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Mainstream economic wisdom favoring cooperative free trade is challenged by a wave of disruptive trade policies. In this paper, we provide quantitative evidence concerning the economic impacts of tariffs implemented by the United States in 2018 and the subsequent retaliations by partner countries. Our analysis builds on a multi-region multi-sector general-equilibrium simulation model of the global economy that includes an innovative monopolistic-competition structure of bilateral representative firms.

JEL codes: C68, F12, F17

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1. Introduction

Academic arguments in favor of cooperative free trade are challenged by a wave of protectionist measures. The literature typically attributes trade barriers to special-interest politics, yet this seems off the mark. At the level of the electorate the economic pain inflicted by the Smoot-Hawley Tariff Act of 1930[1] has been forgotten. A majority feels wronged by global integration and believes it is time for a test of the conventional wisdom. Regardless of the political motivation, a new trade war is in progress, and most observers are worried about economic consequences. In our view, an empirically grounded assessment is warranted.

In this paper we use a suite of computational models of global trade to quantify the impacts of the trade war between the US and its main trading partners. We

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[1] The Smoot-Hawley Tariff Act of 1930 raised US tariffs on over 20,000 imported goods to a record level followed by retaliatory tariffs of America's trading partners. There is the consensus view among economists and economic historians that "The passage of the Smoot-Hawley Tariff exacerbated the Great Depression" (Whaples, 1995) and thus worked counter the initial objective to strengthen the US economy.

offer general-equilibrium results under three alternative structural assumptions about international trade that include a traditional perfect competition model and two variations of monopolistic competition. Relative to perfect competition, adverse variety impacts under monopolistic competition are shown to be a substantial contributor to welfare losses. We proceed in the paper to report additional structural sensitivities through a diagnostic decomposition of the sectoral and welfare impacts beginning with a simple partial-equilibrium calculation. Our approach facilitates an intuitive and transparent explanation of the sources of the impacts from a complex trade model.

In our simulation analysis we find that announced US and retaliatory tariffs (as of 2018) are costly for both the US and the Chinese economies, but convey economic benefits for other regions (especially Europe) through trade diversion. These results are driven by the fact that beyond the US and China the distortions from additional trade barriers are small relative to aggregate trade. In our central case simulation with monopolistic competition and free entry and exit of firms, the welfare cost of the trade war for the US amounts to $124 billion (1% of private consumption).[2] The implications at the level of US industries are more accentuated and include losers and winners. Steel and some manufacturing industries gain while the agriculture, motor vehicle, and services sectors lose. Income for most US primary factors of production fall by about 1%, rents on sector-specific factors in certain monopolistically-competitive sectors increase by 7%. Income from land (as a primary input to agriculture) is reduced by over 5%.

A 1% decline in welfare may seem unimpressive. It is important to acknowledge that tariffs are, in fact, a relatively efficient instrument as compared with various non-tariff barriers. With the current tariff rates the rents from the distortions are retained in the form of tariff revenues (on the order of $33 billion for the US). Non-tariff distortions, like the steel voluntary export restraints (VERs) agreed to by South Korea as a part of the steel and aluminum dispute, are significantly more costly to the US than a tariff equivalent, because with the VERs the US does not capture the rents. We can see that the welfare impact of $124 billion would increase if the $33 billion in tariff revenue was lost to the US economy.

To assess the quantitative significance of the actual trade war, Figures 1 and 2 report the US and Chinese reference trade flows and initial tariff rates, as well as the first-order impact of the trade war as indicated by the new tariffs and GTAP[3]

[2] We measure welfare as Hicksian equivalent variation in money-metric utility.

[3] In this paper we rely on economic statistics from the Global Trade Analysis Project (GTAP). GTAP is a research consortium initiated in 1992 to provide the trade policy analysis community with a global economic dataset for use in the quantitative analysis of international economic issues. The GTAP project was founded by Thomas Hertel at Purdue University (see notably Hertel, 1997). The Center's staff of economists is responsible for the regular updates of the database (see e.g. Angel Aguiar and McDougall, 2016). Software development within the GTAP project has been assisted greatly by researchers from

trade elasticities.[4] We focus on the US and China because their tariff escalations are substantial and quantitatively dominate tariffs changes related to the steel and aluminum dispute. We consider the full escalation of tariffs in 2018, including those tariffs slated to be imposed on January 1, 2019. Each of the 57 commodities in the GTAP data underlying our quantitative analysis are represented in the figures for the most recent GTAP base year, 2014. The three-letter identifiers are mapped to descriptions in Table 2 in section 4, which offers a complete taxonomy of the GTAP database. The purpose here is to provide a quantitative primer for our more elaborate general-equilibrium analysis and to highlight the importance of those sectors that are heavily impacted by the new tariffs. In the benchmark GTAP data for 2014 the US imports $157 billion worth of electronic equipment from China at an initial tariff rate of just under 2%. This is represented in Figure 1 by the black square in the lower right corner of the figure. The 2018 US tariff rates on these imports escalates to over 10%. Under the GTAP trade elasticities this translates to a first-order partial-equilibrium reduction in electronic equipment (`eeq`) trade to $98 billion, which is indicated by the red circle in the figure connected to the benchmark point.Other US imports from China that have substantial benchmark trade include machinery and equipment (`ome`), manufactures (`omf`), wearing apparel (`wap`), chemical, rubber, and plastic products (`crp`), and leather products (`lea`). Of these, the relatively high elasticity combined with tariffs that escalate to 25% on machinery and equipment (`ome`) indicate a reduction in trade from nearly $80 billion to about $12 billion.

In Figure 2 we consider trade in the other direction. There are substantially lower trade volumes and higher benchmark tariffs on trade from the US to China than there are on trade from China to the US. The motor vehicles and parts (`mvh`) exports from the US to China are an exception with benchmark tariffs of over 20%. These tariffs escalate under the 2018 tariff retaliations to 55%. Important commodities among other exports from the US to China include electronic equipment (`eeq`), transport equipment (`otn`), chemical, rubber, plastic products (`crp`), oil seeds (`osd`); and machinery and equipment (`ome`). The partial-equilibrium illustrations in Figures 1 and 2 are useful for first-round insights into how scheduled tariff changes translate into economic impacts driven by the magnitude of the tariff change, the base year trade flows and estimated trade elasticities. We proceed in this analysis to refine these estimates on the basis of a more comprehensive general-equilibrium model.

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[4] The calculations for Figures 1 and 2 are based on a Marshallian partial-equilibrium model formulated as a linear complementarity problem and calibrated to the GTAP 10 trade elasticities and benchmark transactions for 2014. The results shown here are virtually identical to those which arise from an isoelastic model calibrated to the same elasticities and value shares, but the results differ from the three general-equilibrium models we subsequently investigate.

Figure 1. US imports from China: benchmark trade, tariffs, and implied partial-equilibrium responses

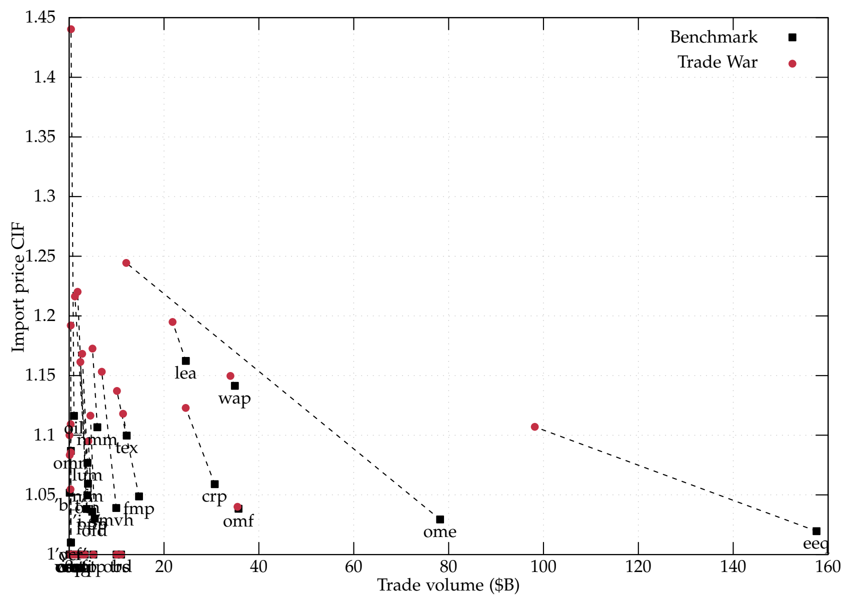
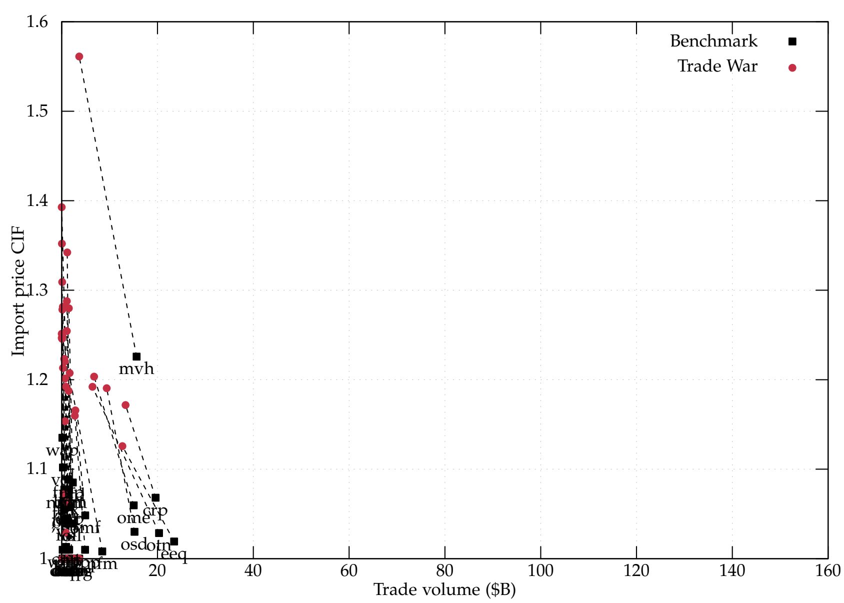


Figure 2. Chinese imports from the US: benchmark trade, tariffs, and implied partial-equilibrium responses



The remainder of this paper is organized as follows. In section 2 we provide a brief literature review on the evolution of theory-based quantitative analysis of trade policy which motivates the choice and design of our modeling framework. In section 3 we offer a non-technical description of our modeling framework.[5] In section 4 we lay out the key empirical data sources underlying our quantitative simulation analysis. In section 5 we outline the disruptive policies triggered by the US. In section 6 we present our quantitative assessment of the trade disruptions. In section 7 we conclude.

2. Literature review

There are gains from international trade. Few things are more agreed upon by economists. From the original statement of comparative advantage (Ricardo, 1817) to the formal neoclassical general equilibrium (Samuelson, 1939, 1962; Kemp, 1962) to advanced models of industrial organization (Melitz, 2003) the intuition is clear and compelling. Equally clear, however, is the fact that the gains will not be distributed equally among countries that engage in trade (Ray, 1977), and the fact that some agents may lose from trade even if their country gains on average (Stolper and Samuelson, 1941). Furthermore, we know that the distribution of the gains can be manipulated by countries acting strategically (Johnson, 1953), or through the rent-seeking activities of special interest groups (Grossman and Helpman, 1994).

With a broad consensus on the potential benefits from international trade, the global community established a set of institutions, most notably the World Trade Organization (WTO) as governed by the General Agreement on Tariffs and Trade (GATT), to provide guidance towards a cooperative global trading system (Bagwell and Staiger, 1999).[6] The primary goal of the WTO is to promote free trade through a set of multilateral rules and dispute settlement procedures. These discouraged countries from implementing trade distortions motivated either by strategic *beggar-thy-neighbor* incentives or by their interest in placating rent-seeking special-interest groups. Bagwell and Staiger (1999) argue that the GATT's reciprocity and nondiscrimination rules assisted governments in their implementation of globally sound trade policy when they faced politically powerful constituents interested in distorting trade to capture rents.[7]

[5] The technical (algebraic) description is provided in Appendices B and C.

[6] The WTO started operations on January 1, 1995 as the successor to the General Agreement on Tariffs and Trade (GATT), which was created in 1947 in liberalizing world trade.

[7] The WTO has six key objectives: (1) to set and enforce rules for international trade, (2) to provide a forum for negotiating and monitoring further trade liberalization, (3) to resolve trade disputes, (4) to increase the transparency of decision-making processes, (5) to cooperate with other major international economic institutions involved in global economic management, and (6) to help developing countries benefit fully from the global trading system.

More recently, however, the global trading system seems to be entering a new order of disruptive unilateral policies. As the prime protagonist of protectionism, the United States is currently pursuing trade policies that put little weight on global efficiency and overall gains from trade. The US president has argued that "the WTO has treated [the US] very badly." and has expressed contempt for the WTO's principles and procedures. The US administration has implemented significant tariffs in 2018 and its trade partners have quickly retaliated with tariffs on US goods. The WTO's ruling on the legitimacy of the US tariffs and its partner responses will arrive late and might not effectively hinder the escalation towards a trade war.

Against this background, a quantitative economic impact assessment on what is at stake with disruptive trade policies is indispensable for informing the policy debate.

The international trade structure that dominated computational (applied) trade policy analysis in the past is based on the Armington (1969) assumption of differentiated regional goods within a constant-returns-to-scale (CRTS) perfect competition setting. The proposition to differentiate products by country of origin has several empirical advantages, but it has been criticised for its inconsistency with micro-level observations and questionable counterfactual implications. The Armington assumption provides a tractable solution to various problems associated with the standard neoclassical (Heckscher-Ohlin) perspective of trade in homogeneous goods (Whalley, 1985): (i) it accommodates the empirical observation that a country imports and exports the same good (so-called cross-hauling); (ii) it avoids over-specialisation implicit to trade in homogeneous goods; and (iii) it is consistent with trade in geographically differentiated products. While the Armington assumption provides a convenient lens to view trade data, it may introduce terms-of-trade effects which dominate the welfare results of policy changes. Even in the absence of market power by individual firms, the Armington assumption of product heterogeneity provides implicit market power in a perfectly competitive market conduct which is the higher the larger are the trade flows and the smaller are the demand elasticities for the traded goods by trading partners (de Melo and Robinson, 1989).

Balistreri and Rutherford (2013) discuss the inherent tensions between standard Armington (CRTS) models and more advanced computational approaches incorporating modern trade theory based on firm-level product differentiation and imperfect competition (Krugman, 1980; Melitz, 2003). Krugman (1979, 1980) uses firm-level product differentiation in a monopolistic-competition framework to illustrate that there are gains from trade even in the absence of comparative advantage. The Krugman (1980) model illustrates that additional varieties are a key source of the gains from trade under a standard constant-elasticity-of-substitution demand system. Ethier (1982) further expands the notion of variety gains to intermediate inputs, where new varieties available through trade increase the productivity of domestic firms. FDI and the theory of multinationals are an additional source of gains, especially in producer services that are not easily traded (Markusen, 1989, 2002; Markusen and Venables, 1998; Ethier and Markusen, 1996). Markusen, Rutherford, and Tarr (2005) show that introducing foreign direct investment in services with endogenous variety effects and specialized *home-office* inputs substantially increase the gains.[8]

The theory of international trade moved forward again with Melitz (2003), who introduced the competitive selections of heterogeneous firms in a monopolistic competition model with fixed cost associated with supplying external markets. In the Melitz model trade induces a reallocation of within-industry resources away from low-productivity firms toward high-productivity firms. There is compelling empirical support for both the basic structure of heterogeneous firms (Bartelsman and Doms, 2000; Bernard and Jensen, 1999) and the endogenous reallocation toward more productive firms (Aw, Chen, and Roberts, 2001; Trefler, 2004). A key feature of the Melitz (2003) model is that there will be a unique number of varieties on each bilateral link, because trade policy affects selection. This is in contrast to models based on Krugman (1980) where once a variety is produced (a firm enters the market) that variety is consumed in every market.

Most of the conventional computational studies adopting the Armington-CRTS framework (i.e. ignoring innovations of monopolistic competition and FDI) focused on changes in rent generating tariffs triggered by trade policy reforms. The studies often reported seemingly small welfare gains associated with trade liberalization, generally in the range of less than one percent. There is reason to suspect that the early studies understated the gains from trade. It is recognized that Armington models imply high optimal tariffs (Brown, 1987). Balistreri and Markusen (2009) argue that the Armington structure misallocates market power over varieties away from firms and toward the discretion of the policy authority. The monopolistic competition structure properly allocates market power over varieties to firms and thus results in lower optimal tariffs. Another source of potential bias in trade modeling is the fact that many trade distortions do not generate tariff revenues for the importing country. An important example are the current voluntary export restraints (VERs) that South Korea is imposing to avoid the recent US steel and aluminum tariffs.[9] In general, non-tariff barriers to trade are impor-

[8] Foreign direct investment in our model is characterized by a technology incorporating both home-office and subsidiary inputs—knowledge capital inputs are produced in the exporting country and customer-facing services are employed at the point of provision. These technologies are further characterized by external scale economies—more firms imply increased efficiency. These mechanisms play an important role in sectors such as business and financial services (Markusen, Rutherford, and Tarr, 2005).

[9] Allowing a trade partner to collect the rents associated with a trade distortion, through a VER, is a good way to avoid retaliation; but it is also a good way to *lose* a trade war. Optimal tariffs rely on a collection of the tariff revenues!

tant and substantially increase the welfare impacts. For example, de Melo and Tarr (1990) and Jensen and Tarr (2003) use standard perfect competition models to show substantial gains from trade liberalization when the rents associated with the distortion are surrendered.[10]

With the rise of the new trade theories, there is also a growing number of computational studies that include imperfect competition. Harris (1984) considers the gains associated with behavioral responses by oligopolistic firms engaged in international trade. Adopting an oligopolistic model setting Harrison, Rutherford, and Tarr (1997) report small gains associated with increased firm size (reduced average cost). Rutherford and Tarr (2002) use an endogenous-growth model with variety gains to show that the welfare impacts can be many times larger than in a standard constant-returns perfect competition model. Markusen, Rutherford, and Tarr (2005) and Rutherford and Tarr (2008) introduce FDI in services with variety effects which generates substantially larger welfare impacts.

More recently, the Melitz (2003) theory has inspired a new generation of computational approaches to quantitative trade policy analysis. Zhai (2008) introduces the first calibrated computational model that includes competitive selection of heterogeneous firms. This model is extended and applied in an analysis of the Trans-Pacific Partnership by Petri, Plummer, and Zhai (2012). The model, while including selection, does not include endogenous entry so the mass of potential firms is held fixed. Balistreri, Hillberry, and Rutherford (2011) implement a model with the full Melitz theory applied to the manufacturing sector. They find that, relative to an otherwise equivalent Armington model, the Melitz model generates welfare impacts that are on average four times larger. Balistreri and Rutherford (2013) provide a more comprehensive guide to applying monopolistic competition theories, including the Melitz structure, in computational models that are calibrated to data.[11]

Costinot and Rodríguez-Clare (2014) quantify the welfare impacts of globalization in a large-scale computational model that extends the simple gravity-based welfare calculations put forward by Arkolakis, Costinot, and Rodríguez-Clare (2012). In a similar computational setting Caliendo et al. (2015) consider the welfare impacts of tariff liberalization over the period from 1990 to 2010.

[10] Regulations which increase trade costs without retaining rents produce "efficiency cost rectangles" and are more likely to lower welfare of both parties. Regulations such as VERs (and tariffs) which increase trade costs while transferring rents to one or the other party may improve outcomes for one country at the expense of the other.

[11] Although not directly related to trade policy, we have applied the Melitz structure in analyses of climate policy, carbon leakage, and carbon-content tariffs (Balistreri, Böhringer, and Rutherford, 2018; Balistreri and Rutherford, 2012).

3. Modeling framework

In the interest of revealing the inherent structural sensitivity of quantitative trade policy analysis we develop a flexible modeling framework which encompasses three alternative representations of international trade denoted:

- **Armington** (1969) is based on perfectly competitive markets and constant returns to scale.
- **Krugman** (1979, 1980) is based on imperfect competition in which changes in the number of firms (varieties) influence aggregate productivity. An important (simplifying) assumption of the Krugman trade specification is that all varieties are sold in all regions.
- **Bilateral Representative Firms (BRF)** emphasizes the extensive margin of trade. Like Krugman, BRF incorporates a Dixit-Stiglitz variety effect, but unlike Krugman, not all varieties from a region are sold in every region.

Apart from the differences in trade specification which are laid out in more detail below, the model variants share an identical core logic of standard multi-region multi-sector computable general equilibrium models. Decisions about the allocation of resources are decentralized, and the representation of behavior by consumers and firms in the model follows the canonical microeconomic optimization framework: (i) consumers maximize welfare through private consumption subject to a budget constraint; (ii) producers combine intermediate inputs, and primary factors (several categories of labor, land, resources, and physical capital) at least cost subject to technological constraints. By default, labor and capital are treated mobile across sectors within a region while specific resources are tied to sectors in each region. Preferences and technological constraints are described through nested constant-elasticity-of-substitution (CES) functions that capture demand and supply responses to changes in relative prices. Government demand, investment demand, and the balance of payment surplus are fixed at the base year level.

For the sake of brevity, the algebraic description of the canonical model structure with details on the model variables and equations is relegated to Appendices B and C.

3.1 Armington

The perfectly competitive Armington variant incorporates regionally differentiated goods and is immediately appealing from an empirical perspective. Any observed pattern of bilateral trade flows can be replicated, and the benchmark trade pattern goes along with any choice of empirical cross-price elasticities of substitution. The Armington model variant captures gains from specialization and inter-industry trade due to differences in comparative advantage emerging from differences in technologies and factor endowments. The trade literature refers to these effects as perfect competition static allocation effects induced by trade reforms which show up as changes in the trade volume (trade creation and trade diversion) due to changes in trade barriers. The multi-region structure of the core model endogenizes international prices and thus can track policy-induced terms-of-trade effects which may dominate the impacts of trade creation and trade diversion.

The Armington composite is typically represented by a constant-returns CES technology, i.e.:[12]

$$Y_s = \left(\sum_r \lambda_{rs} x_{rs}^{\rho} \right)^{1/\rho}$$

In this functional form we have one free parameter, λ_{rs}, for each bilateral trade flow of the associated commodity from region r to region s, and given benchmark prices $\overline{p}_{rs}$ we can assign values λ_{rs} such that

$$\min \sum_r \overline{p}_{rs} x_{rs} \quad \text{s.t.} \quad Y_s = 1$$

has the solution $x_{rs} = \overline{x}_{rs}$, where $\overline{x}_{rs}$ represents base-year trade flows for the Armington composite in a cost-minimizing manner.

3.2 Krugman

The CRTS Armington model does not capture imperfect competition static allocation effects (likewise referred to as pro-competitive effects from trade liberalization) which play a prominent role in the new trade theory established by Krugman (1979, 1980). The assumptions of internal scale economies, monopolistic competition and product varieties can be used to explain intra-industry trade as an empirical trade pattern between industrialized countries. Specialization within industries implies a decrease in unit cost of production and a gain in scale economies. Thus, specialization and trade pay off even in the absence of differences in technologies or factor endowments. Trade furthermore increases varieties as input to industries (leading to productivity gains) and input to consumption (directly increasing welfare due to the increased availability of foreign varieties based on a love-of-variety assumption).

In our Krugman increasing-returns-to-scale (IRTS) imperfect competition variant goods are differentiated by firm, and net supply of the composite commodity reflecting both the number of firms (variety) and output per firm:

$$Y_r = \left(\sum_{j=1}^{N_r} x_{jr}^{1-1/\sigma} \right)^{\sigma/(\sigma-1)} = N_r^{1/\sigma} X_r$$

[12] For notational simplicity we suppress the commodity index i in this expression as well as in subsequent descriptions of the Krugman and BRF models.

where

σ	is the elasticity of substitution between varieties
N_r	is the number of firms operating in region r,
x_{jr}	is output of the jth firm and
x_r	is output of a representative firm ($x_{jr} = x_r \quad \forall j$), and
X_r	is the resource cost of output:

$$X_r = N_r x_r$$

Note that in the Krugman model firms enter or exit based on global demand for their product, and once a firm enters any market its variety is consumed in every market.

3.3 Bilateral Representative Firms (BRF)

Our third structural model variant assumes a single firm type on each bilateral trade link (and each potential FDI opportunity). This extends the standard Krugman structure to allow for independent entry (and variety impacts on each bilateral market). The BRF variant captures firm-level productivity effects and mimics the bilateral selection margin key to trade responses under the Melitz structure while avoiding the complexity associated with linking selected export firms to the pool of entered domestic firms with heterogeneous technologies.

Like the Krugman model, goods in the BRF model are differentiated by region of origin, but not all goods from region r are sold in all regions s. In the BRF framework the variety-adjusted supply of goods is given by:

$$Y_{rs} = \left(\sum_{j=1}^{N_{rs}} x_{jrs}^{1-1/\sigma} \right)^{\sigma/(\sigma-1)} = N_{rs}^{1/\sigma} X_{rs}$$

where

σ	is the elasticity of substitution between varieties
N_{rs}	is the number of firms from region r supplying region s,
x_{jrs}	is output of the jth firm from region r supplying region s,
x_{rs}	is output of a representative firm ($x_{jrs} = x_{rs} \quad \forall j$), and
X_{rs}	is the resource cost of goods supplied from region r in region s:

$$X_{rs} = N_{rs} x_{rs}$$

A logical shortcoming of the standard Krugman framework is that a small country has a negligible impact on the entry of firms associated with its imports, and therefore small countries fail to experience love-of-variety gains associated with unilateral liberalization. Rutherford and Tarr (2008) address this logical problem in an open-economy Krugman model application by adopting what is

Table 1. Regions and primary factors used in the application

GTAPINGAMS Identifier	Definition	GTAPINGAMS Identifier	Definition
EUR	EU-27 plus	LAB	Unskilled labor
USA	U.S.A	TEC	Technicians and Professionals
CHN	China		
CAN	Canada	CLK	Clerks
MEX	Mexico	MGR	Managers and Officials
MRC	Mercosur		
KOR	S. Korea	SRV	Service workers
OEC	Rest of OECD		
ROW	Rest of World	CAP	Capital
		LND	Land
		RES	Resource

essentially the BRF structure. Our present analysis is the first application of the BRF structure in a multi-region framework.

4. Data

Beyond structural assumptions on causal relationships (i.e., model logic) a quantitative impact assessment of policy interventions calls for empirical data. To simulate the impacts of new tariffs introduced by trade wars we need globally-consistent data that characterize technologies and preferences at the country level as well as a set of price response parameters (elasticities). Our primary data source is a pre-release of GTAP version 10. These data are aggregated and organized using the GTAPINGAMS software (Lanz and Rutherford, 2016).[13] GTAP 10 features detailed national accounts on production and consumption (input-output tables) together with bilateral trade flows, initial tariff rates and export taxes for the base-year 2014 across 57 commodities and 120 countries as well as 20 composite regions.[14] The database furthermore provides empirically estimated elasticities that determine the responses of agents to policy-induced price changes.

Our analysis utilizes recent versions of the General Algebraic Modeling System (GAMS Development Corporation, 2013) and the PATH solver (Dirkse and Ferris, 1995) which permits high-dimensional resolution. We maintain the full GTAP disaggregation of commodities to capture the effects of trade policy that may vary with initial input cost shares, the ease of input substitution (as reflected by sector-specific cross-price elasticities) and sector-specific regulations, e.g. with respect to tariff rates or non-tariff barriers.

[13] The documentation of GTAP 10 is forthcoming, but the full documentation of GTAP 9 is available (Angel Aguiar and McDougall, 2016).
[14] The composite regions in the GTAP database represent 114 different countries aggregated on a regional basis, e.g. Rest of Eastern Africa (XEC) and Rest of Western Asia (XWS).

Table 2. Commodities and Industries in the GTAP 10 database

GTAPINGAMS Identifier	Definition	GTAPINGAMS Identifier	Definition
pdr	Paddy rice	**lum**	Wood products
wht	Wheat	**ppp**	Paper products, publishing
gro	Cereal grains nec	**oil**	Petroleum, coal products
v_f	Vegetables, fruit, nuts	**crp**	Chemical, rubber and plastic products
osd	Oil seeds	**nmm**	Mineral products nec
c_b	Sugar cane, sugar beet	**i_s**	Ferrous metals
pfb	Plant-based fibers	**nfm**	Metals nec
ocr	Crops nec	**fmp**	Metal products
ctl	Cattle,sheep,goats,horses	**mvh**	Motor vehicles and parts
oap	Animal products nec	**otn**	Transport equipment nec
rmk	Raw milk	**eeq**	Electronic equipment
wol	Wool, silk-worm cocoons	**ome**	Machinery and equipment nec
frs	Forestry	**omf**	Manufactures nec
fsh	Fishing	ele	Electricity
col	Coal	gdt	Gas manufacture, distribution
cru	Crude oil	wtr	Water
gas	Natural gas	cns	Construction
omn	Minerals nec	trd	Trade
cmt	Meat: cattle, sheep, goats, horse	otp	Transport nec
omt	Meat products nec	wtp	Sea transport
vol	Vegetable oils and fats	atp	Air transport
mil	Dairy products	**cmn**	Communication
pcr	Processed rice	**ofi**	Financial services nec
sgr	Sugar	**isr**	Insurance
ofd	Food products nec	**obs**	Business services nec
b_t	Beverages and tobacco products	ros	Recreation and other services
tex	Textiles	osg	Public administration, defense, health, education
wap	Wearing apparel	dwe	Dwellings
lea	Leather products		

Notes: Monopolistically competitive sectors appear in **bold** face. "nec" indicates not elsewhere classified.

For our simulations of contemporary disruptive trade policies, we focus on key regions of interest and therefore aggregate to the nine regions listed in Table 1. Table 1 also lists the primary factors of production. The full set of GTAP commodities is listed in Table 2. Those sectors that are potentially treated as monopolistically competitive, under the Krugman and BRF structures, appear in bold face. These include processing, manufacturing, and business services sectors. Business services sectors, indicated with an underline, are modeled to include foreign direct investment.

5. Policy scenario

As of November 2018 the trade war between the US and most of its trade partners (although significantly biased toward China) has escalated quickly to the point of substantial disruptions to the world trading system. The rapid escalation of the trade war is both surprising and haphazard. Our analysis finds that the tariffs which have been announced are at levels in excess of their optimum.

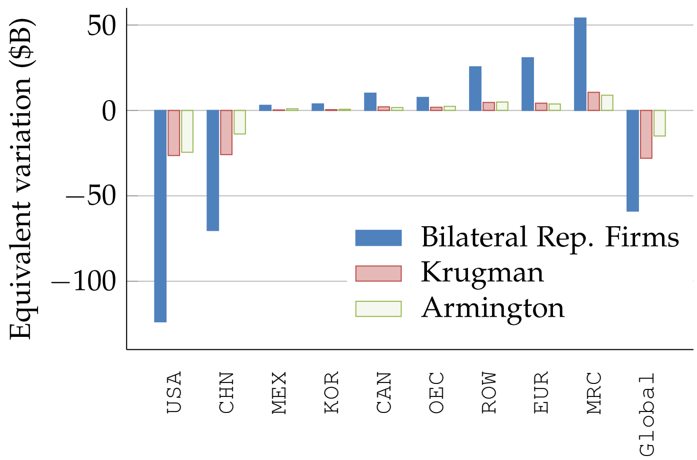
A rough description of the progression of the 2018 trade war follows.[15] The trade war began with the US imposing tariffs on steel and aluminum imports. Major producers facing these tariffs retaliated. Exempted from the steel and aluminum tariffs are Australia, South Korea, Argentina, and Brazil. These countries negotiated and received exemptions based primarily on their willingness to impose Voluntary Export Restraints (VERs) in the form of quotas. The next escalation was prompted by the US's announcement of 25% tariffs on $50 billion worth of imports from China over two rounds. China responded to each round with its own tariffs covering $50 billion of US exports to China. At the end of September 2018 the US announced and imposed tariffs on an additional $200 billion worth of imports from China, with initially lower tariff rates that escalate to their full value as of January 2019. China has retaliated with tariffs covering an additional $60 billion of imports from the US.

We use data consistent with the GTAP sectoral structure and regions on the tariffs and other distortions related to the 2018 trade war (updated to include the most recent escalations).[16] Our central scenario includes the escalated tariff rates as proposed for January 1, 2018. For those countries that negotiated an exemption from the steel tariffs (Brazil and Argentina, and South Korea) we apply a Voluntary Export Restraint (VER) equal to 15% ad valorem of the respective bilateral trade flows. This gives us a rough approximation of the VER impacts. The important issue here is that the rents associated with the VER accrue to the export region not the US. Brazil and Argentina are a part of our composite Mercosur region. Given the relatively small value of steel imports from Mercosur we simply apply the VER to the whole Mercosur region. We perform ex-ante counterfactual comparisons, of the 2018 trade war against the established benchmark equilibrium consistent with the 2014 GTAP accounts.

[15] For details, see the Crowell & Moring LLP web page, https://www.cmtradelaw.com/.

[16] The tariff data are available at https://www.card.iastate.edu/china/trade-war-data/. See Li (2018).

Figure 3. Welfare impacts



6. Results

Our modeling framework permits us to investigate the outcome of policy shocks for three alternative structural assumptions which figure prominently in applied trade analysis. For our central case we rely on the BRF model variant which combines theoretical innovations in the area of firm-level product differentiation with imperfect competition and endogenous FDI.

Table 3 reports the welfare impacts on private households (measured as equivalent variation) across the three model structures. The largest impacts are under our central model structure, the bilateral representative firms structure. Figure 3 provides a graphical exposition. Across regions damages from the trade war are concentrated on the US and China as we might expect. The steel and aluminum tariffs affect a relatively small share of global trade, whereas the tariffs between the US and China represent significant distortions on those links. Our central case simulation suggests that the trade war costs the US on the order of $123.4 billion annually. While this is a sizeable cost in dollars its share of aggregate US consumption (1.0%) is not large. Spread evenly across the 126 million households the annual welfare cost is still on the order of about $1,000 per household. The cost are not spread evenly, however, and so it is useful to consider some of the detailed results generated by the model. We primarily focus on our central model structure of bilateral representative firms (BRF).

Table 3. Welfare impacts across model structures

	Benchmark GDP ($B)	Benchmark Consumption ($B)	Equivalent Variation ($B)			Equivalent Variation (%)		
			BRF	Krugman	Armington	BRF	Krugman	Armington
EUR EU-27 plus	19,118	11,105	54.1	10.6	8.9	0.49	0.10	0.08
USA U.S.A	17,360	12,122	-123.7	-26.4	-24.5	-1.02	-0.22	-0.20
ROW Rest of World	15,254	8,743	30.9	4.2	3.8	0.35	0.05	0.04
CHN China	10,653	4,100	-70.3	-25.9	-13.8	-1.71	-0.63	-0.34
OEC Rest of OECD	8,316	4,944	25.6	4.7	4.9	0.52	0.09	0.10
MRC Mercosur	3,052	1,915	7.6	1.8	2.4	0.40	0.10	0.12
CAN Canada	1,783	1,043	3.0	0.3	1.0	0.29	0.03	0.09
KOR S. Korea	1,411	716	10.1	2.1	1.7	1.41	0.30	0.24
MEX Mexico	1,298	884	3.8	0.5	0.7	0.43	0.05	0.08

Figure 4 reports the gross output changes for US sectors across the model structures. Figures 5 and 6 focus in on the ten sectors with the largest percentage losses and the ten sectors with the larges percentage gains. In the lower panel of Figures 5 and 6 we also report the losses and gains in dollars to give an indication of their importance in the broader economy.[17] The general pattern is that the bilateral representative firms model generates larger output responses, while the Krugman and Armington models generate similar output changes. There are a couple of exceptions, however. In particular, the Krugman and Armington models indicate larger output responses in a couple of agricultural sectors: the oil seed (primarily soybeans) and plant based fiber (primarily cotton) sectors. It is clear that the Chinese retaliatory tariffs have a heavy impact on specific export dependent US agriculture sectors. Real revenue from oil seed production is off by between $4.8B (12.7%) and $5.5B (14.6%) across the model structures.

In Figure 6 we isolate the ten sectors with the greatest percentage increases in gross output. We show expansion in import competing industries like ferrous metals (iron and steel) as well as machinery and equipment. There are some agriculture sectors that expand, e.g., wheat and rice, as factors used intensively in agriculture move out of crops exported to China. The sector with the largest percentage increase in output, wool and silk-worm cocoons, is a small sector in terms of overall US production and therefore the value of the output increase is relatively unimportant. The most important sectors, in terms of value, are again machinery and equipment and ferrous metals. Output for the machinery and equipment sector expands by between $32.2B (2.8%) and $11.5B (1.0%). In this case the difference between the market structures is critical. Under the bilateral representative firms model the output expansion is more than two times larger in this important increasing returns sector.

Another useful decomposition of the impacts involves considering the expenditure and income components of GDP. Table 4 provides the decomposition. In each record the value component is divided by the true-cost-of-living index (as established by the representative agent's unit expenditure function). Each record is thus measured in household consumption units, and the reported change in consumption expenditure represents the equivalent variation in private consumption (welfare). It is important to note that the changes in the other expenditure accounts (investment (I), government (G), and exports less imports ($X - M$)) represent price changes, because the model is closed by holding these expenditures fixed (in their own prices). That is a -0.4% change in government expenditures reflects a -0.4% change in the price of the government Leontief expenditure bundle relative to the price index associated with consumption (the true-cost-of-living in-

[17] Our measure of gross output in this case is calculated as the change in the sectoral revenue divided by the true-cost-of-living index for the US household. Thus, these reports are real revenue changes evaluated in household consumption units.

Figure 4. US sectoral impacts across models

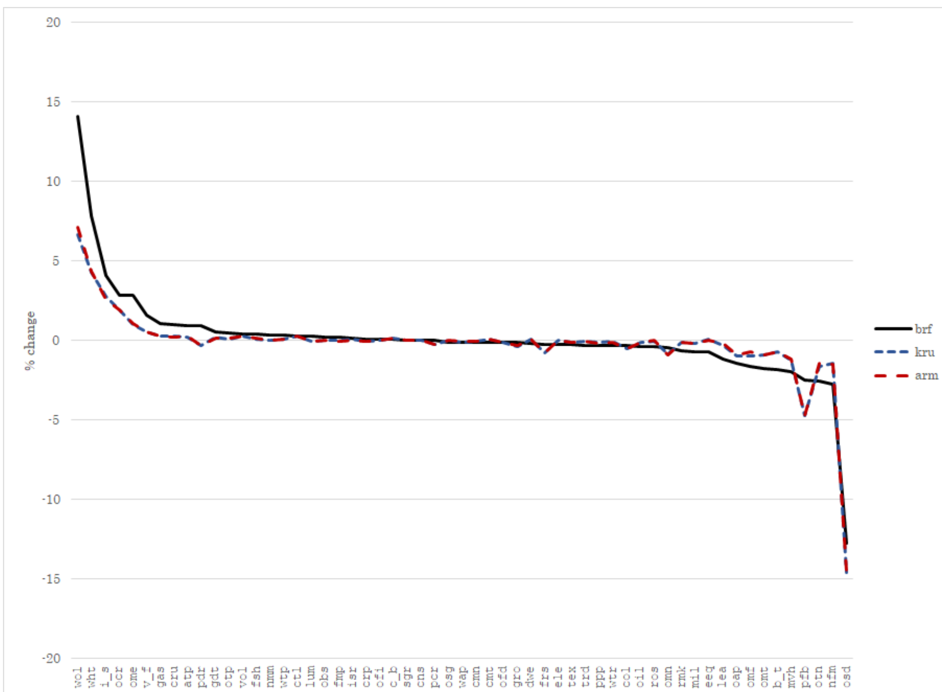


Figure 5. US Sectoral impacts: losers

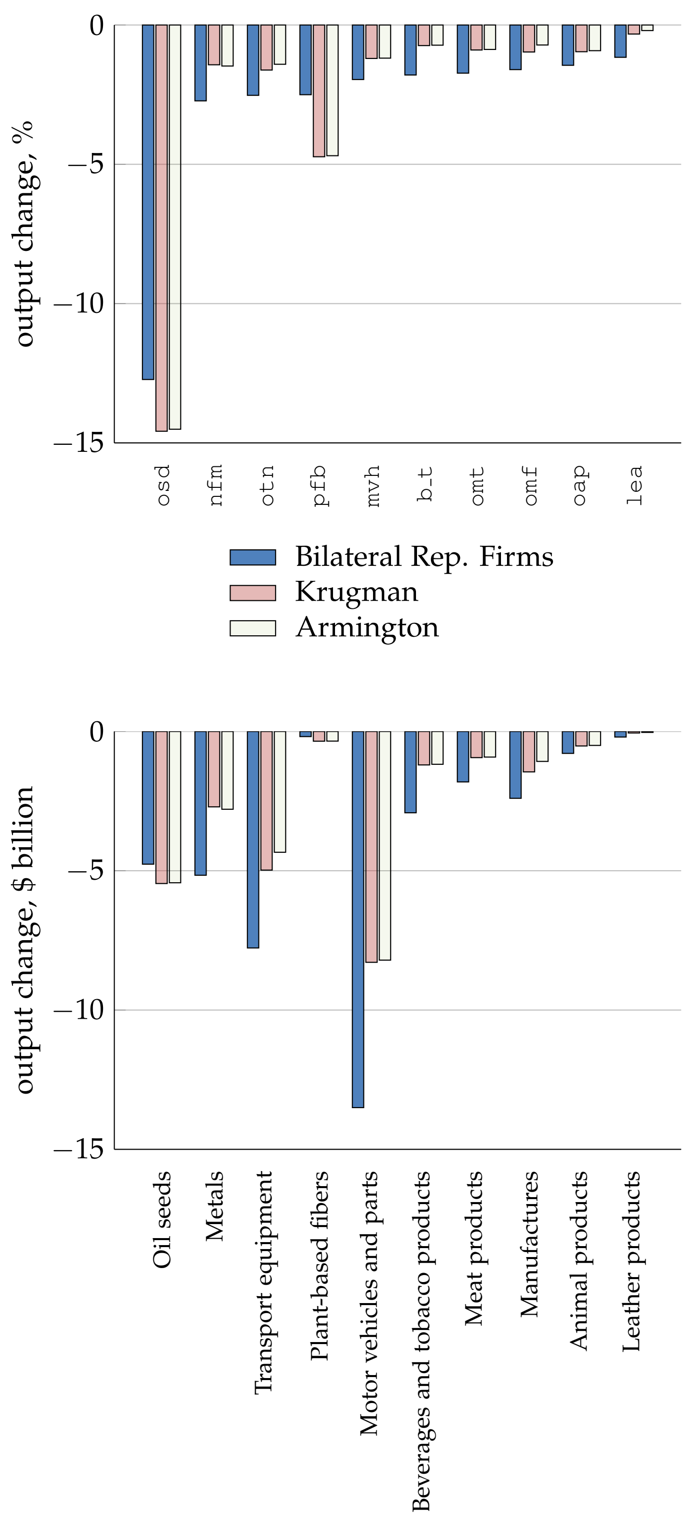
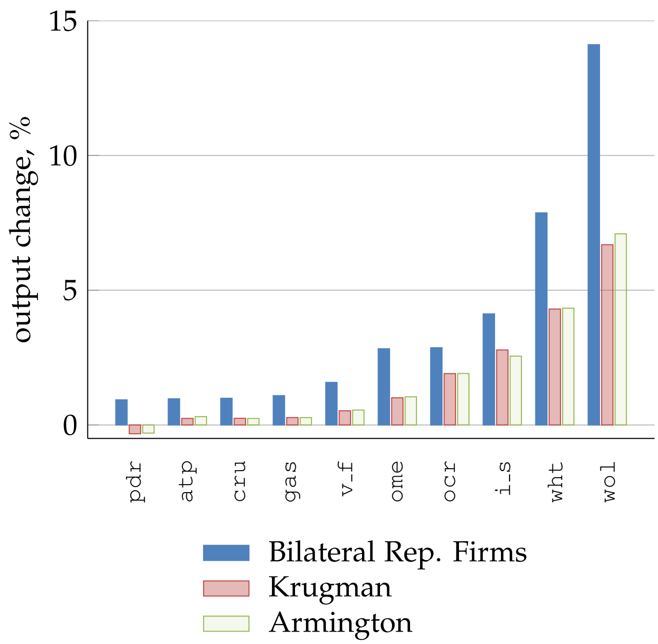
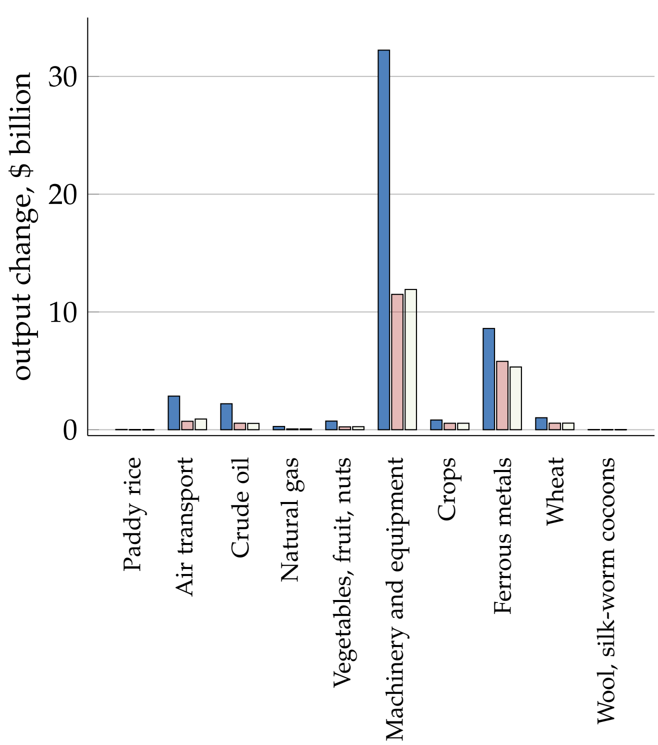


Figure 6. US sectoral impacts: winners





dex). It does not reflect a change in the quantity of any government expenditures. We make the simplest assumption about model closure: investment, government, and the trade balances are fixed in real quantity terms.[18]

Table 4. US real GDP impacts decomposed

	Benchmark ($B)	Change ($B)	Change (%)
Expenditures			
Consumption	12,122	-123.7	-1.0
Investment	3,439	83.0	2.4
Government	2,601	-11.3	-0.4
Net Exports (X-M)	-802	-14.7	1.8
Total	17,360	-66.8	-0.4
Income by recipient			
`LAB` Unskilled Labor	2,142	-17.3	-0.8
`TEC` Technicians and Professionals	938	-9.2	-1.0
`CLK` Clerks	1,292	-12.2	-0.9
`MGR` Managers and Officials	5,053	-48.1	-1.0
`SRV` Services workers	751	-7.4	-1.0
`CAP` Capital	3,605	-36.3	-1.0
`LND` Land	48	-2.6	-5.4
`RES` Resource	82	3.4	4.1
Specific factors	665	47.9	7.2
Direct factor taxes	1,516	-13.5	-0.9
Output tax revenue	729	-3.3	-0.5
Indirect tax (domestic)	106	-0.6	-0.6
Tariff and import tax	427	32.7	7.6
Export tax revenue	6	-0.3	-4.6
Total	17,360	-66.8	-0.4
Income by sector			
`osg` Public administration, defense, health, education	3,746	-38.8	-1.0
`trd` Trade	2,244	-26.7	-1.2
`obs` Business services	1,718	-2.5	-0.1
`dwe` Dwellings	1,541	-17.4	-1.1

[18] In a neoclassical general equilibrium a real commodity unit (or a linearly homogeneous index of commodity units) must be established for the capital flow (X-M). To dissipate the impacts of choosing a particular good from a particular region, which might generate anomalous terms-of-trade effects, we choose an index over all goods consumed. Technically, the price index that establishes the fixed aggregated capital flow is constructed as the benchmark household-consumption weighted average of prices throughout the world.

ofi Financial services	1,323	-3.6	-0.3
cns Construction	1,125	-8.8	-0.8
ros Recreation and other services	589	-7.2	-1.2
ome Machinery and equipment	576	19.5	3.4
crp Chemical, rubber, plastic products	461	2.7	0.6
cmn Communication	372	-1.1	-0.3
isr Insurance	362	-0.1	0.0
otp Transport	324	-1.2	-0.4
ppp Paper products, publishing	274	-0.6	-0.2
fmp Metal products	193	1.8	0.9
mvh Motor vehicles and parts	177	-0.5	-0.3
ele Electricity	196	-2.2	-1.1
ofd Food products	166	0.2	0.1
cru Crude Oil	169	4.7	2.8
lum Wood products	153	0.6	0.4
otn Transport equipment	139	-2.7	-2.0
atp Air transport	104	0.5	0.5
eeq Electronic equipment	100	13.2	13.2
nmm Mineral products	89	0.5	0.6
i_s Ferrous metals	78	8.6	11.0
tex Textiles	78	0.2	0.2
wtr Water	76	-0.9	-1.2
omf Manufactures	67	-0.7	-1.1
b_t Beverages and tobacco prod	66	-0.9	-1.3
nfm Metals	53	1.1	2.0
wap Wearing apparel	48	0.1	0.3
oil Petroleum, coal products	47	0.9	1.9
col Coal	45	-0.9	-2.1
wtp Sea transport	43	-0.2	-0.5
gdt Gas manufacture, distribution	38	-0.1	-0.4
cmt Meat: cattle,sheep,goats,horse	38	0.2	0.5
gro Cereal grains	32	-0.7	-2.1
omn Minerals	32	-0.5	-1.4
mil Dairy products	32	0.0	0.1
omt Meat products	30	-0.3	-1.1
v_f Vegetables, fruit, nuts	25	0.0	0.1
ocr Crops	20	0.3	1.5
osd Oil seeds	20	-3.5	-16.9
gas Gas	18	0.6	3.2
frs Forestry	15	-0.2	-1.3
oap Animal products	12	-0.4	-3.3

`lea` Leather products	12	0.6	5.0
`ctl` Cattle,sheep,goats,horses	11	-0.2	-1.6
`rmk` Raw milk	7	-0.2	-2.7
`wht` Wheat	7	0.5	7.7
`fsh` Fishing	4	0.0	1.0
`sgr` Sugar	4	0.0	0.6
`vol` Vegetable oils and fats	4	0.1	2.1
`pfb` Plant-based fibers	3	-0.2	-5.2
`c_b` Sugar cane, sugar beet	2	0.0	-1.9
`pdr` Paddy rice	1	0.0	-0.8
`pcr` Processed rice	1	0.0	1.2
`wol` Wool, silk-worm cocoons	0	0.0	23.1
Consumption	92	-0.9	-1.0
Investment	12	0.5	4.0
Government	0	0.0	0.3
Total	17,360	-65.6	-0.4

In the second panel of Table 4 we decompose income to accommodate a standard functional incidence analysis. We see modest percentage losses for capital and the labor categories (in the 1% range), but large losses for land owners (5.4%). This, again, reflects the focus of foreign retaliation on agricultural goods. It is important to consider that the near 5.4% loss in land income is a change in the income *flow*. If this is a persistent decrease in land income the capitalized value of that decline would have substantial impacts on farm values. There are, of course, sizeable gains in tariff revenue on the income side. The third panel of Table 4 decomposes real income by sectors. These sectoral income accounts indicate value added by sector, but also include all tax revenue or payments associated with the sector including the payment of trade taxes on inputs and final demand. This is where the consumption, investment, and government accounts are included.

In Table 5 we report the weighted-average Dixit-Stiglitz variety impacts for the monopolistically competitive sectors. The statistic reported is the percentage change in the Feenstra ratio.[19] The Feenstra ratio is calculated for each of the monopolistically competitive sectors, and then averaged based on initial absorption (consumption plus intermediate use) shares. A key feature of the bilateral representative firms structure is that the number of firms can vary across trade partners. While US tariffs may induce *exit* of Chinese firms exporting to the US

[19] In his Theorem 2, Feenstra (2010) provides a theoretic justification for this measure. The Feenstra ratio indicates the portion of the change in the composite price index for good i in region r that is due purely to changes in the number of varieties.

Table 5. Variety impacts across model structures

	Weighted average % change in Feenstra ratio	
	Bilat. Rep. Firm	Krugman
EUR EU-27 plus	0.029	-0.002
USA U.S.A	-0.158	-0.012
ROW Rest of World	0.035	-0.003
CHN China	-0.090	-0.039
OEC Rest of OECD	0.024	-0.010
MRC Mercosur	0.035	-0.022
CAN Canada	-0.025	-0.066
KOR S. Korea	0.031	-0.006
MEX Mexico	0.055	-0.037

(resulting in adverse variety impacts on the US), the US tariffs may induce *entry* of Chinese firms exporting to Europe resulting in variety gains for Europe. This intensifies trade diversion along the extensive margin of trade. This margin is not available under the standard Krugman structure. Under the Krugman structure varieties are only indexed by the exporting region. If the US tariffs induce exit of Chinese varieties this impact is felt by all of China's trade partners. Table 5 shows that the 2018 trade disruptions induce varieties losses for all regions of the world under the Krugman structure. The Krugman structure indicates that Europe benefits from the bilateral dispute between the US and China through trade diversion along the intensive margin, but suffers from the overall loss of varieties. In contrast, the bilateral representative firms model indicates variety gains for all regions except China, the US, and Canada.

Figure 1 and 2 presented the raw benchmark trade flows and partial-equilibrium price impacts. We now compare these in the context of our general-equilibrium simulations. Figures 7 and 8 compare the Marshallian model with the three general-equilibrium models. In this diagram vertical shifts correspond to changes in protection and terms of trade, and horizonal shifts characterize consequent quantity adjustments (through interaction of supply and demand). Quantity responses in the general-equilibrium frameworks are muted by income effects and changes in the terms of trade. The differeneces depend on input-output linkages and model closure (fixed balance of payments). Trade quantity responses in the Armington model are muted relative to the Marshall model. This indicates that from a perfect competition perspective partial-equilibrium calculations might significantly overstate the trade impacts. Trade responses are again higher in the Dixit-Stiglitz framework with bilateral representative firms.

7. Conclusion

Protectionist movements around the world challenge the mainstream economic proposition that trade liberalization provides welfare gains. While such welfare

Figure 7. US imports from China: benchmark trade, tariffs, and implied partial-equilibrium responses

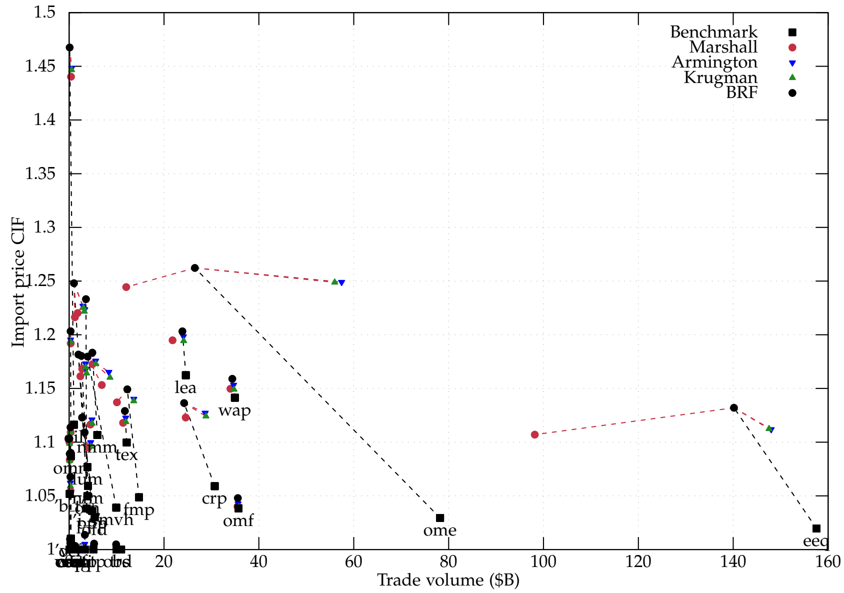
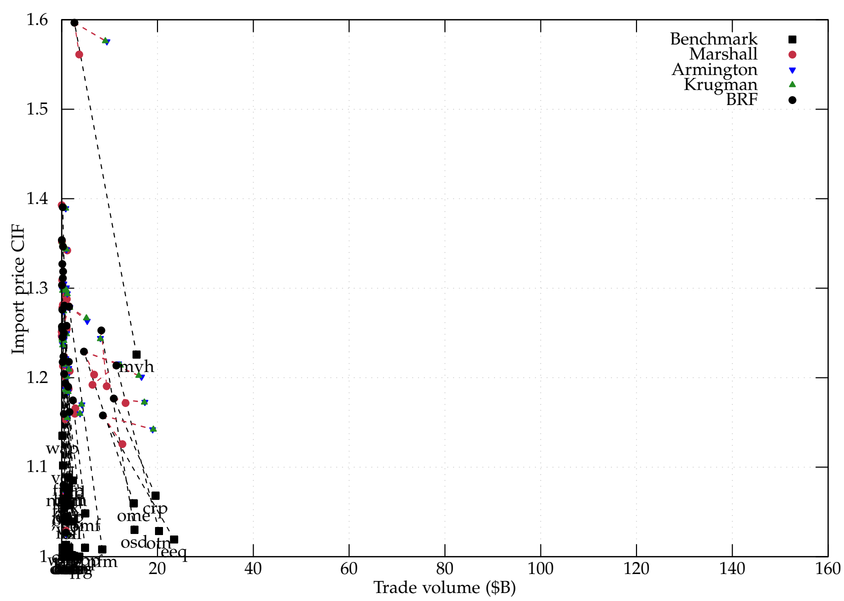


Figure 8. Chinese imports from the US: benchmark trade, tariffs, and implied partial-equilibrium responses



gains may occur in aggregate it is fair enough to realize that freer trade does not necessarily lead to Pareto improvements at the level of individual regions, industries or households. Given the more recent wave of protectionism, applied trade policy analysis can play a useful role in informing the public debate on the magnitude and distribution of economic impacts triggered by trade policy interventions. At best it helps to reject or confirm arguments by interest groups about the societal desirability of policy reforms. Such quantitative analysis, however, must be based on a rigorous assessment of the key drivers for trade and how these channels will be affected via policy instruments such as tariffs or non-tariff barriers translating into tangible welfare impacts. Against this background we have developed a modeling framework to conduct structural sensitivity analysis on the outcomes of policy reforms across three alternative microeconomic foundations of international trade: (i) the neoclassical Armington approach of product differentiation in competitive markets, (ii) the perspective of the theory established by Krugman on the importance of scale economies, monopolistic competition and product varieties, and (iii) a more recent innovation emphasizing the role of firm selection into bilateral markets. This final structure is generally consistent with bilateral variety changes (as in Melitz), but does not consider direct changes in firm productivity through intra-industry reallocations.

We have applied our modeling framework to assess the escalating tariffs between US and China, as well as the dispute started by US tariffs on steel and aluminum. We find that such disruptive trade policies, restricting free trade, come at non-negligible welfare cost for the global economy. In their specific implementations they may also not live up to assertions of providing national gains to the initiating countries. In that sense, they have to be defended on more specific strategic grounds or at least involve trade-offs with objectives such as food or national security, or asset diversification which are outside the cost-benefit scheme of our modeling framework.

The structural sensitivity analysis on alternative trade assumptions reveals the importance of taking into account scale economies and variety effects to quantify the magnitude and distribution of economic impacts at the level of countries and sectors. Future extensions of the current framework may cover different dimensions. From an applied policy perspective, we can exploit the computational power of our modeling framework to include significant sectoral detail. This provides specific insights into the performance of individual industries and can reveal potential aggregation biases of more compact policy assessments. In a similar vein, more refined incidence analysis calls for the incorporation of household heterogeneity: A narrow utilitarian perspective focusing on aggregate efficiency gains may naively miss out on the distributional dimension as inequality concerns come into play. On the methodological dimension, it could be useful to re-cast the current model as an MPEC (mathematical program subject to equilibrium constraints) in order to track down the scope for strategic trade policies (optimal tariffs). And finally, it could be insightful to cross-compare our reduced-form BRF representation of firm heterogeneity with a fully fleshed out Melitz structure that includes intra-industry reallocation of resources.

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Appendix A. GTAP Sectors and Primary Factors

Table A.1. Commodities and Industries in the GTAP 9 database

Identifier	Definition	Identifier	Definition
PDR	Paddy rice	LUM	Wood products
WHT	Wheat	PPP	Paper products, publishing
GRO	Cereal grains nec	P_C	Petroleum, coal products
V_F	Vegetables, fruit, nuts	CRP	Chemical,rubber,plastic prods
OSD	Oil seeds	NMM	Mineral products nec
C_B	Sugar cane, sugar beet	I_S	Ferrous metals
PFB	Plant-based fibers	NFM	Metals nec
OCR	Crops nec	FMP	Metal products
CTL	Cattle,sheep,goats,horses	MVH	Motor vehicles and parts
OAP	Animal products nec	OTN	Transport equipment nec
RMK	Raw milk	ELE	Electronic equipment
WOL	Wool, silk-worm cocoons	OME	Machinery and equipment nec
FRS	Forestry	OMF	Manufactures nec
FSH	Fishing	ELY	Electricity
COA	Coal	GDT	Gas manufacture, distribution
OIL	Oil	WTR	Water
GAS	Gas	CNS	Construction
OMN	Minerals nec	TRD	Trade
CMT	Meat: cattle,sheep,goats,horse	OTP	Transport nec
OMT	Meat products nec	WTP	Sea transport
VOL	Vegetable oils and fats	ATP	Air transport
MIL	Dairy products	CMN	Communication
PCR	Processed rice	OFI	Financial services nec
SGR	Sugar	ISR	Insurance
OFD	Food products nec	OBS	Business services nec
B_T	Beverages and tobacco products	ROS	Recreation and other services
TEX	Textiles	OSG	PubAdmin/Defence/Health/Educat
WAP	Wearing apparel	DWE	Dwellings
LEA	Leather products	CGD	Aggregate investment

Table A.2. Primary Factors in the GTAP 9 database

	Identifier	Definition
Mobile factors:		
	MGR	Officials and Managers legislators (ISCO-88 Major Groups 1-2),
	TEC	Technicians and associate professionals
	CLK	Clerks
	SRV	Service and market sales workers
	LAB	Agricultural and unskilled workers (Major Groups 6-9)
	CAP	Capital
Sluggish factors:		
	LND	Land
	RES	Natural resources

Table B.1. Definitions of set indices.

Set	Definition
i, j	Sectors, an aggregation of the 57 sectors in the GTAP 9 Data Base
g	Production sectors i, plus private consumption "C", public demand "G" and investment "I"
r, s	Regions, an aggregation of the 140 regions in the GTAP 9 Data Base
f	Factors of production (consisting of *mobile factors*, $f \in m_f$, skilled labor (i. officials, mangers and legislators (ISCO-88 Major Groups 1-2), ii. technicians and associated professionals, iii. clerks, and iv. service and market sales workers), unskilled labor, capital, and *sector-specific*, $f \in s_f$, agricultural land and other resources)

Appendix B. Technology and Preferences

In the following, we start by describing the basic notation, and then present the structure of the data together with benchmark accounting identities. We then present a "primal" description of agents' optimization problems (i.e. specified in terms of quantity variables), which leads to the equilibrium conditions presented in the subsequent section.

B.1 Notation

The notation used in the model is summarized in the Tables B.1 - B.3. Table B.1 defines the various dimensions which characterize an instance of the model, including the set of sectors/commodities (i, j), the set of regions (r, s), the set of factors of production (f). Set g combines the production sectors i and private and public consumption demand (indices "C" and "G") and investment demand (index "I"). It allows for a much tighter formulation of the model as they can all be conceived of "goods" produced in similar fashion. To simplify the exposition of the model, however, we describe private consumption, public consumption and investment demand as stand alone components.

Table B.2 defines the primal variables (activity levels) which characterize an equilibrium. The model determines values of all the variables except international capital flows, a parameter which would be determined endogenously in an intertemporal model. Table B.2 also displays the concordance between the variables and their GAMS equivalents.

Table B.3 defines the relative price variables for goods and factors in the model. As is the case in any Shoven-Whalley CGE model, the equilibrium conditions determine *relative* rather than *nominal* prices.

Finally, Table B.5 reports the definition of tax and subsidy rates applied in the

Table B.2. Definitions of activity levels (quantity variables).

Variable	Definition	GAMS variable	Benchmark (GTAP) value
Y_{ir}	Production	`Y(i,r)`	`vom(i,r)`
C_r	Discretionary consumption	`Y("c",r)`	`vom("c",r)`
G_r	Aggregate public	`Y("g",r)`	`vom("g",r)`
I_r	Aggregate investment	`Y("i",r)`	`vom("i",r)`
M_{ir}	Aggregate imports	`M(i,r)`	`vim(i,r)`
FT_{fr}	Factor transformation	`FT(f,r)`	`evom(f,r)`
YT_j	International transport services	`YT(j)`	`vtw(j)`

model, both in terms of the notation employed to describe the model and that used in the GAMS code. Note that revenues from taxes and subsidy expenditures do not appear as explicit variables in the GTAP Data Base and are defined on the basis of expenditures and tax rates. We come back to this below.

B.2 Benchmark data structure and accounting identities

The economic structure underlying the GTAP dataset and model is illustrated in Figure B.1. Symbols in this flow chart correspond to variables in the economic model (see Table B.2): Y_{ir} is the production of good i in region r, C_r, I_r and G_r portray private consumption, investment and public demand, respectively, M_{ir} portrays the import of good i into region r, RA_r stand for representative consumers, and $FT_{s_f r}$ is the activity through which the set of sector-specific factors of production (s_f) are allocated to individual sectors. Further, solid lines represent commodity and factor market flows, while dotted lines indicate tax revenues and transfers.

Domestic and imported goods markets are represented by horizontal lines at the top of the figure. Domestic production (vom_{ir}) is distributed to exports ($vxmd_{irs}$), international transportation services (vst_{ir}), intermediate demand ($vdfm_{ijr}$), household consumption ($vdfm_{iCr}$), investment ($vdfm_{iIr}$), and government consump-

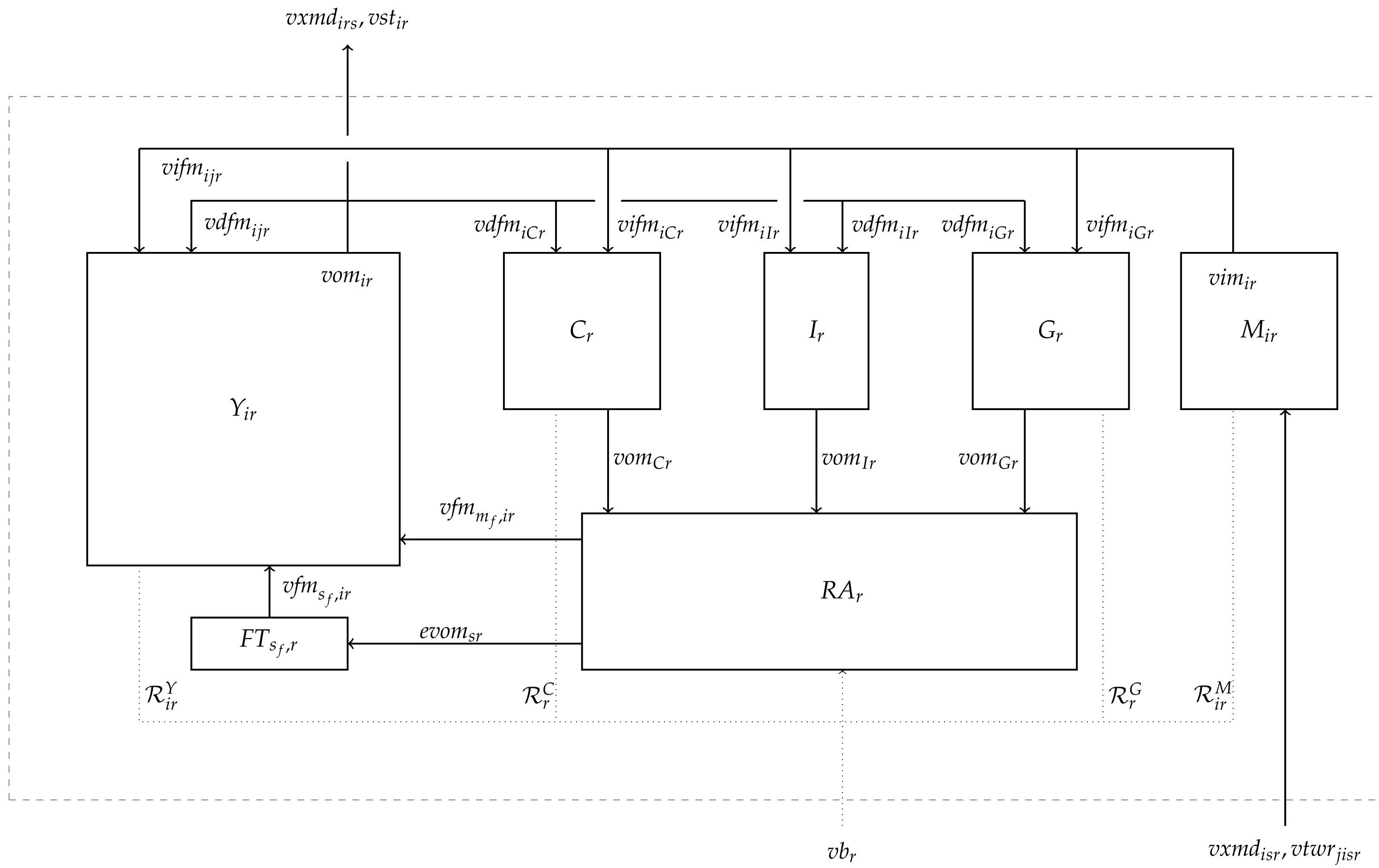


Figure B.1. Regional economic structure.

Table B.3. Definitions of price variables.

Variable	Definition	GAMS variable
p^C_r	Final demand price index for the Cobb-Douglas demand system	`P("C",r)`
p^G_r	Public provision price index	`P("G",r)`
p^I_r	Investment price index	`P("I",r)`
p^Y_{ir}	Supply price, gross of indirect producer taxes (when $\eta^{DX}_i < \infty$, the supply price is replaced by and export price, p^X_{ir} and domestic supply price, p^D_{ir})	`P(i,r)`
p^M_{ir}	Import price, gross of export taxes and tariffs.	`PM(i,r)`
p^E_{ir}	Export price from endogenous or exogenous regions.	`PE(i,r)`
p^T_j	Marginal cost of transport services	`PT(j)`
$p^F_{f,r}$	Price of mobile primary factors (m_f include labor, land and resources)	`PF(f,r)`
$p^S_{s_f,ir}$	Price of sector-specific primary factors	`PS(sf,i,j)`

tion ($vdfm_{iGr}$).[20] The accounting identity in the GTAP 9 dataset is thus:

$$vom_{ir} = \sum_s vxmd_{irs} + vst_{ir} + \sum_j vdfm_{ijr} + vdfm_{iCr} + vdfm_{iIr} + vdfm_{iGr}\,,$$

where j indexes all goods. Similarly, imported goods (with aggregate value vim_{ir}) enter intermediate demand ($vifm_{ijr}$), private consumption ($vifm_{iCr} + vifm_{iSDr}$) and public consumption ($vifm_{iGr}$). The accounting identity for these flows is thus:

$$vim_{ir} = \sum_j vifm_{ijr} + vifm_{iCr} + vifm_{iSDr} + vifm_{iGr}\,.$$

[20] Recall that in the GAMS implementation of the model the index `"g"` includes all sectors represented in the model plus private consumption `"C"`, public demand `"G"` and investment `"I"`. (See Table B.1.) For the LES demand representation, it also includes price indices for discretionary demand `"dd"` and subsistence demand `"sd"`.

Table B.4. Additional variables for the demand systems.

Variable	Definition	GAMS variable
SD_r	Subsistence demand	`Y("sd",r)`
ND_r	Necessary demand	`Y("nd",r)`
DD_r	Discretionary demand	`Y("dd",r)`
p_r^{DD}	Discretionary demand price index	`P("dd",r)`
p_r^{SD}	Subsistence demand price index	`P("sd",r)`

Inputs to production of good i (Y_{ir}) include intermediate inputs (domestic $vdfm_{ijr}$ and imported $vifm_{ijr}$), mobile factors of production ($vfm_{m_f,ir}$, where m_f is a subset of the set f designating all factors of production), and sector-specific factors of production ($vfm_{s_f,ir}, s_f \subset f$). Factor market equilibrium is given by an identity relating the value of factor payments to factor income:

$$\sum_i vfm_{fir} = evom_{fr}\,,$$

and factor earnings accrue to households.

International market clearance conditions require that region r exports of good i ($vxmd_{ir}$ at the top of the figure) equal the imports of the same good from the same region summed across all trading partners ($vxmd_{isr}$ at the bottom of the figure):

$$vxm_{ir} = \sum_s vxmd_{irs}\,,$$

where s, an alias for r, indexes regions. Likewise, market clearance conditions apply for international transportation services. The supply-demand balance in the market for transportation service j requires that the sum across all regions of service exports (vst_{ir}, at the top of the figure) equals the sum across all bilateral trade flows of service inputs ($vtwr_{jisr}$ at the bottom of the figure):

$$\sum_r vst_{jr} = \sum_{isr} vtwr_{jisr}$$

Turning to tax revenues and transfers, shown as dotted lines in figure B.1, flows labeled with $\mathcal{R}$ correspond to tax revenues. For each country, tax flows consist of indirect taxes on production/exports of each good ($\mathcal{R}_{ir}^{Y}$), on consumption ($\mathcal{R}_r^{C}$), on public demand ($\mathcal{R}_r^{G}$) and on imports ($\mathcal{R}_{ir}^{M}$). The regional budget constraint thus relates tax payments ($\mathcal{R}_{ir}^{Y}, \mathcal{R}_r^{C}, \mathcal{R}_r^{G}, \mathcal{R}_{ir}^{M}$), factor income ($evom_{fr}$), and the current

Table B.5. Tax and subsidy rates (net basis unless noted).

Parameter	Definition		GAMS Parameter
t^{o}_{ir}	Output taxes (gross basis)		`rto(i,r)`
t^{f}_{fir}	Factor taxes		`rtf(f,i,r)`
t^{fd}_{ijr}	Intermediate input taxes	Domestic	`rtfd(i,j,r)`
t^{fi}_{ijr}		Imported	`rtfi(i,j,r)`
t^{pd}_{ir}	Consumption taxes	Domestic	`rtfd(i,"C",r)`
t^{pi}_{ir}		Imported	`rtfi(i,"C",r)`
t^{gd}_{ir}	Public demand taxes	Domestic	`rtfd(i,"G",r)`
t^{gi}_{ir}		Imported	`rtfi(i,"G",r)`
t^{gd}_{ir}	Investment demand taxes	Domestic	`rtfd(i,"I",r)`
t^{gi}_{ir}		Imported	`rtfi(i,"I",r)`
t^{xs}_{isr}	Export subsidies		`rtxs(i,s,r)`
t^{ms}_{isr}	Import tariffs		`rtms(i,s,r)`

account deficit (i.e., net transfers from abroad, vb_r) to total private consumption expenditure vom_{Cr}, total public consumption expenditure vom_{Gr}, and total investment vom_{Ir}, yielding:

$$vom_{Cr} + vom_{Gr} + vom_{Ir} = \sum_f evom_{fr} + \sum_i \mathcal{R}^Y_{ir} + \mathcal{R}^C_r + \mathcal{R}^G_r + \sum_i \mathcal{R}^M_{ir} + vb_r\,.$$

To this point we have outlined two types of consistency conditions which are part of any GTAP Data Base: market clearance (supply = demand for all goods and factors), and income balance (net income = net expenditure). A third set of identities involve net operating profits by all sectors in the economy. In the core GTAP model "production" takes place under conditions of perfect competition with constant returns to scale, hence there are no excess profits, and the cost of inputs must equal the value of outputs. This condition applies for each production sector:

$$\begin{aligned}
Y_{ir}:&\quad \textstyle\sum_f vfm_{fir} + \sum_j \left(vdfm_{ijr} + vifm_{ijr}\right) + \mathcal{R}^Y_{ir} = vom_{ir}\,,\\
C_r:&\quad \textstyle\sum_i \left(vdfm_{iCr} + vifm_{iCr}\right) + \mathcal{R}^C_{ir} = vom_{Cr}\,,\\
I_r:&\quad \textstyle\sum_i vdfm_{iIr} = vom_{Ir}
\end{aligned}$$

$$
\begin{aligned}
G_r\colon &\quad \textstyle\sum_i \left(vdfm_{iGr} + vifm_{iGr}\right) + \mathcal{R}^G_{ir} = vom_{Gr}\,,\\
M_{ir}\colon &\quad \textstyle\sum_s \left(vxmd_{isr} + \sum_j vtwr_{jisr}\right) + \mathcal{R}^M_{ir} = vim_{ir}\\
FT_{fr}\colon &\quad evom_{fr} = \textstyle\sum_i vfm_{fir}
\end{aligned}
$$

B.3 Decentralized optimization problems

The benchmark identities presented in the previous section indicate the market clearance, zero profit and income balance conditions which define the GTAP model. The displayed equations do not, however, characterize the behavior of agents in the model. In a competitive equilibrium setting, the standard assumption of optimizing atomistic agents applies for both producers and consumers. This section lays out the optimization problem of each component in the model, and thereby provides the structure of production technology (production functions) and preferences (characterizing final demand), as well as the representation of trade.

Note that in order to simplify notation, we denote decision variables corresponding to the benchmark data structures with the initial "v" replaced by "d." Hence, while $vdfm_{jir}$ represents benchmark data on intermediate demand for good j in the production of good i in region r, $ddfm_{jir}$ represents the corresponding decision variable in the equilibrium model. This approach to the scaling of variables is consistent with the GAMS code, and it provides a flexible and transparent approach with respect to the calibration of activity variables.

B.3.1 Production technology

Starting with producers, profit maximization in the constant returns to scale setting is equivalent to cost minimization subject to technical constraints. For sector Y_{ir} we characterize input choices as though they arose from minimization of unit costs:

$$
\begin{aligned}
\min_{ddfm,dfm,difm} \quad & c^D_{ir} + c^M_{ir} + c^F_{ir} \\
s.t. \quad & c^D_{ir} = \sum_j p^Y_{jr}(1+t^{fd}_{jir})ddfm_{jir}\\
& c^M_{ir} = \sum_j p^M_{jr}(1+t^{fi}_{jir})difm_{jir}\\
& c^F_{ir} = \sum_f (p^F_{fr}|_{f\in m_f} + p^S_{fir}|_{f\in s_f})(1+t^f_{fir})dfm_{fir}\\
& F_{ir}(ddfm, difm, dfm) = Y_{ir}
\end{aligned}
\tag{B.1}
$$

where $F(\cdot)$ represents the production function, which is described by a nested constant-elasticity-of-substitution (CES) form, with structure displayed in Figure B.2.

In the figure, σ values in different nests represent substitution elasticities between inputs, with $\sigma^D_i = esubd_i$ measuring substitution possibility between in-

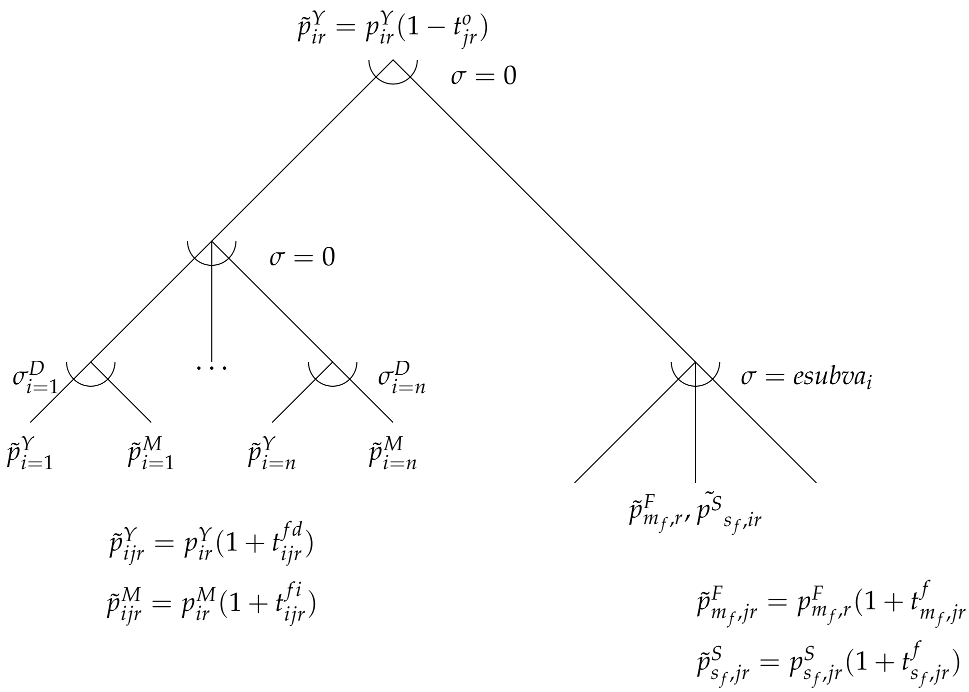


Figure B.2. CES nesting structure for production function $Y_{ir} = F_{ir}(ddfm, difm, dfm)$.

termediate inputs produced domestically and imported from abroad which are similarly a composite of imports from varieties from different regions. $esubva_i$ represents the elasticity of substitution between primary inputs in the value added nest. (Both of these parameters are provided in the GTAP 9 Data Base (see Chapter 14 in Angel Aguiar and McDougall, 2016).) Note further that the specific source of tax revenue is indicated in this figure, consisting of output taxes, taxes on intermediate inputs and taxes on factor demands, all of which are applied on an ad-valorem basis.

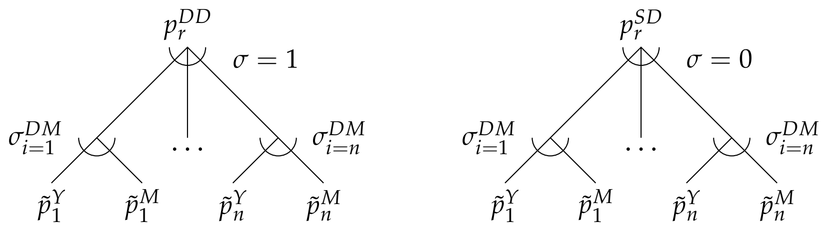
B.3.2 Preferences and final demand

Private consumption consistent with utility maximization is portrayed by minimization of the cost of a given level of aggregate consumption:

$$\min_{ddfm_{iCr}, difm_{iCr}} \quad \sum_i p^Y_{ir}(1 + t^{pd}_{ir})ddfm_{iCr} + p^M_{ir}(1 + t^{pi}_{ir})difm_{iCr} \qquad \text{(B.2)}$$
$$s.t. \quad H_r(ddfm_{iCr}, difm_{iCr}) = C_{ir}$$

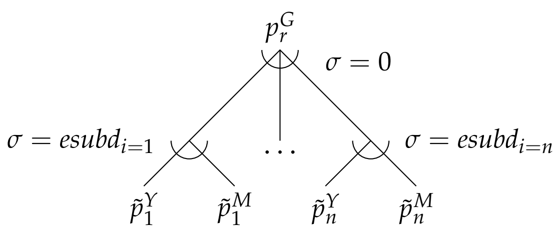
where H_r represents final demand from the representative consumer.

Final demand in the core model is characterized by Cobb-Douglas preferences. *Details of the demand system go here.*



$$\tilde{p}_{ir}^Y = p_{ir}^Y(1 + t_{ir}^{pd})$$
$$\tilde{p}_{ir}^M = p_{ir}^M(1 + t_{ir}^{pi})$$

Figure B.3. LES nesting for discretionary and subsistence consumption.



$$\tilde{p}_{ir}^Y = p_{ir}^Y(1 + t_{ir}^{gd})$$
$$\tilde{p}_{ir}^M = p_{ir}^M(1 + t_{ir}^{gi})$$

Figure B.4. Nesting structure for public consumption $G_r = G_r(ddfm_{iGr}, difm_{iGr})$.

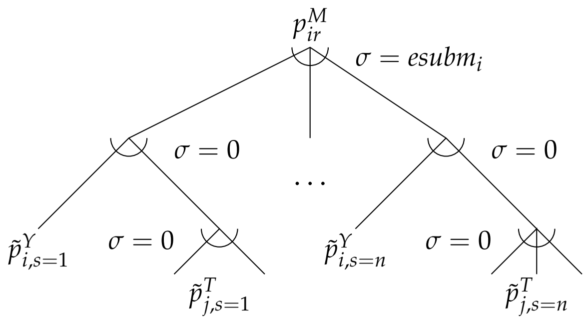
B.3.3 Government and public consumption

Public consumption in the model is represented as a fixed coefficient (Leontief) aggregation of domestic-import composites. This formulation introduces substitution at the second level between domestic and imported inputs while holding sectoral commodity aggregates constant. Figure B.4 illustrates the functional form.

B.3.4 International trade

The choice among imports from different trading partners is based on Armington's idea of regionally differentiated products. The following cost minimization problem formalizes this choice:

$$\min_{dxmd,dtwr} \quad \sum_s (1 + t_{isr}^{ms}) \left(p_{is}^Y (1 - t_{isr}^{xs}) dxmd_{isr} + \sum_j p_j^T dtwr_{jisr} \right) \qquad \text{(B.3)}$$
$$s.t. \quad A_{ir}(dxmd, dtwr) = M_{ir}$$



$$\tilde{p}^Y_{is} = p^Y_{is}(1 - t^{xs}_{isr})(1 + t^{ms}_{isr})$$
$$\tilde{p}^T_{js} = p^T_j(1 + t^{ms}_{isr})$$

Figure B.5. Armington aggregation of traded goods $M_{ir} = A_{ir}(dxmd{,}dtwr)$.

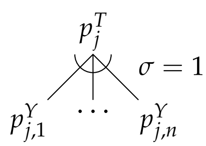


Figure B.6. International transportation services aggregator $YT_j = T_j(dst)$.

where A is the import aggregation function, described by the nested CES-Leontief function shown in Figure B.5.

Note that transportation services enter on a proportional basis with imports from different countries, reflecting differences in unit transportation margins across different goods and trading partners. Therefore, substitution at the top level in an Armington composite involves trading off of both imported goods and associated transportation services. Trade flows are subject to export subsidies and import tariffs, with subsidies paid by government in the exporting region, and tariffs collected by government in the importing region.

The provision of international transportation services is modeled through an aggregation of transportation services exported from countries throughout the world. More specifically, we consider the following cost minimization problem for the aggregation of transportation services:

$$\min_{dst} \quad \sum_r p^Y_{ir} dst_{ir} \quad \text{s.t.} \quad T_i(dst) = YT_i$$

where the aggregation function T_i combines transport service exports from multiple regions. The functional form which aggregates services from different regions is illustrated in Figure B.6.

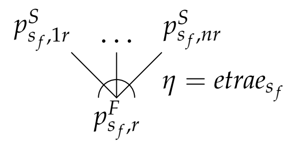


Figure B.7. Sector-specific factor CET transformation function $FT_{s_f} = \Gamma_{s_f}(dfm)$.

B.3.5 Supply of sector-specific factors

Land and natural resources are portrayed as sector-specific factors of production. These are supplied through constant-elasticity-of-transformation (CET) production function which allocates composite factors to sectoral markets. Formally, the supply of sectoral factors of production is modeled through the following profit-maximization problem:

$$\max_{dfm} \quad \sum_j dfm_{s_f,jr} p^S_{s_f,jr} \tag{B.4}$$

$$s.t. \quad \Gamma_{s_f,r}(dfm) = evom_{s_f,r} \tag{B.5}$$

where Γ is the CET function with structure illustrated in Figure B.7. Note that in the figure η represents transformation elasticities provided in the GTAP 9 Data Base.

Appendix C. Market Equilibrium

An Arrow-Debreu model concerns itself with the interactions of decentralized decisions by consumers and producers in markets. Mathiesen (1985) proposed a representation of this class of models in which two types of equations define an equilibrium: zero profit and market clearance. The corresponding variables defining an equilibrium are activity levels (for constant-returns-to-scale firms) and commodity prices.[21] Here we extend Mathiesen's framework with a third class of variables corresponding to consumer income levels. Commodity markets encompass primary endowments of households with producer outputs. In equilibrium the aggregate supply of each good must be at least as great as total intermediate and final demand. Initial endowments are exogenous. Producer supplies and demands are defined by producer activity levels and relative prices. Final demands are determined by market prices.

Economists who have worked with conventional textbook equilibrium models can find Mathiesen's framework to be somewhat opaque because many quantity variables need not be explicitly specified in the model. Variables such as final demand by consumers, factor demands by producers and commodity supplies by producers, are defined implicitly in Mathiesen's model. For example, given equilibrium prices for primary factors, consumer incomes can be computed, and given income and goods prices, consumers' demands can then be determined. The consumer demand functions are written down in order to define an equilibrium, but quantities demanded need not appear in the model as separate variables. The same is true of inputs or outputs from the production process: relative prices determine conditional demand, and conditional demand times the activity level represents market demand. Omitting decisions variables and suppressing definitional equations corresponding to intermediate and final demand provides significant computational advantages at the cost of a somewhat more complicated model statement.

In the following, we detail (i) zero profit conditions, (ii) market clearance conditions, and (iii) income balance conditions, which in the present case is equivalent to the regional budget constraint. These three sets of conditions form the basic system of equation to be solved. Note that the actual code for the model is implemented both in the algebraic mixed complementarity format (GAMS/MCP, see Rutherford, 1995) and through the more compact formulation afforded by the Mathematical Programming System for General Equilibruim (MPSGE) syntax

[21] Under a maintained assumption of perfect competition, Mathiesen (1985) may characterize technology as constant-returns-to-scale without loss of generality. Specifically, decreasing returns are accommodated through introduction of a specific factor, while increasing returns are inconsistent with the assumption of perfect competition. Note that in this environment zero excess profit is consistent with free entry for atomistic firms producing an identical product.

(Rutherford, 1999).

C.1 Zero profit (arbitrage) conditions

All production activities in the model are represented by constant-returns-to-scale technologies, and markets are assumed to operate competitively with free entry and exit. As a consequence, equilibrium profits are driven to zero and the price of output reflects the cost of inputs. The following sets of equations relating output price to marginal cost are part of the definition of an equilibrium.[22]

The calculation of unit cost and unit revenue functions involves the definition of a number of ancillary variables (that do not appear in the GAMS code as explicit choice variables). In the following we define ancillary variables in un-numbered equations, indicating that these variables are "optional" in the sense that they may be substituted out of the non-linear system of equations. Moreover, we use the symbol θ to portray value shares from the base year data. In most cases subscripts on these value shares are omitted in order to economize on notation. Finally, to denote benchmark values we use an overline, so that $\bar{t}^{pd}_{ir}$ represents the benchmark value of t^{pd}_{ir}.

C.1.1 Sectoral production (`Y(j,r)`)

Sectoral production combines intermediate inputs with a value-added nest combining primary inputs (see Figure B.2). The unit cost of value-added is a CES composite of skilled and unskilled labor, land, resources and capital inputs to production, gross of taxes. Factor inputs may be sector-specific or mobile across sectors:

$$p^{pf}_{fjr} = \begin{cases} p^F_{fr} \frac{(1+t^f_{fjr})}{1+\bar{t}^f_{fjr}} & f \in m_f \\ p^S_{fjr} \frac{(1+t^f_{fjr})}{1+\bar{t}^f_{fjr}} & f \in s_f \end{cases}$$

and the unit cost function is given by:

$$c^f_{jr} = \left(\sum_f \theta_f \left(p^{pf}_{fjr} \right)^{1-\sigma} \right)^{1/(1-\sigma)},$$

in which θ_f represents the factor share of value added [`theta_vfm(f,g,r)`].

The user cost of intermediate inputs differs from the market price due to the

[22] To retain consistency with the MCP format, we express zero profit conditions as "oriented equations," with marginal (=average) cost on the LHS and marginal (=average) revenue on the RHS.

presence of taxes on intermediate inputs:

$$p^d_{ijr} = p^Y_{ir}\frac{1+t^{fd}_{ijr}}{1+\bar{t}^{fd}_{ijr}}$$

$$p^i_{ijr} = p^M_{ir}\frac{1+t^{fi}_{ijr}}{1+\bar{t}^{fi}_{ijr}}$$

A CES cost function describes the minimum cost of a bundle of domestic and imported inputs to production, based on benchmark value shares and an elasticity of substitution σ[`esubd(i)`]:

$$c^i_{ijr} = \left(\theta(p^d_{ijr})^{1-\sigma} + (1-\theta)(p^i_{ijr})^{1-\sigma}\right)^{1/(1-\sigma)},$$

in which θ represents the domestic share of the Armington composite [`theta_vdfm(i,j,r)`].

Unit cost of sectoral output is then a Leontief (linear) composite of the costs of intermediate and value-added composite inputs, based on base-year value shares:

$$c^Y_{jr} = \sum_i \theta_i c^i_{ijr} + \theta^f c^f_{jr},$$

in which θ_i represents the cost share of intermediate input i [`theta_cm0(i,j,r)`]; and θ^f represents the cost share of value added in sectoral output [`theta_cf0(j,r)`].

Having formulated the unit cost function, it is possible to compactly portray the zero profit condition for y_{jr}. In equilibrium, the marginal cost of supply equals the market price, net of taxes:

$$c^Y_{jr} = p^Y_{jr}\frac{1-t^o_{jr}}{1-\bar{t}^o_{jr}} \tag{C.1}$$

C.1.2 Consumer demand (`Y("c",r)`)

Details of the NNCES demand system go here.

Similar to the LES demand system, this approach permits calibrating empirical evidence on both own-price and income elasticities.

C.1.3 Government demand (`Y("g",r)`)

Public expenditure is a fixed-coefficient aggregate of Armington composite goods. Within each composite domestic and imported goods trade off with a constant elasticity of substitution. The unit price indices for domestic and imported goods are given by:

$$p^{dg}_{ir} = p^Y_{ir}\frac{1+t^{dg}_{ir}}{1+\bar{t}^{gd}_{ir}}$$

and

$$p^{ig}_{ir} = p^M_{ir} \frac{1 + t^{ig}_{ir}}{1 + \bar{t}^{ig}_{ir}}$$

The composite price of the ith good is then:

$$pg_{ir} = \left(\theta (p^{dg}_{ir})^{1-\sigma} + (1-\theta)(p^{ig}_{ir})^{1-\sigma}\right)^{1/(1-\sigma)},$$

in which θ represents the domestic share of public demand [`theta_vdfm(i,"g",r)`].

The unit cost of public services (G_r) is defined by the Leontief cost coefficients:

$$\sum_i \theta_i pg_{ir} = p^G_r, \tag{C.2}$$

in which θ_i represents the value share of commodity i in public expenditure [`theta_cm0(i,"g",r)`].

C.1.4 Aggregate imports (`M(i,r)`)

An import cost index applies export taxes, trade and transport margins and import tariffs to the producer supply prices in exporting regions:

$$py^m_{isr} = p^Y_{is} \frac{(1 - t^{xs}_{isr})(1 + t^{ms}_{isr})}{(1 - \bar{t}^{xs}_{isr})(1 + \bar{t}^{ms}_{isr})}.$$

Transportation margins enter as fixed coefficients with bilateral trade flows, so the unit delivered price is a convex combination of the unit prices with weights corresponding to base year value shares:

$$pyt^m_{isr} = \theta py^m_{isr} + \sum_j \theta^T_j pt^m_{jisr},$$

in which θ represents good i share of imports [`theta_vxmd(i,s,r)`]; and θ^T_j represents the value share of transportation service j in the import price [`theta_vtwr(j,i,s,r)`].

Having formed a price index for bilateral imports from region s to region r, the CES cost index can be defined on the basis of value shares and the elasticity of substitution across imports from different regions, $\sigma = esubm_i$:

$$cim_{ir} = \left(\sum_s \theta_s (pyt^m_{isr})^{1-\sigma)}\right)^{1/(1-\sigma)},$$

in which θ_s is the value share of bilateral imports from region s [`theta_m(i,s,r)`].

The import activity (m_{ir}) has a zero profit condition which relates the unit cost of imports to the market price of the import aggregate:

$$cim_{ir} = p^M_{ir}. \tag{C.3}$$

C.1.5 International transportation services (`YT(j)`)

For simplicity, the unit cost of a transportation service depends on the benchmark value shares of region-specific services through a Cobb-Douglas cost function. Under perfect competition with free entry, the unit cost of international transport services equals the equilibrium market price:

$$\prod_r (p^Y_{jr})^{\theta_r} = p^T_j \tag{C.4}$$

in which θ_r represents the region r share of transportation service j [`theta_vst(j,r)`].

C.1.6 Sector-specific factor transformation (`FT(f,r)`)

The unit value of sector-specific factors is defined as a CET aggregate of returns to factor f across sectors j:

$$pvfm_{fr} = \left(\sum_j \theta_j ps^{1+\eta}_{fjr}\right)^{1/(1+\eta)} \qquad f \in s_f\,.$$

in which θ_j is the sector j share of earnings for factor f [`theta_evom(f,j,r)`].

The constant elasticity of transformation frontier defines the profit-maximizing allocation of factors to individual sectors. In equilibrium, the unit value of the aggregate factor is equal to the maximum unit earnings:

$$p^S_{fr} = pvfm_{fr} \quad f \in s_f \tag{C.5}$$

C.2 Market clearance

Supply-demand conditions apply to all goods and factors. Benchmark demand and supply quantities appear as scale factors in many of these equations, typically multiplied by activity levels which are equal to unity in the reference equilibrium.[23]

C.2.1 Firm output (`P(i,r)`)

Aggregate output of good i in region r in the reference equilibrium is `vom(i,r)`:

$$Y_{ir} vom_{ir} = \sum_j ddfm_{ijr} + ddfm_{iCr} + ddfm_{iIr} + ddfm_{iGr} + \sum_s dxmd_{irs} + dst_{ir} \tag{C.6}$$

[23] While not crucial for representation of the model as a nonlinear system of equations, we follow the MCP convention in writing out the market clearance conditions. The equations are "oriented", with supply variables on the LHS and demands on the RHS. Hence, the sense of the equation is $supply \geq demand$. In the core model equilibrium prices should always be positive, but in extensions of the standard model it might be quite common to introduce inequalities and complementary slackness, in which case the proper orientation of the equations is essential. Hence, in equilibrium should the price of a good be zero, economic equilibrium is then consistent with a market in which $supply > demand$.

where the compensated demand functions can be obtained by differentiating the unit cost functions:

$$\begin{aligned}
ddfm_{ijr} &= Y_{jr} vdfm_{ijr} \left(\frac{ci_{ijr}}{p^d_{ijr}}\right)^{\sigma} \\
ddfm_{iCr} &= C_r \left(vdfm_{iCr} \frac{p^C_r}{pc_{ir}}\right) \left(\frac{p^C_{ir}}{p^{dc}_{ir}}\right)^{\sigma} \\
ddfm_{iIr} &= I_r vdfm_{iIr} \\
ddfm_{iGr} &= G_r vdfm_{iGr} \left(\frac{pg_{ir}}{p^{dg}_{ir}}\right)^{\sigma} \\
dxmd_{isr} &= M_{ir} vxmd_{isr} \left(\frac{p^M_{ir}}{pyt^m_{isr}}\right)^{\sigma} \\
dst_{jr} &= YT_j vst_{jr} \frac{p^T_j}{p^Y_{jr}}
\end{aligned}$$

C.2.2 Private consumption (`P("c",r)`)

Consumer demand in region r in the reference equilibrium is vom_{Cr} hence:

$$C_r vom_{Cr} = \frac{RA_r}{p^C_r} \tag{C.7}$$

C.2.3 Composite imports (`PM(i,r)`)

The aggregate value of imports of good i in region r in the reference equilibrium is vim_{ir}:

$$M_{ir} vim_{ir} = \sum_j difm_{ijr} + difm_{iCr} + difm_{iGr} \tag{C.8}$$

where compensated demand functions are given by:

$$\begin{aligned}
difm_{ijr} &= Y_{jr} vifm_{ijr} \left(\frac{ci_{ijr}}{p^i_{ijr}}\right)^{\sigma} \\
difm_{iCr} &= C_r vifm_{iCr} \left(\frac{pc_{ir}}{p^{ic}_{ir}}\right)^{\sigma} \frac{p^C_r}{pc_{ir}} \\
difm_{iGr} &= G_r vifm_{iGr} \left(\frac{pg_{ir}}{p^{ig}_{ir}}\right)^{\sigma}
\end{aligned}$$

C.2.4 Transport services (`PT(j)`)

The aggregate demand (and supply) for transport service j in the benchmark equilibrium is vtw_j:

$$YT_j vtw_j = \sum_{isr} dtwr_{jisr} \tag{C.9}$$

where

$$dtwr_{jisr} = M_{ir} vtwr_{jisr} \left(\frac{p^M_{ir}}{pyt^m_{isr}} \right)^{\sigma}.$$

C.2.5 Primary factors (`PF(f,r)`)

The aggregate demand (and supply) of primary factor f in region r is $evom_{fr}$:

$$evom_{fr} = \begin{cases} \sum_j dfm_{fjr} & f \in m_f \\ evom_{fr} FT_{fr} & f \in s_f \end{cases} \tag{C.10}$$

where the demand for primary factor is given by:

$$dfm_{fjr} = Y_{jr} vfm_{fjr} \left(\frac{c^f_{jr}}{p^{pf}_{fjr}} \right)^{\sigma}.$$

C.2.6 Specific factors (`PS(f,j,r)`)

The net value of benchmark payments to factor f in sector j in region r is `vfm(f,j,r)`:

$$vfm_{fjr} \left(\frac{p^S_{s_f,jr}}{p^F_{s_f,r}} \right)^{\eta} = dfm_{fjr} \tag{C.11}$$

where the demand for primary factor is written above.

C.3 Regional budget (`RA(r)`)

Private and public incomes are given by :

$$RA_r = \sum_f p^F_{fr} evom_{fr} + p^C_n vb_r - p^I_r vom_{Ir} - p^G_r vom_{Gr} + \mathcal{R}_r \tag{C.12}$$

The base year current account deficit in region r is `vb(r)`, and region $r = n$ corresponds to the "numeraire region" who's consumption prices denominates international capital flows (following conventional static trade theory, we hold the current account deficit fixed in counterfactual analysis). Furthermore, tax revenue in region r consists of output taxes, intermediate demand taxes, factor taxes, final demand taxes, import tariffs and export subsidies:

$$\begin{aligned}\mathcal{R}_r = \;& \sum_j \mathcal{R}^o_{jr} + \sum_{ij} \left(\mathcal{R}^{fd}_{ijr} + \mathcal{R}^{fi}_{ijr}\right) + \sum_{fj} \mathcal{R}^f_{fjr} \\ & + \sum_i \left(\mathcal{R}^{pd}_{ir} + \mathcal{R}^{pi}_{ir} + \mathcal{R}^{gd}_{ir} + \mathcal{R}^{gi}_{ir}\right) - \sum_{is} \mathcal{R}^{xs}_{irs} + \sum_{is} \mathcal{R}^{ms}_{isr}\end{aligned} \tag{C.13}$$

Each of these components of tax revenue can be calculated as an ad-valorem or proportional tax rate times a market price times the quantity demanded or produced.

Taxes related to Y_{jr} include output taxes:[24]

$$\mathcal{R}^o_{jr} = t^o_{jr} vom_{jr} p^Y_{jr} Y_{jr} \quad [\texttt{REV\_TO(g,r)}],$$

tax revenue from intermediate inputs:

$$\mathcal{R}^{fd}_{ijr} = t^{fd}_{ijr} p^Y_{ir} ddfm_{ijr} \quad [\texttt{REV\_TFD(i,j,r)}],$$

$$\mathcal{R}^{fi}_{ijr} = t^{fi}_{ijr} p^M_{ir} difm_{ijr}, \quad [\texttt{REV\_TFI(i,j,r)}],$$

and factor tax revenue:

$$\mathcal{R}^f_{fjr} = t^f_{fjr} p^F_{fr} dfm_{fjr} \quad [\texttt{REV\_TF(f,g,r)}].$$

Taxes on household consumption of domestic and imported goods are:

$$\mathcal{R}^{pd}_{ir} = t^{pd}_{ir} p^Y_{ir} ddfm_{iCr}, \quad [\texttt{REV\_TFD(i,"C",r)}],$$

and

$$\mathcal{R}^{pi}_{ir} = t^{pi}_{ir} p^M_{ir} difm_{iGr} \quad [\texttt{REV\_TFI(i,"C",r)}].$$

Taxes on public demand for domestic and imported goods are:

$$\mathcal{R}^{gd}_{ir} = t^{gd}_{ir} p^Y_{ir} ddfm_{iGr} \quad [\texttt{REV\_TFD(i,"G",R)}],$$

and

$$\mathcal{R}^{gi}_{ir} = t^{gi}_{ir} p^M_{ir} difm_{iGr} \quad [\texttt{REV\_TFI(i,"G",r)}].$$

Export subsidies (paid by the government in the exporting region) are:

$$\mathcal{R}^{xs}_{irs} = t^{xs}_{irs} p^Y_{ir} dxmd_{irs} \quad [\texttt{REV\_TXS(i,r,s)}],$$

and import tariff revenues are given by:

$$\mathcal{R}^{ms}_{isr} = t^{ms}_{isr} \left(p^Y_{is}(1 - t^{xs}_{isr}) dxmd_{isr} + \sum_j p^T_j dtwr_{jisr} \right) \quad [\texttt{REV\_TMS(i,s,r)}].$$

[24] Tax revenues in the GAMS codes – both MCP and MGE are represented by the *macros* indicated in square brackets.

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