 21 of Table 4.3 follow in a mechanical way from the export results. Consequently, no further explanation is required.

4.4. World Widget industry in 2000: technology and tariff assumptions, and GSC solution

Now imagine that we are specialists on the Widget industry, wishing to project the industry's prospects from 1990 to 2000 using the GSC model described earlier. Our views on exogenous variables for the Widget industry in 2000 are shown in Table 4.4A. Movements in these variables from their 1990 values can be deduced by comparing Table 4.4A with Table 4.1A.

As in 1990, we assume for 2000 that: Design requires no intermediate inputs; one unit of Design is required per unit of Components; one unit of Components is required per unit of Assembly; and one unit of Assembly is required per unit of SalesDist.

Consistent with our CGE simulations, we assume that between 1990 and 2000 there will be labour-saving technical change of 15 per cent in R1's Widget industry, and that this applies to the four Widget activities. In 1990, output per unit of labour in the four activities in R1 at standard scale was one (Table 4.1A). Thus, as shown in panel (b) of Table 4.4A, R1's output per unit of labour at standard scale in the four activities in 2000 is assumed to be 1.1765 [= 1/(1-0.15)].

Table 4.4. World Widget sector in 2000
A. Technology assumptions and data for 2000

	Design	Components	Assembly	SalesDist
(a) Intermediate inputs for producing 1 unit of output of each commodity in both regions				
Design	0	1	0	0
Components	0	0	1	0
Assembly	0	0	0	1
SalesDist	0	0	0	0
(b) Output per unit of labour input, standard scale (Productivity, PROD)				
R1 (US)	1.1765	1.1765	1.1765	1.1765
R2 (Asia)	0.1765	0.3922	0.3069	0.3460
(c) Powers of tariffs (T) on imports by importing region				
R1 (US)	1.05	1.05	1.1	1
R2 (Asia)	1.05	1.05	1.1	1
(d) Demand for final product:				
R1 (US)				Y(R1) = 1
R2 (Asia)				Y(R2) = 0.75
	(e) Wage rate (W)			
	R1 (US)	1.0		
	R2 (Asia)	0.3		
(f) Labour costs per unit of output at standard scale, that is W/PROD				
R1 (US)	0.85	0.85	0.85	0.85
R2 (Asia)	1.70	0.76	0.98	0.87

B. Output, employment, trade and prices in 2000: solution from GSC model

	Price	Output	Employment	Exports, qty	Exports, value
R1					
Design	0.808	1.75	1.413	1.75	1.413
Components	1.657	0.00	0.000	0.00	0.000
Assembly	2.503	1.00	0.850	0.00	0.000
SalesDist	3.353	1.00	0.850	0.00	0.000
Total			3.113		1.413
			VA=3.113		
R2					
Design	1.700	0.00	0.000	0.00	0.000
Components	1.575	1.75	4.239	1.00	1.575
Assembly	2.552	0.75	2.444	0.00	0.000
SalesDist	3.419	0.75	2.168	0.00	0.000
Total			8.851		1.575
			VA=2.655		

As CGE modellers in subsection 4.3 we assumed labour-saving technical progress between 1990 and 2000 in R2's Widget industry of 27.75 per cent, made up of 15 per cent background labour-saving technical progress applying generally in R2 plus an extra 15 per cent in Ind1.

In 1990 the only Widget activity in R2 was SalesDist (Table 4.1B). Now as GSC modellers we assume that the 27.75 per cent labour-saving technical progress applies in R2 to this activity. This is reflected in panels (b) of Tables 4.1A and 4.4A which show an increase in

PROD for SalesDist in R2 from 0.25 in 1990 to 0.3460 in 2000.[6] In each of the other three Widget activities we assume that PROD in R2 more than doubles from its very low levels in 1990. Despite this, as can be seen from Table 4.4A panel (b), R2's productivity levels in traded Widget activities in 2000 remain well below those in R1.

On tariffs, we note the trend towards free trade. As can be seen from panels (c) in Tables 4.4A and 4.1A, we assume that tariffs on Design will fall from 10 per cent in 1990 in both regions to 5 per cent in 2000. For Components we assume a fall from 20 per cent to 5 per cent and for Assembly a fall from 20 per cent to 10 per cent.

In our role as Widget specialists wishing to apply the GSC model, we need to make assumptions about economy-wide wage rates and final demands for Widgets (demands for the product SalesDist). These assumptions must be guided by movements in productivity and income outside the Widget industry. Comparing panels (d) and (e) in Table 4.4A with the corresponding panels in Table 4.1A shows our wage and demand assumptions: 20 per cent wage and 50 per cent demand growth in R2, and zero growth in these variables in R1. This is consistent with rapid catch-up by R2.

Given the assumptions in Table 4.4A, cost minimizing in the GSC model produces the solution shown in Table 4.4B. Comparing this 2000 solution with the 1990 solution (Table 4.1B), we see that production of Components has switched entirely from R1 to R2. Although R2's productivity in Components in 2000 is low relative to that in R1, R2's wage rate remains sufficiently low relative to that in R1 to give R2 a competitive edge in Component production. As can be seen from panel (f) in Table 4.4A, labour cost at standard scale per unit of output in Components in R2 in 2000 is less than that in R1 (0.76 compared with 0.85). For Assembly, R2's labour cost per unit of output remains above that in R1 (0.98 compared with 0.85). Despite this, R2 undertakes Assembly production to satisfy its own needs. R1 continues to produce Assembly but no longer exports. Why shouldn't R1 continue to produce all of the Assembly required by both regions?

Given that Components are entirely produced in R2, splitting Assembly production not only saves trade costs (tariff payments) on Assembly but also on Components. It turns out that the saving of trade costs more than offsets the now relatively small reduction in world Assembly costs that would follow from leaving R1 as the sole Assembler.

With the complete switch of world Components productions and the partial switch of Assembly production from R1 to R2, together with rapid productivity growth, Widget employment in R1 declines sharply, from 5.275 in 1990 to 3.113 in 2000. By contrast, Widget employment in R2 increases sharply, from 2 in 1990 to 8.851 in 2000. R1's 1990 trade surplus in Widgets of 1.425 (Table 4.1B) turns into a 2000 trade deficit of 0.162 (= 1.575-1.413, Table 4.4B).

4.5. Iterating to impose the GSC solution on the CGE model: a non-converging case

In section 3 (Figure 3.1) we described an algorithm that aims to ensure consistency between: (a) wage rate and Widget demand assumptions in GSC solutions and outcomes for these variables in CGE solutions; and (b) tariff and Widget technology assumptions in CGE solutions and outcomes for these variables in GSC solutions. Achievement of these consistencies is what we call integration of the models.

[6] Labour-saving technical progress of 27.75 per cent means that a given level of output can be produced with 27.75 per cent less workers. Hence output per worker increases by 38.4 per cent [= 100*(1/(1-0.2775)-1)]. The movement in PROD from 0.25 to 0.3460 is a 38.4 per cent increase.

Table 4.5 shows our first attempt to implement the consistency algorithm. We started with CGE iter1. This is the baseline CGE solution described in subsection 4.3. It incorporates the shocks listed in subsection 4.3 together with the assumption of no change in labour input in either region. As shown in the CGE iter1 column of Table 4.5, this solution implies a wage increase in R2 of 13.8192 per cent (zero in R1 by the numeraire assumption) and Widget demand increases in R1 and R2 of 9.7714 and 32.4588 per cent. These results can also be seen (with less decimal places) in rows 3 and 9 of Table 4.3.

In GSC iter1 we solve the GSC model with the Widget assumptions given in Table 4.4A except that the wage (W) and final demand assumptions (Y) are replaced by results from CGE iter1.[7] This replacement is indicated by the arrow from the CGE iter1 column in Table 4.5 to the GSC iter1 column. After the GSC model is solved with these new W and Y values, selected results are passed to the CGE model.

The block of selected GSC results from GSC iter1 that are passed to the CGE model are indicated by the arrow from the GSC iter1 column to the CGE iter2 column. These GSC results show percentage changes between 1990 and 2000 in labour and intermediate inputs per unit of output in each region's Widget industry and also average powers of tariffs. They are derived for each region's Widget industry as a whole by aggregating results for Widget activities in the GSC model. The aggregation formulas are in subsection A.2 of the appendix.

After the CGE model is solved in CGE iter2 with these selected inputs from GSC iter1, wage and final demand results from CGE iter2 are passed to the GSC model as indicated by the arrow from the CGE iter2 column to the GSC iter2 column. The GSC model is re-solved in GSC iter2 and passes revised Widget tariff and technology results to the CGE model to be used in CGE iter3 and so on.

Before discussing convergence or lack of it, we pause to look at the GSC iter1 results that are passed to CGE iter2.

Results from GSC iter1

The GSC iter1 solution is in Table 4.6. Although the wage and final demand assumptions in GSC iter1 are different from those in the stand-alone GSC solution for 2000 in Table 4.4B, the solution is quite similar. In both these GSC solutions R2 takes over the entire world production of Components, the production of Assembly is split between the two regions and R1 continues to be responsible for world production of Designs.

With R2 taking over Components production and Assembly shared, R2 supplies Components to Assembly in both regions. As shown in the GSC iter1 column of Table 4.5, this generates huge percentage increases (31301.7 & 8950.6) in the use of C1 from R2 as an intermediate input per unit of output in Widget production (Ind1) in R1 and R2. The percentage increases are huge because they are calculated from the negligible 1990 values (0.01) adopted in the 1990 input-output database (see Table 4.2B).[8] Corresponding to the huge percentage increases in the use of C1 from R2 in the production of C1 in both regions, GSC iter1 implies sharp decreases in the use of C1 from R1 as an intermediate input in Widget production per unit of output (39.3689 per cent in R1 and 70.3976 per cent in R2).

[7] Instead of W(R2) = 0.3 as in Table 4.4A, in GSC iter1 we use W(R2) = 0.2845 (i.e. the 1990 value, 0.25, times 1.138192). Instead of Y(R1) = 1 as in Table 4.4A, in GSC iter1 we use Y(R1) = 1.097714 (i.e. 1*1.097714). Instead of Y(R2) =0.75 as in Table 4.4A, in GSC iter1 we use Y(R2) = 0.6623 (i.e.0.5*1.324588).

[8] It might be objected that because the negligible starting points, the 0.01s, are arbitrary then so are the percentage increases. But this doesn't matter. The important point is that the percentage increases will take us to the correct 2000 values.

Table 4.5 Iterating between the CGE and GSC models: non-converging (percentage differences between values of variables in 1990 and 2000)

	CGE iter1	GSC iter1	CGE iter2	GSC iter2	CGE iter3	GSC iter3	CGE iter4
Baseline shocks (1) to (5)	YES						
Baseline shocks (2) and (4) (excludes Widget shocks, these come from GSC model)			YES		YES		YES
GSC productivity and tariff assumptions for Widget activities		YES		YES		YES	
Widget results from GSC used as shocks in CGE							
labour per unit of output, Ind1, R1		-14.4245		-14.0802		-14.5368	
labour per unit of output, Ind1, R2		5.4564		-27.7126		5.5539	
C1 from R1 per unit output in Ind1, R1		-39.3689		-0.8059		-39.3070	
C1 from R1 per unit output in Ind1, R2		-70.3976		0.0457		-70.2490	
C1 from R2 per unit output in Ind1, R1		31301.7		8.5895		31326.4	
C1 from R2 per unit output in Ind1, R2		8950.6		-10.1346		8917.7	
power of tariff on R1's imports of C1		5[#]		0[#]		5[#]	
power of tariff on R2's imports of C1		-12.5		-8.33		-12.5	
Results from CGE used as shocks in GSC							
quantity of final demand for C1 in R1	9.7714		7.0179		9.7609		7.0208
quantity of final demand of C1 in R2	32.4588		37.8331		30.5935		37.8380
wage rate in R2	13.8192		25. 2489		13.8918		25.2412

[#] As shown in Table 4.2B, in 1990 R1 collected zero tariff revenue on negligible but non-zero imports of C1. These data imply (artificially) that the power of the tariff on R1's imports of C1 was one. In the GSC iter1 and iter3 solutions, R1 imports Components with a tariff of 5 per cent. Thus from the point of view of the CGE model, the average power of the tariff on R1's imports of C1 has risen from 1 in 1990 to 1.05 on 2000, an increase of 5 per cent. In the GSC iter2 solution R1 imports no Widget products, giving us no basis for calculating the average power of the tariff applying to R1's Widget imports. We made the arbitrary (but harmless) decision to assume that the average power was 1, implying zero deviation from the value in the 1990 CGE database.

Table 4.6. Output, employment, trade and prices in 2000: solution from GSC iter1#

	Price	Output	Employment	Exports, qty	Exports, value
R1					
Design	0.808	1.76	1.421	1.76	1.421
Components	1.657	0.00	0.000	0.00	0.000
Assembly	2.464	1.10	0.933	0.00	0.000
SalesDist	3.314	1.10	0.933	0.00	0.000
Total			3.287		1.421
			VA=3.287		
R2					
Design	1.612	0.00	0.000	0.00	0.000
Components	1.537	1.76	4.264	1.10	1.687
Assembly	2.464	0.66	2.158	0.00	0.000
SalesDist	3.287	0.66	1.914	0.00	0.000
Total			8.338		1.687
			VA=2.372		

This GSC solution was generated with W(R1) = 1, W(R2) = 0.2845, Y(R1) = 1.097714 and Y(R2) = 0.6623. In the solution in Table 4.4B, W(R1) = 1, W(R2) = 0.3, Y(R1) = 1 and Y(R2) = 0.75.

With regard to labour input per unit of output in Widgets, GSC iter1 shows an increase of 5.4564 per cent in R2 between 1990 and 2000 and a decrease of 14.4245 per cent in R1. The increase in R2 is the outcome of two factors, one positive and one negative. The positive factor reflects the changing composition of R2's Widget production from being purely SalesDist in 1990 to also including Components and Assembly in 2000. Because the value of output in SalesDist is dominated by the cost of the intermediate input (Assembly), labour input per unit of output in SalesDist is low. Thus, the move towards Components and Assembly production in R2 has a positive effect on the overall use of labour per unit of output for the sector. The negative factor is increased labour productivity occurring in all of R2's Widget activities. For R2, the positive effect of the compositional change on labour input per unit of output outweighs the negative effect of productivity improvement. The 14.4245 per cent decrease in R1's use of labour per unit of output in Widget production is mainly a reflection of the 15 per cent productivity increases assumed for all of R1's Widget activities. R1's employment per unit of output in the Widget sector is also affected by compositional changes (loss of Component production) and by loss of scale in Assembly production.

The tariff results in GSC iter1 reflect the composition of each region's Widget imports and the powers of the tariffs applying to the separate Widget commodities. In 1990, R2's Widget imports consisted entirely of Assembly with a tariff power of 1.2. In the GSC iter1 solution for 2000, R2's Widget imports consist entirely of Design with a tariff power of 1.05. Thus for R2 the average power falls by 12.5 per cent. In 1990, R1 had no Widget imports. As explained in the note below Table 4.5, the 5 per cent increase in the power of the tariff on R1's Widget imports shown in the GSC iter1 column is an artefact of the emergence of Widget imports from a negligible base.

Why didn't the algorithm work?

It is clear from Table 4.5 that our first attempt to implement the GSC-CGE integrating algorithm failed. The differences between the solutions in CGE iter4 and CGE iter3 are no smaller than the differences between CGE iter3 and CGE iter2. Rather than converging, our results are cycling between two solutions: one given by CGE iter2 & 4 and the other given by

CGE iter1 & 3. From the point of view of the GSC model we can also see two distinct solutions: one given by GSC iter1 & 3 and the other given by GSC iter2.

The behaviour of the wage rate in R2 is the key to the cycling that is apparent in Table 4.5. In CGE iter1 there are no shocks from the GSC model. Given the CGE baseline productivity and tariff shocks listed in subsection 4.3, the CGE model implies a moderate increase in the wage rate for R2, 13.8192 per cent. On the basis of this moderate wage increase and the productivity and tariff shocks assumed at the Widget activity level, GSC iter1 produced the radical location changes in Widget activities that we can see in the comparison of Tables 4.6 and 4.1B (or in the earlier comparison of Tables 4.4B and 4.1B). Given the changes in inputs per unit of Widget output implied by GSC iter1, CGE iter2 gives a large wage increase for R2, 25.2489 per cent.

With this large wage increase, the GSC model tells us that Widget activity will not be transferred from R1 to R2. Consequently, GSC iter2 shows relatively mild percentage changes in inputs per unit of Widget output, reflecting mainly the background productivity changes assumed for the four Widget activities in R1 and for SalesDist in R2. Given these relatively small Widget shocks, CGE iter3 implies a moderate wage increase for R2, close to that in CGE iter1 in which there were no shocks from the GSC model.

When the moderate wage increase for R2 from CGE iter3 is introduced to the GSC model, the GSC model once more generates the radical location shift in Widget activity that we saw in Table 4.6. Thus, when used in CGE iter4, the shocks coming out of GSC iter3 again support a large wage increase in R2, 25.2412 per cent. And hence the cycling continues.

Figure 4.1 is a picture of what is happening in Table 4.5. The figure shows three CGE demand curves for labour in R2: the demand curve in 1990; the demand curve in 2000 on the assumption that R2 is not receiving any GSC shocks; and the demand curve in 2000 under the assumption that R2 is receiving GSC shocks such as those going into CGE iter2 and CGE iter4. The figure also shows the labour-supply curve for 1990 and 2000 assumed in the CGE simulations in Table 4.5: no-change in employment. The demand and supply curves in Figure 4.1 are drawn to be consistent with our CGE results. They imply wage increases in R2 of about 25.2 per cent when R2 benefits from participation in Widget GSC activities and about 13.8 per cent in the no-GSC case. As we move across the CGE solutions in Table 4.5, we cycle between the solution on the low demand curve for 2000 and the solution on high demand curve.

The figure makes it clear that no amount of fine-tuning of our algorithm (e.g. partial adjustment between iterations) is going to lead to a converged solution. The truth is that there is no converged solution under the assumptions we are making. If R2 is participating in the Widget GSC then the CGE model implies that it can't participate – its wage rate is too high. If R2 is not participating in the Widget GSC then the CGE model implies that it will participate – its wage rate is sufficiently low.

4.6. Obtaining GSC-CGE convergence: giving R2 surplus labour

As illustrated in Figure 4.2, the opportunity to participate in GSC trade in effect gives R2 a demand curve for labour that contains a hole. By experiment, we found that if the wage rate in R2 is greater than about 0.301, then the GSC model indicates that R2 will be on the *without*-GSC demand curve in 2000, otherwise it will be on the *with*-GSC curve. The vertical labour supply curve that we assumed in our initial formulation of the GSC-CGE integration problem happens to pass through the hole between the two segments of the demand curve. In theory, we could determine the exact value of W(R2) at which the global agent controlling the Widget industry is indifferent between radical location switches, of the type we saw in Tables 4.6 and 4.4B, and leaving all traded Widget activities entirely in R1. But, with a vertical labour supply curve, this still wouldn't give us a solution to the combined GSC-CGE model. If, at the indifference-level of W(R2) the global agent chose to switch, then demand for labour in R2 would exceed supply. If, on the other hand, the global agent chose not to switch, then supply of labour in R2 would exceed demand.

Figure 4.2 not only helps us understand why there is no solution to the GSC-CGE problem with inelastic labour supply in R2, but it also suggests how we should reformulate the GSC-CGE problem. We need to recognize that the opportunity to participate in GSC activity can affect R2's labour supply, not the supply of people but the supply of labour input.

Assume that R2 has surplus labour. We are thinking of a developing country, e.g. China in 1990, with large numbers of agriculture workers whose marginal product is close to zero. As explained by Lewis (1954), these workers can survive in agriculture because they are paid the average product of their family group rather than their individual marginal product. Now assume that a global supply chain opportunity becomes available that offers jobs compatible with the skills of R2's surplus workers at wages that are considerably higher than average farm product. At these higher wages, we assume that there is an unlimited supply of labour to GSC activities in R2 from workers whose marginal product in their previous employment was zero. We represent this situation in Figure 4.2 by a perfectly elastic supply curve of labour input. Provided labour-input supply is perfectly elastic at a wage below the critical 0.301, Figure 4.2 indicates that a converged GSC-CGE solution with R2 participation in the Widget GSC exists. This is confirmed in Table 4.7.

In generating Table 4.7 we used the algorithm in Figure 4.3. This is a modified version of the initial algorithm in Figure 3.1. In the initial algorithm, the wage rate in R2 is determined endogenously in the CGE model and passed as a shock to the GSC model. Now, under the assumption that labour supply is perfectly elastic in R2, we make an assumption about the wage rate in R2 and feed it exogenously into both the GSC and CGE models.

In applying the modified algorithm we started by generating the CGE solution shown in the CGE iter2b column of Table 4.7. In this solution, we used the GSC-related shocks from GSC iter1 in Table 4.5 (reproduced in the first column of Table 4.7). However, instead of allowing the CGE model to determine the wage rate in R2, we set its increase between 1990 and 2000 exogenously at 20 per cent and determined employment endogenously.

As indicated by the arrow out of the CGE iter2b column of Table 4.7, we transferred the final demand results from CGE iter2b into GSC iter2b. In GSC iter2b we adopted the same wage increase for R2 (20 per cent) that was assumed in CGE iter2b. Continuing as in Table 4.5, we transferred GSC Widget results from GSC iter2b into CGE iter3b. Convergence was achieved quickly.

The R2 wage assumption we chose for our stylized example, an increase between 1990 and 2000 of 20 per cent, takes R2's wage to 0.300 (= 0.25*1.2). This wage is close to the maximum level compatible with R2's participation in the Widget GSC. By choosing this wage increase we illustrate a situation in which R2 receives close to the maximum wage benefit available from GSC participation and close to the minimum labour-input benefit. Other combinations of wage and labour-input benefit are available. But even the minimum labour-input benefit is substantial. In the converged GSC-CGE solution in Table 4.7, labour-input in R2 grows by 20.3 per cent.

Figure 4.1. Demand and supply curves for labour in R2: non-converging CGE solutions

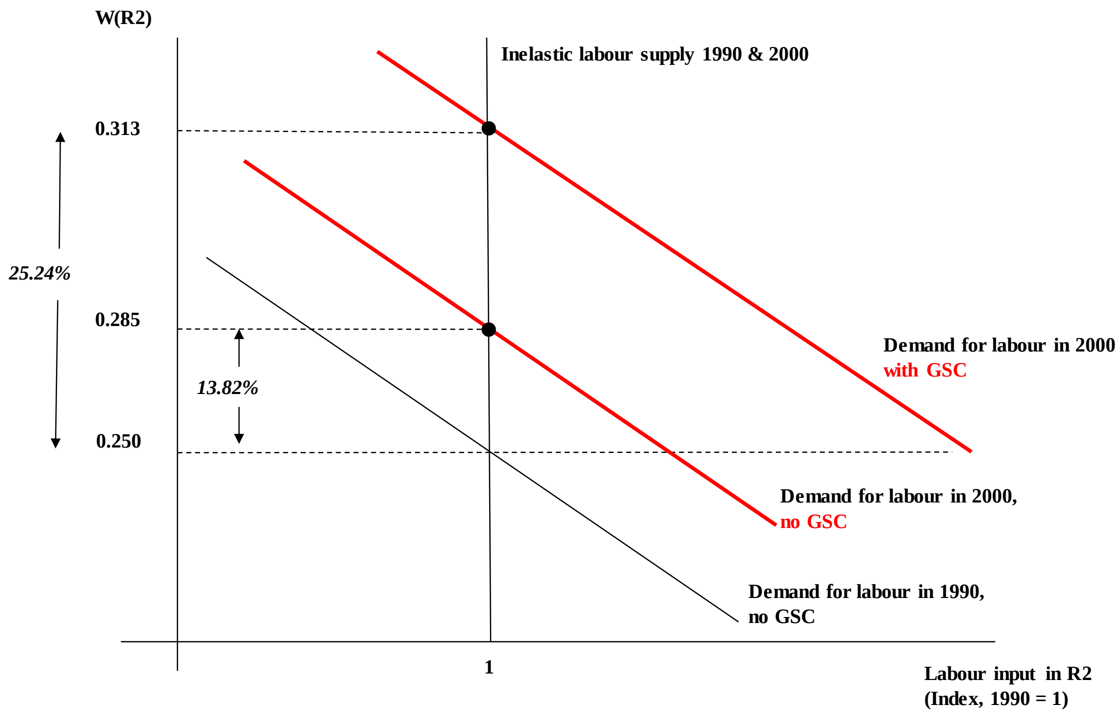


Figure 4.2. Demand and supply curves for labour in R2: converged CGE solution

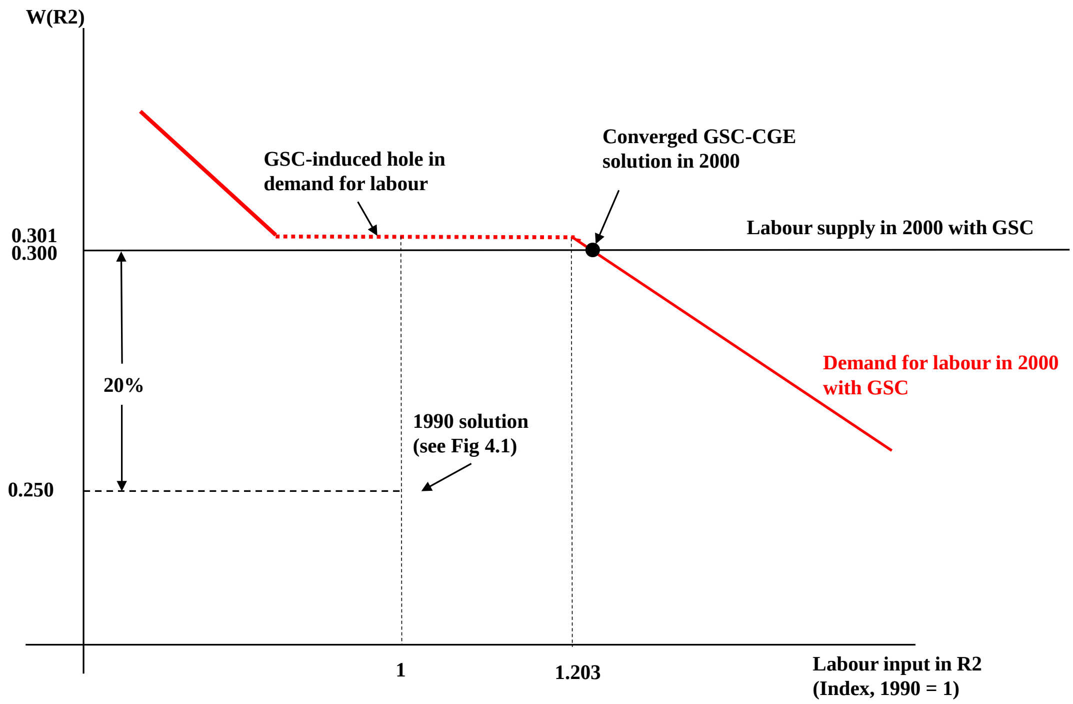
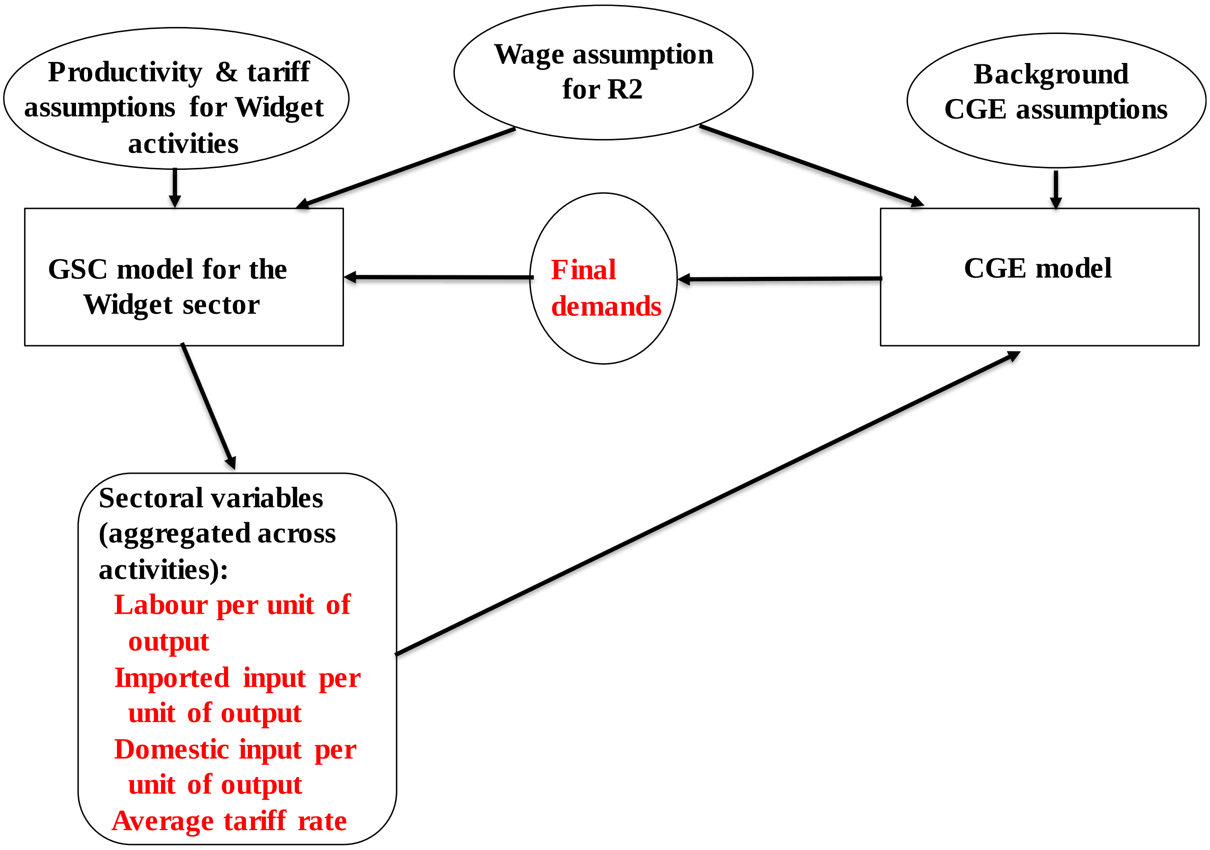


Table 4.7. Iterating between the CGE and GSC models: converging with elastic labour supply in R2 (percentage differences between values of variables in 1990 and 2000)

	GSC iter1	CGE iter2b	GSC iter2b	CGE iter3b	GSC iter3b	CGE iter4b
Baseline shocks (1) to (5)						
Baseline shocks (2) and (4) (excludes Widget shocks, these come from GSC model)		YES		YES		YES
GSC productivity and tariff assumptions for Widget activities	YES		YES		YES	
Widget results from GSC used as shocks in CGE						
labour per unit of output, Ind1, R1	-14.4245		-12.3505		-12.3401	
labour per unit of output, Ind1, R2	5.4564		4.8818		4.8759	
C1 from R1 per unit output in Ind1, R1	-39.3689		-40.1062		-40.1114	
C1 from R1 per unit output in Ind1, R2	-70.3976		-72.7764		-72.7861	
C1 from R2 per unit output in Ind1, R1	31301.7		30320.1		30317.3	
C1 from R2 per unit output in Ind1, R2	8950.6		9427.66		9429.8	
power of tariff on R1's imports of C1	5		5		5	
power of tariff on R2's imports of C1	-12.5		-12.5		-12.5	
Results from CGE used as shocks in GSC						
quantity of final demand for C1 in R1		7.9829		8.0679		8.0678
quantity of final demand of C1 in R2		63.1089		63.4067		63.4083
wage rate in R2		20	20	20	20	20
employment in R2 (labour input)		19.9		20.3		20.3

Figure 4.3. An algorithm for integrating GSC & CGE models: elastic labour supply in R2



4.7. Comparison of the standard CGE and the integrated GSC-CGE projections for 1990 to 2000

Table 4.8 compares the projections in Table 4.3 made using the standard CGE model with those in Table 4.7 implied by the converged GSC-CGE solution.

The inclusion of GSC trade has a generally negative effect on the projected macro prospects of R1. With R2's participation in the Widget GSC, the projected increase in R1's GDP falls from 2.72 per cent to 1.83 per cent (row 1, Table 4.8). While we assume that the GSC makes no difference to aggregate labour-input in R1 (row 22), the recognition of GSC trade reduces R1's GDP growth by transferring resources from Ind1 in which productivity growth is rapid to Ind2 in which productivity growth is slow. Reflecting the reductions in productivity growth and GDP growth, real wage and consumption growth is lower in R1 in the GSC-CGE integrated solution than in the standard CGE solution (1.36 per cent compared with 2.41 per cent and 1.63 per cent compared with 2.41 per cent, rows 4 and 2). A slight positive for R1 from GSC trade is a less negative movement in its terms of trade (-1.42 per cent compared with -2.12 per cent, row 15). With technical change reducing the price of C1 relative to that of C2, the less-negative terms-of-trade outlook for R1 is explained by a GSC-induced reduction in the C1-share in its exports and increase in the C1-share of its imports.

By contrast, for R2 the inclusion of GSC trade has a major positive effect on the region's projected macro prospects. Whereas the standard CGE projection for GDP growth in R2 was 18.76 per cent, this is raised to 45.93 per cent in the converged GSC-CGE solution.

Table 4.8. Projection from 1990 to 2000 using standard CGE and integrated GSC-CGE models (percentage differences between values of variables in 1990 and 2000)

		Standard CGE		**Integrated GSC-CGE**	
		R1	**R2**	**R1**	**R2**
1	Real GDP (% change from 1990 to 2000)	2.72	18.76	1.83	45.93
2	Real consumption, welfare (% change)	2.41	19.76	1.63	46.82
3	Wage rate	0.00	13.82	0.00	20.00
4	Real wage rate, CPI delated (% change)	2.41	22.19	1.36	24.68
5	Factory price of C1 (% change)	-15.01	-23.85	-12.74	-22.30
6	Factory price of C2 (% change)	0.00	-3.25	0.00	2.00
7	Purchasers' price to consumers of C1 (% change)	-15.01	-23.85	-12.74	-22.30
8	Purchasers' price to consumers of C2 (% change)	-0.53	-2.22	0.30	1.32
9	Consumption of C1, quantity (% change)	9.77	32.46	8.07	63.41
10	Consumption of C2, quantity (% change)	1.47	16.89	0.80	43.10
11	Value of exports (% change)	9.11	9.11	36.62	36.62
12	Value of imports (% change)	9.11	9.11	36.62	36.62
13	Quantity of exports (% change)	15.28	12.84	43.26	41.23
14	Quantity of imports (% change)	12.84	15.28	41.23	43.26
15	Terms of trade (% change)	-2.12	2.17	-1.42	1.44
16	Labour input in Ind1	-1.51	-4.29	-35.96	381.48
17	Labour input in Ind2	0.30	0.21	7.18	2.28
18	Exports C1 (100 times change in value at initial prices as share of initial GDP)*	1.47	0.04	1.12	20.52
19	Exports C2 (100 times change in value at initial prices as share of initial GDP)	0.66	5.05	4.54	-2.15
20	Imports C1 (100 times change in value at initial prices as share of initial GDP)	0.01	4.30	6.99	3.30
21	Imports C2 (100 times change in value at initial prices as share of initial GDP)	1.72	1.94	-0.73	13.32
22	Aggregate labour input	0	0	0	20.34

* 100*(Quantity in final year times price in initial year – Value in initial year)/GDP in initial year

.

Correspondingly, the converged GSC-CGE solution shows a much larger increase in R2's real consumption than the standard CGE solution (46.82 per cent compared with 19.76 per cent, row 2).

The extra GDP growth for R2 in the GSC-CGE solution comes mainly from extra labour input, 20.34 per cent (row 22). This extra labour input is not more people in work. Rather, it is more people employed in activities in which their marginal product is non-negligible, in line with their wage. GSC trade has allowed some people to contribute to labour input who, although previously employed, were not adding positively to labour input. Fast technical change in Ind1 relative to Ind2 also contributes to R2's extra GDP growth in the GSC-CGE solution relative to the standard CGE solution.

In subsection 4.3 we explained that the standard CGE model produced conservative business-as-usual projections at the industry/commodity level. By contrast, the integrated GSC-CGE model projects major changes in the industrial composition of employment in each region and the commodity composition of trade.

In rows 16 and 17 of the GSC-CGE projections, R1's labour input (and employment) in Ind1 falls by 35.96 per cent while in Ind2 it increases by 7.18 per cent. With no change in aggregate labour input (row 22), which is the same as employment in R1, this compositional change means that 6 per cent of R1's workforce must be reassigned from Ind1 to Ind2.[9] This can be compared with the standard CGE projection which showed a shift of only 0.25 per cent of the workforce between the two industries.

For R2, the integrated GSC-CGE model projects labour-input increases in both industries: by 381.48 per cent in Ind1 and 2.28 per cent in Ind2, giving an overall increase of 20.34 per cent (row 22). This 20.34 per cent increase in labour input is a transfer of unproductive Ind2 workers into productive work either in Ind1 or Ind2. Enough of these unproductive workers find employment in Ind1 to boost the economy's total labour input by 18.16 per cent [=381.48*0.5/(0.5+10)]. A further 2.17 per cent [=2.28*10/(0.5+10)] boost comes from transfer of unproductive Ind2 workers into productive Ind2 work. Most of R2's extra demand for C2 associated with extra consumption (row 2) is satisfied by extra imports. Nevertheless, under the Armington assumption, extra output of the domestic product is required. This generates the increased demand for labour input in R2's Ind2.

While GSC trade imposes large changes in the industrial composition of employment in both regions, the nature of the structural adjustments in the two regions is quite different. R1 is faced with a situation in which workers in one industry must move to another industry or suffer unemployment. Consequently, R1 faces a potential structural adjustment problem. By contrast, GSC trade gives unproductive workers in R2's Ind2 an opportunity to move voluntarily to higher-wage, more productive employment in Ind1 or to contribute fully to output in Ind2. Rather than a structural problem, GSC trade gives R2 the potential for a structural improvement.

As illustrated by rows 11 to 14 of Table 4.8, the integrated GSC-CGE model projects much more growth in trade values and volumes than the standard CGE model. Trade growth is increased for both regions by the dramatic increase in R2's GDP made possible by GSC trade. Although R2 is the major beneficiary of GSC trade, perhaps counter-intuitively, R1's trade share in GDP is increased much more strongly by GSC trade than R2's trade share. As explained in subsection 4.3 for the standard CGE model, from R1's point of view, the size of export markets increases strongly relative to domestic markets. This effect is accentuated in

[9] This can be worked out from the percentage change results in Table 4.8 and the labour-input data in Table 4.2B as either 35.96*5.265/(5.265+26.375) or 7.18*26.375/(5.265+26.375).

the GSC-CGE model in which the gap widens between GDP growth in R2 (a size indicator of R1's export market) and GDP growth in R1 (a size indicator for R1's domestic market).

Relative to the conservative projections generated by the standard CGE model, the integrated GSC-CGE model shows sharp changes in the commodity composition of trade, particularly R2's exports. Whereas the standard CGE model projected continuation of the status quo from 1990 in which R2's exports are dominated by C2, the integrated model projects an increase in R2's exports of C1 worth (at 1990 prices) 20.52 per cent of R2's 1990 GDP. This boosts the share of C1 in R2's exports from close to zero in 1990 to 30 per cent in 2000.

5. Concluding remarks

Understanding GSC trade requires modelling of multi-stage production processes and optimizing behaviour by global agents. But standalone GSC modelling is not enough. The main message from this paper is that for understanding the implications of GSC trade we need to take an economy-wide perspective. In particular, we need to integrate GSC models into CGE models in which there is an adequate description of labour markets.

In this paper, we have demonstrated a method for building and solving an integrated GSC-CGE model in which the two models are solved separately with information being passed from one to the other. This is a divide-and-conquer approach similar to that used by Balistreri and Rutherford (2013) for solving CGE models with embedded Melitz sectors[10] (heterogeneous firms, imperfect competition and scale economies). Balistreri and Rutherford compute solutions for each Melitz sector separately using guesses for sectoral demands and wage rates. Parts of these solutions (technology and preference variables) are fed into a standard general equilibrium model to generate revised guesses for demands and wage rates. A solution for the Melitz-enhanced CGE model is achieved when wage rates and demands coming out of the CGE model are the same as the guesses going into the previous round of Meltiz sectoral computations.

The divide-and-conquer approach adopted here allows separate development of GSC sectoral models without the clutter of the CGE detail. This is efficient from computational and research management points of view. In this paper, it had the additional bonus of alerting us to the possibility of a hole in the labour demand curve for the developing country. Coping with the hole led us to a surplus-labour specification for the developing country and the striking results showing that low-income countries with surplus labour may be the major beneficiaries from the emergence of GSC trade. This contrasts with analyses based on Shih's (1996) smiling curve. These are sometimes used to argue that high-income countries are the major beneficiaries because they undertake the high value-added activities (Design and Sales/distribution) at the two ends of supply chains.

What our integrated GSC-CGE model suggests is that by providing low-skilled jobs, GSC trade can accelerate the transfer of labour out of agriculture, where workers have low marginal productivity, into manufacturing where their marginal productivity is much higher. At the same time, our integrated model suggests that GSC trade can leave high-income countries having to transfer considerable fractions of their workforce out of manufacturing and into services. Even when they have achieved this potentially expensive structural adjustment, they may be left in the long run with no more than a small equilibrium welfare gain or even a loss.

[10] See Melitz (2003).

Appendix

This appendix has three parts. Subsection A.1 is an algebraic specification of the GSC model described in subsection 4.1. It sets out the model as a constrained optimization problem. Special features of the model including the treatment of scale economies and the computation of prices are noted. Subsection A.2 gives the aggregation formulas mentioned in subsection 4.5. These generate the Widget sectoral results that are passed from the GSC model to the CGE model. Subsection A.3 justifies the algorithm described in section 3 and applied in subsections 4.5 and 4.6. It shows for a converged solution that there are no inconsistencies between the variables common to the GSC and CGE models.

A.1. The GSC model as a constrained optimization model

We assume that for all $r \in R$, the global optimizing agent chooses:

$$
\begin{aligned}
&X^{gsc}_{jW}(r),\ j \in WA; \\
&\qquad \textit{output of Widget commodity/activity j in region r} \\
&A^{gsc}_{ijW}(r,d),\ i \in WCI\ \&\ j \in WA; \\
&\qquad \textit{input of Widget com i from r per unit of output of Widget com j in d} \\
&SCALE^{gsc}_{jW}(r),\ j \in WA; \\
&\qquad \textit{scale-economy variable in production of Widget com j in r} \\
&TTC^{gsc}_{W}; \\
&\qquad \textit{total cost of tariffs to global agent} \\
&LC^{gsc}_{W}; \\
&\qquad \textit{total labour costs in the globaWidget sector}
\end{aligned}
\tag{A.1}
$$

to minimize

$$
\begin{aligned}
&TTC^{gsc}_{W} + LC^{gsc}_{W} \\
&\textit{total cost of satisfying world-wide demand for the final Widget product}
\end{aligned}
\tag{A.2}
$$

subject to

$$
\begin{aligned}
&X^{gsc}_{iW}(r) = \sum_{d \in R} \sum_{j \in WA} A^{gsc}_{ijW}(r,d) * X^{gsc}_{jW}(d) \quad \textit{for all } i \in WCI \textit{ and } r \in R \\
&\textit{supply/demand balance for intermediate Widget com i from region r}
\end{aligned}
\tag{A.3}
$$

$$
\begin{aligned}
&X^{gsc}_{FW}(d) = Y^{gsc}_{W}(d) \quad \textit{for all } d \in R \\
&\textit{supply/demand balance for final (F) Widget com in region d, F is not traded}
\end{aligned}
\tag{A.4}
$$

$$
\begin{aligned}
&\bar{A}^{gsc}_{ijW}(d) = \sum_{r \in R} A^{gsc}_{ijW}(r,d) \quad \textit{for all } i \in WCI, j \in WA \textit{ and } d \in R \\
&\textit{total requirements of i per unit of output of j in d}
\end{aligned}
\tag{A.5}
$$

$$
\begin{aligned}
&LC^{gsc}_{W,} = \sum_{j \in WA} \sum_{r \in R} W^{gsc}(r) * \frac{X^{gsc}_{jW}(r)}{PROD^{gsc}_{jW}(r)} * SCALE^{gsc}_{jW}(r) \\
&\textit{Widget labour costs determined by wage rates, output and productivity modified for scale}
\end{aligned}
\tag{A.6}
$$

$$
\begin{aligned}
&SCALE^{gsc}_{jW}(r) = S^{gsc}_{jrW}(X^{gsc}_{jW}(r)) \qquad \textit{for all } j \in WA \textit{ and } r \in R \\
&\textit{scale modification in production of j in r determined by output}
\end{aligned}
\tag{A.7}
$$

$$
\begin{aligned}
&TTC^{gsc}_{W} = \sum_{i \in WCI} \sum_{r \in R} \sum_{j \in WA} \sum_{d \in R} P^{gsc}_{iW}(r) * [T^{gsc}_{iW}(r,d) - 1] * A^{gsc}_{ijW}(r,d) * X^{gsc}_{jW}(d) \\
&\textit{total cost of tariffs to the global agent}
\end{aligned}
\tag{A.8}
$$

In this optimizing problem:

WCI is the set of Widget commodities used in the Widget sector as intermediate inputs. These are Design, Components and Assembly. This set excludes the final good, SalesDist. We denote the set of all Widget commodities, including SalesDist as WC.

WA is the set of Widget activities. Each activity is responsible for production of the correspondingly named Widget commodity, WA = WC.

R is the set of regions.

$X_{iW}^{gsc}(r)$ is the output of Widget commodity i in region r. It can also be viewed as the output of activity i in region r. When i= F, we are referring to the output of the final good, that is the output of the SalesDist activity.

$A_{ijW}^{gsc}(r,d)$ is the quantity of Widget commodity i from region r that the global optimizing agent chooses to use per unit of Widget activity j in region d.

$\bar{A}_{ijW}^{gsc}(d)$ is the total quantity of Widget commodity i required per unit of Widget activity j in region d. We treat these variables as exogenous or outside the control of the optimizing agent. They reflect Widget technology available in country d.

$Y_{W}^{gsc}(d)$ is the total quantity of Widget commodity required by final uses in region d. These variables are exogenous to the optimizing agent although they are endogenous in the integrated GSC-CGE model. It is easiest to think of final demands as being demands by public and private consumers and by capital creators. However, in a detailed empirical model final demands would include intermediate sales of Widget commodities to industries outside the Widget sector.

LC_{W}^{gsc} is total labour costs incurred in the world-wide Widget sector.

$W^{gsc}(r)$ is the wage rate in region r, which is exogenous to the optimizing agent but possibly endogenous in the integrated GSC-CGE model.

$PROD_{jW}^{gsc}(r)$ is labour productivity in Widget activity j in region r at standard scale for output. This is exogenous to the optimizing agent and remains exogenous in the integrated GSC-CGE model.

$SCALE_{jW}^{gsc}(r)$ allows for variations in labour productivity in Widget activity j in region r reflecting economies of scale. If the optimizing agent chooses to produce Widget commodity j in region r at a scale greater than standard, then through a suitable specification for the S_{jrW}^{gsc} function on the RHS of (A.7) we can allow output per unit of labour input in activity j in region r to be greater than $PROD_{jW}^{gsc}(r)$. For example, in the stylized model described in subsection 4.1 we assume that $SCALE_{jW}^{gsc}(r)$ = 0.95 if region r’s output is sufficiently large to satisfy world requirements for Widget commodity j. In that case output per unit of labour in r’s Widget activity j is greater than $PROD_{jW}^{gsc}(r)$: it is $PROD_{jW}^{gsc}(r)/0.95$.

$T_{iW}^{gsc}(r,d)$ is the power (one plus the rate) of tariffs applying to the flow of Widget commodity i from region r to region d. This is a naturally exogenous variable. We could also include transport costs between r and d. But in this simple model we ignore that complication. We refer to the T_{iW}^{gsc}s as tariffs, but we will not make a special case for domestic flows (r = d). For exposition, it is convenient to allow for “tariffs” on (r,r) flows of intermediate inputs. In the computations in section 4 we set $T_{iW}^{gsc}(r,r)=1$ for all i and r.

TTC_{W}^{gsc} is total cost of tariffs to the global agent. This is the sum over all regions of tariffs charged on intermediate inputs to Widget activities.

$P_{iW}^{gsc}(r)$ is the price before tariffs of Widget commodity i produced in region r. As discussed below, it may seem that $P_{iW}^{gsc}(r)$ can be controlled by the global agent. Nevertheless, we treat $P_{iW}^{gsc}(r)$ as exogenous in the global agent's optimization problem. In the integrated GSC-CGE model, it is endogenous.

Via (A.3) – (A.8) we assume that for given values of the variables $\bar{A}_{ijW}^{gsc}(d)$, $Y_{W}^{gsc}(d)$, $W^{gsc}(r)$, $PROD_{jW}^{gsc}(r)$, $T_{iW}^{gsc}(r,d)$ and $P_{iW}^{gsc}(r)$, the variables listed in (A.1) are determined by minimizing total tariff and labour costs, defined by (A.2), of satisfying final demands for Widget commodities, the $Y_{W}^{gsc}(d)$s. In this simple GSC model, we assume that Widget activities use only one primary factor (labour) and no intermediate inputs from outside the Widget sector. Equations (A.3) and (A.4) ensure that the output of Widget commodity i in region r satisfies intermediate and final demands. Equation (A.5) imposes the assumption of perfect substitutability between Widget commodity i from different sources in satisfying intermediate demands in Widget activity j in region d. Equations (A.6) to (A.8) define labour costs, the scale variable and total tariff costs.

The only role of prices, $P_{iW}^{gsc}(r)$, in the global optimizing problem is in the calculation of *ad valorem* tariff costs in (A.8). We assume that these prices are set to reflect production costs according to

$$P_{iW}^{gsc}(d) = \sum_{j\in WCI}\sum_{r\in R} P_{jW}^{gsc}(r) * T_{jW}^{gsc}(r,d) * A_{jiW}^{gsc}(r,d) + \frac{W^{gsc}(d)}{PROD_{iW}^{gsc}(d)} * SCALE_{iW}^{gsc}(d) \quad \text{(A.9)}$$

$$\text{for all } i \in WC \text{ and } d \in R$$

We can think of these prices as being imposed by governments to ensure that the global agent cannot avoid tariff costs by "clever" setting of Widget prices. The use of (A.9) to determine within-sector prices for the purpose of calculating TTC_{W}^{gsc} seems relatively harmless. In the integrated GSC-CGE system we also assume that $P_{FW}^{gsc}(d)$ determined in (A.9) applies to sales of the final Widget commodity to final users. This seems more problematic. Despite modelling the global agent as a monopolist, we assume that pricing of final goods is competitive. In the background, we are assuming that the global agent is constrained by potential entry of rivals.

Solving the Widget GSC model

A&deG solved their GSC model by first calculating prices and then calculating quantities. The separation of the price and quantity calculations was made possible because they assumed constant returns to scale in production activities. Under this assumption, prices can be determined independently of quantities. Our Widget GSC model introduces economies of scale. This prevents separation of price and quantity determination. Nevertheless, computations of solutions was straight-forward. We simply evaluated the cost function (A.2) under each of the 27 possible location possibilities. These 27 possibilities consist of 3 for Design (all in R1, all in R2 and shared between both) *times* 3 for Components *times* 3 for Assembly.

A.2. Defining aggregate GSC Widget variables for passing to the CGE model

The GSC-CGE algorithm in Figure 4.3 requires results for the aggregated Widget sector to be passed between the two models. Defining these variables in the CGE model presents no conceptual difficulty: the CGE model generates results for the aggregate sector without recognition of outputs, trade, and prices for underlying activities. However, before we can pass variables from the GSC model to the CGE model we must decide how to aggregate GSC activity results into results for the Widget sector as a whole. As indicated in Figure 4.3, the aggregate results that we need to compute from the GSC model for passing to the CGE model are:

labour input per unit of Widget output in region d, which we denote as $ALAB_W^{gsc}(d)$;

Widget input from region r used per unit of Widget output in region d, $A_{WW}^{gsc}(r,d)$; and

the power of the tariff applying to d's imports of Widget products from r, $T_W^{gsc}(r,d)$.

We compute these aggregate GSC variables via the following formulas:

$$X_W^{gsc}(r) = \frac{\sum_{i \in WC} P_{iW}^{gsc}(r) * X_{iW}^{gsc}(r)}{P_{FW}^{gsc}(r)} \quad \text{for all } r \in R \tag{A.10}$$

$$A_{WW}^{gsc}(r,d) = \frac{\sum_{i \in WCI} \sum_{j \in WA} P_{iW}^{gsc}(r) * A_{ijW}^{gsc}(r,d) * X_{jW}^{gsc}(d)}{P_{FW}^{gsc}(r)} * \frac{1}{X_W^{gsc}(d)} \quad \text{for all } r, d \in R \tag{A.11}$$

$$EMP_W^{gsc}(r) = \sum_{j \in WA} X_{jW}^{gsc}(r) * \frac{SCALE_{jW}^{gsc}(r)}{PROD_{jW}^{gsc}(r)} \quad \text{for all } r \in R \tag{A.12}$$

$$ALAB_W^{gsc}(d) = \frac{EMP_W^{gsc}(d)}{X_W^{gsc}(d)} \quad \text{for all } d \in R \tag{A.13}$$

$$V_W^{gsc}(r,d) = \sum_{i \in WCI} \sum_{j \in WA} P_{iW}^{gsc}(r) * A_{ijW}^{gsc}(r,d) * X_{jW}^{gsc}(d) \quad \text{for all } r,d \in R,\ r \neq d \tag{A.14}$$

$$V_W^{gsc}(r,r) = \sum_{i \in WCI} \sum_{j \in WA} P_{iW}^{gsc}(r) * A_{ijW}^{gsc}(r,r) * X_{jW}^{gsc}(r) + P_{FW}^{gsc}(r) * Y_W^{gsc}(r) \quad \text{for all } r \in R \tag{A.15}$$

$$VT_W^{gsc}(r,d) = \sum_{i \in WCI} \sum_{j \in WA} \left[T_{iW}^{gsc}(r,d) - 1 \right] * P_{iW}^{gsc}(r) * A_{ijW}^{gsc}(r,d) * X_{jW}^{gsc}(d) \quad \text{for all } r,d \in R \tag{A.16}$$

$$T_W^{gsc}(r,d) = 1 + \frac{VT_W^{gsc}(r,d)}{V_W^{gsc}(r,d) - \delta(r,d) * P_{FW}^{gsc}(r) * Y_W^{gsc}(r)} \quad \text{for all } r, d \in R \tag{A.17}$$

(A.10) gives the definition for the GSC model of output [$X_W^{gsc}(r)$] by the Widget sector in region r. It adds over outputs of Widget commodities using price-ratio weights [$P_{iW}^{gsc}(r)/P_{FW}^{gsc}(r)$]. $P_{iW}^{gsc}(r)$ is the value of inputs embedded in the production of a unit of Widget commodity i. Consequently, $P_{iW}^{gsc}(r)/P_{FW}^{gsc}(r)$ is the fraction of a unit of the final good completed by the production of a unit of Widget commodity i. In (A.10), production of the final good gets a weight of one in the calculation of sectoral output whereas production of a Widget commodity i half way along the production process to the final good gets a weight of 0.5.

(A.11) gives the definition for the GSC model of Widget input from region r per unit of Widget output in region d, [$A_{WW}^{gsc}(r,d)$]. The quantity of Widget input from region r is defined in accordance with (A.10) as a price-ratio-weighted [$P_{iW}^{gsc}(r)/P_{FW}^{gsc}(r)$] sum of the quantities of individual Widget goods ($i \in$WCI) flowing from r to Widget activities ($j \in$WA) in d, [$A_{ijW}^{gsc}(r,d) * X_{jW}^{gsc}(d); i \in \text{WCI}, j \in \text{WA}$].

(A.12) gives the definition for the GSC model of employment [$EMP_W^{gsc}(r)$] in region r's Widget sector. This is the sum of labour inputs over individual Widget activities ($j \in$WA) in region r. Labour input in each activity is calculated as output [$X_{jW}^{gsc}(d)$] times labour requirement per unit of output, [$SCALE_{jW}^{gsc}(r)/PROD_{jW}^{gsc}(r)$].

(A.13) gives the definition for the GSC model of labour input per unit of Widget sector output in region d, [$ALAB_W^{gsc}(d)$]. This is the ratio of sectoral employment to sectoral output.

(A.14) and (A15) give the definition for the GSC model of the total factory value of Widget flows from r to d, [$V_W^{gsc}(r,d)$].

(A.16) defines total tariff collection by d on Widgets from r, [$VT_W^{gsc}(r,d)$]. As mentioned earlier, it is convenient not to make a special case for domestic flows.

(A.17) defines the average power of the tariff [$T_W^{gsc}(r,d)$] in the GSC model on the Widget flow from r to d. In this equation, $\delta(r,d)$ is one for r = d and zero otherwise. Thus , $T_W^{gsc}(r,d)$ is one plus the ratio of the tariff collection to the factory value of the flow on which the tariff is charged. Notice that $T_W^{gsc}(r,r)$ is one plus the ratio of the "tariff collection" on the flow of domestic intermediate input to the Widget industry in r.

A.3. Justifying the GSC-CGE algorithm: do all the variables common to the two models have the same value in a converged solution?

In a converged solution of the algorithm described in Figure 4.3 and applied in subsection 4.6, we can be sure that

$$W^{gsc}(d) = W^{cge}(d) \quad \text{for all } d \in R \tag{A.18}$$

$$Y_W^{gsc}(d) = Y_W^{cge}(d) \quad \text{for all } d \in R \tag{A.19}$$

$$T_W^{gsc}(r,d) = T_W^{cge}(r,d) \quad \text{for all } r,d \in R \tag{A.20}$$

$$A_{WW}^{gsc}(r,d) = A_{WW}^{cge}(r,d) \quad \text{for all } r,d \in R \tag{A.21}$$

$$ALAB_W^{gsc}(d) = ALAB_W^{cge}(d) \quad \text{for all } d \in R \tag{A.22}$$

The LHSs of (A.18) – (A.22) with the superscript gsc refer to variables generated by the GSC model. The RHSs with the superscript cge refer to variables generated by the CGE model. In a converged solution these equalities hold because these are the variables that are passed between the two models. But there are other variables that appear in both models but are not passed between them. Can we be sure that there are no inconsistencies between these variables in a converged solution? Specifically, can we be sure that in a converged solution the values in the two models are the same for: Widget trade flows; Widget domestic flows; tariff collections on Widgets; prices of the final Widget commodity (SalesDist); Widget employment; and Widget output? To rule out inconsistencies, we need to establish that:

$$V_W^{gsc}(r,d) = V_W^{cge}(r,d) \quad \text{for all } r,d \in R, r \neq d \tag{A.23}$$

$$V_W^{gsc}(r,r) = V_W^{cge}(r,r) \quad \text{for all } r \in R \tag{A.24}$$

$$VT_W^{gsc}(r,d) = VT_W^{cge}(r,d) \quad \text{for all } r,d \in R \tag{A.25}$$

$$P_{FW}^{gsc}(d) = P_W^{cge}(d) \quad \text{for all } d \in R \tag{A.26}$$

$$EMP_W^{gsc}(d) = EMP_W^{cge}(d) \quad \text{for all } d \in R \tag{A.27}$$

$$X_W^{gsc}(d) = X_W^{cge}(d) \quad \text{for all } d \in R \tag{A.28}$$

In establishing (A.23) – (A.28) we draw on: the equations of the GSC model set out in subsection A.1; the definitions of Widget sectoral variables in the GSC model given in (A.10) to (A.17); the convergence conditions in (A.18) to (A.22); and CGE equations relating Widget sectoral variables to each other. These CGE equations are:

$$X_W^{cge}(r) = \sum_d A_{ww}^{cge}(r,d) * X_W^{cge}(d) + Y_W^{cge}(r) \quad \text{for all } r \in R \tag{A.29}$$

$$P_W^{cge}(d) = \sum_{r \in R} P_W^{cge}(r) * T_W^{cge}(r,d) * A_{WW}^{cge}(r,d) + ALAB_W^{cge}(d) * W^{cge}(d) \quad \text{for all } d \in R \tag{A.30}$$

$$V_W^{cge}(r,d) = P_W^{cge}(r) * A_{WW}^{cge}(r,d) * X_W^{cge}(d) \quad \text{for all } r,d \in R, \; r \neq d \tag{A.31}$$

$$V_W^{cge}(r,r) = P_W^{cge}(r) * A_{WW}^{cge}(r,r) * X_W^{cge}(r) + P_W^{cge}(r) * Y_W^{cge}(r) \quad \text{for all } r \in R \tag{A.32}$$

$$VT_W^{cge}(r,d) = P_W^{cge}(r) * \left[T_W^{cge}(r,d) - 1 \right] * A_{WW}^{cge}(r,d) * X_W^{cge}(d) \quad \text{for all } r,d \in R \tag{A.33}$$

$$EMP_W^{cge}(r) = ALAB_W^{cge}(r) * X_W^{cge}(r) \quad \text{for all } r \in R \tag{A.34}$$

(A.29) is the CGE condition equating supply of Widgets from region r to demand. This equation reflects the special assumptions in our Widget sector: Widgets from region r can be used as intermediate inputs to Widget production in all regions and in final demand only in region r. (A.30) imposes the CGE condition that the factory-door price of Widgets from region d equals unit costs consisting of the costs of labour and inputs of Widget intermediate products. (A.31) and (A.32) define the factory value of Widget flows from r to d. (A.33) defines the tariff collections on these flows. We assume that there are no transport costs or other margins separating the factory value of the r,d Widget flow from the CIF value. (A.34) computes employment in the CGE Widget industry as the product of output and labour input per unit of output.

Showing that (A.23) to (A.28) hold

The first step in this demonstration is to show that the following sectoral relationships are valid in the GSC model:

$$X_W^{gsc}(r) = \sum_d A_{WW}^{gsc}(r,d) * X_W^{gsc}(d) + Y_W^{gsc}(r) \quad \text{for all } r \in R \tag{A.35}$$

and

$$P_{FW}^{gsc}(d) = \sum_{r \in R} P_{FW}^{gsc}(r) * T_W^{gsc}(r,d) * A_{WW}^{gsc}(r,d) + ALAB_W^{gsc}(d) * W^{gsc}(d) \quad \text{for all } d \in R \tag{A.36}$$

(A.35) and (A.36) require that supply equals demand and prices equal costs for Widget aggregates in the GSC model. Establishing the validity of (A.35) and (A.36) is a check on the aggregation formulas in (A.10) to (A.17).

To prove that (A.35) and (A.36) hold we start by splitting the RHS of (A.10) into intermediate and final demand. Then we use (A.4) to give

$$X_{W}^{gsc}(r)=\frac{\sum_{i\in WCI}P_{iW}^{gsc}(r)*X_{iW}^{gsc}(r)}{P_{FW}^{gsc}(r)}+Y_{W}^{gsc}(r)\quad \text{for all } r\in R \tag{A.37}$$

By substituting from (A.3) we obtain

$$X_{W}^{gsc}(r)=\frac{\sum_{i\in WCI}\sum_{d\in R}\sum_{j\in WA}P_{iW}^{gsc}(r)*A_{ijW}^{gsc}(r,d)*X_{jW}^{gsc}(d)}{P_{FW}^{gsc}(r)}+Y_{W}^{gsc}(r)\quad \text{for all } r\in R \quad , \tag{A.38}$$

and using (A.11) we arrive at (A.35).

To obtain (A.36) we start by substituting (A.9), with arguments d and r interchanged, into (A.10):

$$X_{W}^{gsc}(r)=\frac{\sum_{i\in WC}\sum_{j\in WCI}\sum_{d\in R}P_{jW}^{gsc}(d)*T_{jW}^{gsc}(d,r)*A_{jiW}^{gsc}(d,r)*X_{iW}^{gsc}(r)}{P_{FW}^{gsc}(r)} + \frac{\sum_{i\in WC}\frac{W^{gsc}(r)}{PROD_{iW}^{gsc}(r)}*SCALE_{iW}^{gsc}(r)*X_{iW}^{gsc}(r)}{P_{FW}^{gsc}(r)}\quad \text{for all } r\in R \tag{A.39}$$

Substituting (A.14), (A.15) and (A.16) into (A.17) and interchanging i and j arguments and r and d arguments we obtain

$$T_{W}^{gsc}(d,r)=\frac{\sum_{j\in WCI}\sum_{i\in WA}\left[T_{jW}^{gsc}(d,r)\right]*P_{jW}^{gsc}(d)*A_{jiW}^{gsc}(d,r)*X_{iW}^{gsc}(r)}{\sum_{j\in WCI}\sum_{i\in WA}P_{jW}^{gsc}(d)*A_{jiW}^{gsc}(d,r)*X_{iW}^{gsc}(r)}\quad \text{for all } r,\, d\in R \tag{A.40}$$

Then using (A.40) in (A.39), recalling that WA = WC, we find that

$$X_{W}^{gsc}(r)=\sum_{d}\frac{T_{W}^{gsc}(d,r)}{P_{FW}^{gsc}(r)}*\sum_{i\in WC}\sum_{j\in WCI}P_{jW}^{gsc}(d)*A_{jiW}^{gsc}(d,r)*X_{iW}^{gsc}(r) + \frac{\sum_{i\in WC}\frac{W^{gsc}(r)}{PROD_{iW}^{gsc}(r)}*SCALE_{iW}^{gsc}(r)*X_{iW}^{gsc}(r)}{P_{FW}^{gsc}(r)}\quad \text{for all } r\in R \tag{A.41}$$

Multiplying through by $P_{FW}^{gsc}(r)/X_{W}^{gsc}(r)$ and using (A.11), (A.12) and (A.13) leads to (A.36).

Having established (A.35), we compare it with (A.29). Invoking (A.19) and (A.21) we can conclude that:

$$X_{W}^{gsc}(r)=X_{W}^{cge}(r)\quad \text{for all } r\in R\, , \tag{A.42}$$

establishing (A.28).

Having established (A.36), we compare it with (A30). Invoking (A.18) and (A.20) to (A.22) we can conclude that:

$$P_{FW}^{gsc}(r)=P_{W}^{cge}(r)\quad \text{for all } r\in R \quad . \tag{A.43}$$

establishing (A.26).

Now we consider the values of Widget flows in the GSC and CGE models.

From (A.11) and (A.14):

$$V_W^{gsc}(r,d) = P_{FW}^{gsc}(r) * A_{WW}^{gsc}(r,d) * X_W^{gsc}(d) \quad \text{for all } r,d \in R,\ r \neq d \quad . \tag{A.44}$$

Comparing (A.44) with (A.31) and invoking (A.21), (A.42) and (A.43) we see that

$$V_W^{gsc}(r,d) = V_W^{cge}(r,d) \quad \text{for all } r,d \in R,\ r \neq d\,, \tag{A.45}$$

establishing (A.23).

From (A.11) and (A.15):

$$V_W^{gsc}(r,r) = P_{FW}^{gsc}(r) * A_{WW}^{gsc}(r,r) * X_W^{gsc}(r) + P_{FW}^{gsc}(r) * Y_W^{gsc}(r) \quad \text{for all } r \in R \quad . \tag{A.46}$$

Comparing (A.46) with (A.32) and invoking (A.19), (A.21), (A.42) and (A.43) we see that

$$V_W^{gsc}(r,r) = V_W^{cge}(r,r) \quad \text{for all } r \in R \quad , \tag{A.47}$$

establishing (A.24).

Next we consider the values of tariff collections.

From (A.11), (A.40) and (A.16):

$$VT_W^{gsc}(r,d) = P_{FW}^{gsc}(r) * \left[T_W^{gsc}(r,d) - 1 \right] * A_{WW}^{gsc}(r,d) * X_W^{gsc}(d) \quad \text{for all } r,d \in R \tag{A.48}$$

Comparing (A.48) with (A.33) and invoking (A.20), (A.21), (A.42) and (A.43) see that

$$VT_W^{gsc}(r,d) = VT_W^{cge}(r,d) \;, \tag{A49}$$

establishing (A.25).

Finally, we consider Widget employment in the two models. Comparing (A.13) and (A.34) and invoking (A.22) and (A.42) we see that

$$EMP_W^{gsc}(r) = EMP_W^{cge}(r) \quad \text{for all } r \in R\,, \tag{A50}$$

establishing (A.27).

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