CHAPTER 12

Global Applied General Equilibrium Analysis Using the Global Trade Analysis Project Framework

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Abstract

This chapter provides an overview of the first two decades of the Global Trade Analysis Project (GTAP) — an effort to support a standardized database and computable general equilibrium (CGE) modeling platform for international economic analysis. It characterizes GTAP in four different dimensions: institutional innovation, a network, a database and a standardized modeling platform. Guiding principles for the GTAP modeling framework include flexibility, ease of use, transparency, and symmetric treatment of production and utility fundamentals across regions. The chapter reviews core modeling assumptions relating to the regional household, private consumption behavior, welfare decomposition, the "Global Bank," treatment of the international trade and transport sector, and imports. Model validation and sensitivity analysis, as well as software issues receive attention as well. The chapter also offers brief overviews of the two major areas of application: international economic integration and global environmental issues. It closes a discussion of future directions for the Project.

Keywords

CGE modeling, GTAP, global economic analysis, international trade policy, climate policy, global database, Center for Global Trade Analysis, institutional innovation

JEL classification codes

C82, D58, F11, F12, F21, F22, Q17, Q31, Q41

12.1 INTRODUCTION: WHAT IS GTAP AND WHY HAS IT SUCCEEDED?[1]

GTAP stands for Global Trade Analysis Project — a term coined in 1991 at the Project's inception. Inspiration for GTAP drew heavily on the Australian experience — specifically the IMPACT project[2] — and sought to dramatically lower the entry barriers to global

1 This section draws heavily on a paper written by Alan Powell for the 10th Anniversary of the Annual Conference on Global Economic Analysis.
2 An excellent history of the IMPACT Project and the contribution of AGE analysis to policy reform in Australia is offered by Powell and Snape (1993).

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applied general equilibrium (AGE) analysis, as well as increasing the potential for independent replication of findings. In his retrospective paper presented at the 10th Annual GTAP Conference, Alan Powell (2007, p. 5) speculates about why GTAP came about:

> *At the most basic level, the 1990s presented a politically ripe time for closer intimacy between countries in trade and capital flows. Yet analysis of the benefits (and/or costs) which might be expected to flow from such closer relations required an analytical framework from which such outcomes could be estimated. This in turn required a comprehensive data base .... Whilst the primary source of such data would usually be from national accounts and related sources in particular countries, the total picture generated by them would have to be free from internal contradictions: the exports from A to B would have to equal the imports into B from A; moreover, this balance would have to be preserved on a commodity-by-commodity basis, for all commodities.*

The first GTAP database was released in 1993, along with a publicly available version of the core model. This release was accompanied by a week-long short course designed to introduce participants to the model and database. Participants from this short course undertook the first outside applications of the GTAP framework, and these were subsequently replicated by graduate students and published in the Cambridge University Press volume, which also documented the model, its parameters and database (Hertel, 1997).

The network grew rapidly, reaching nearly 10,000 members registered on the website at the time of this writing, with few signs of slowing (Figure 12.1a). Database coverage has also grown strongly over the 18 years since the project's inception (Figure 12.1b). Whereas the version 1 database had just 13 regions, the version 7[3] database disaggregated the global economy into 113 regions! In his 2007 evaluation of GTAP, Alan Powell goes so far as to suggest that: "In the discipline of economics there has never been a research oriented community as large or as enthusiastic as the associates of GTAP" (Powell, 2007, p. 2). The remainder of this section will review some of the key elements of GTAP's success, exploring each of these ingredients in turn: institutional design, the network, the database, and finally, the model.

12.1.1 GTAP as an institutional innovation[4]

Economists have long understood the problem with suboptimal provision of public goods, and the GTAP database is fundamentally a public good. "Consumption" of this database by one individual or institution does not diminish the marginal value of consumption of the same database by another researcher. Indeed, as more institutions around the world use this database, its use by any one policy-making agency becomes

[3] For documentation of this version, see Narayanan and Walmsley (2008). Older version documentations are available at https://www.gtap.agecon.purdue.edu/databases/archives.asp. References for data inputs for various data versions are available from https://www.gtap.agecon.purdue.edu/resources/citations.asp.

[4] Readers interested in more details on the history, mistakes, successes and personalities at work during the early years of GTAP are referred to Powell (2007).

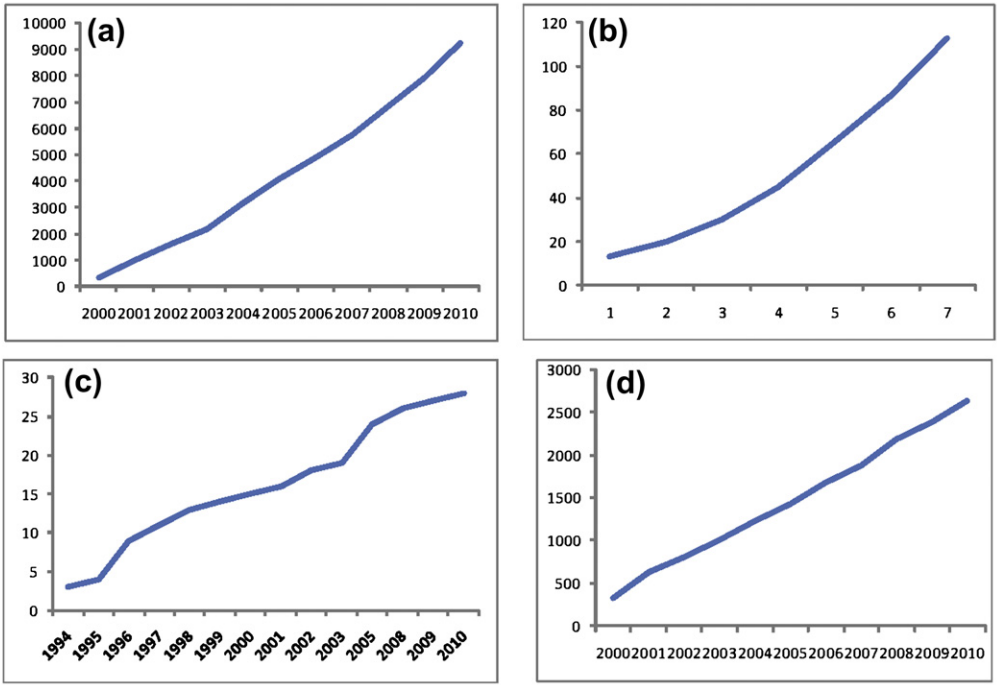

Figure 12.1 Measures of growth in GTAP activities over time. (a) Membership of the GTAP network (website registration). (b) Number of regions in the GTAP database (versions). (c) Number of GTAP Consortium members. (d) Number of resources on the GTAP website.

more valuable, due to its widespread acceptance in international policy circles. Indeed, GTAP may be considered to be a quantitative language, the attractiveness of which grows with the number of fluent speakers. These network externalities are further underscored by the decentralized nature of the database contributions, of which more will be said below. The more countries are using and contributing to this international database, the higher its quality is likely to be. Overall, this seems to be a sound application of "Metcalfe's law," which suggests that the value of a network rises with the square of the number of participants (Shapiro and Varian, 1998).

For these reasons, our original thought in distributing the database was to make it freely available, since the optimal price for such a good, with a zero marginal cost of distribution, is itself zero. Unfortunately, such a pricing strategy also generates zero revenue for the producers of the data and while we managed to cross-subsidize the first version from other grants, financing the production subsequent versions of the GTAP database posed a serious problem. Additionally, we discovered that, in the early 1990s, many institutions were suspicious of free datasets. Accordingly, we introduced a pricing scheme, which has evolved over time into a highly differentiated structure, requiring significant contributions from government agencies and consulting firms, and more modest fees for academics, with extremely low fees for individual researchers in developing countries.

However, even in today's reasonably mature market, database sales revenues cover only a fraction of the cost of producing the GTAP database. This is partly due to the difficulty in excluding use by non-subscribers and partly due to the paucity of funding for many research groups studying global economic policy — particularly in developing countries. Another problem is that the inputs required for this global database are far-ranging and involve contributions by many of the world's leading international economic and policy institutions. In order to solve these funding and data access issues, we established the GTAP Consortium in 1993. This is a group of national and international agencies which use the GTAP database heavily, and which have a strong interest in seeing it succeed and in shaping its future. Each Consortium member is represented on the GTAP Advisory Board, which meets in conjunction with the Annual Conference on Global Economic Analysis co-organized by the Center for Global Trade Analysis at Purdue University. Board members play a key role in securing data contributions, evaluating the quality of the data inputs and outputs, and generally building confidence among policy makers in the final product. Membership in the Consortium has mirrored growth in other Project metrics, rising from four members in 1993 to 27 in 2011 (Figure 12.1c). The recent leveling off of this curve reflects the combination of two factors: relative satiation of the pool of public-minded institutions active in quantitative analysis of global economic issues and also the limited capacity of a relatively small Center to relate to a larger group of sponsors.

There is little doubt that the formation of this Consortium, and the associated Advisory Board, has played critical role in the long-term success of GTAP. It ensures continuity of funding from a wide range of institutions so that no one institution has undue influence on the outcome. It also ensures that those constructing the database listen closely to a cross-section of policy-making interests as they make plans for the next release. However, because this publicly funded project is based in academia[5], there is some inertia — a good thing in this case — and so the Project is not excessively influenced by the latest idea adopted by a particular President, Prime Minister or Minister of Finance!

12.1.2 GTAP as a network

If the Advisory Board has been the steering wheel for the GTAP vehicle, the network has been its engine. As shown in Figure 12.1(a), membership in the network has grown steadily since electronic records were systematically saved (the year 2000). With nearly 10,000 members, this is one of the largest networks of economists worldwide. This growth has been fueled by a variety of factors — some on the "supply side" and hence under the

5 There is little doubt that GTAP would not have succeeded in the absence of strong leadership and support at Purdue University, particularly in the Department of Agricultural Economics where this Project is housed.

influence of the Center, and some on the “demand side” and largely exogenous to the Project itself. On the demand side, there has been an explosion of interest in the quantitative analysis of global economic issues since the Project’s inception. In the first few years of the GTAP Advisory Board meetings, the interests of the members from Australia, Asia, North America and Europe were rather diverse, and often inward-looking. However, by the conclusion of the Uruguay Round of World Trade Organization (WTO) trade negotiations in the mid-1990s, there was a remarkable convergence of interests, first around trade policy issues, including the explosion of free trade agreements (FTAs) and then around environmental issues – particularly climate change and associated greenhouse gas mitigation policies. Together, these two broad areas have fueled much of the demand for GTAP-based analyses. Both issues cut across nearly all sectors of the economy and both are global in their impacts – hence necessitating global CGE analyses.

On the supply side of this picture, the Center has invested considerable resources in building the network. Indeed, the first database was released as part of a public short course offered on the campus of Purdue University in the summer of 1993. These short courses have been offered on an annual basis since that time, although they have been subsequently unlinked from the database releases. Over the past two decades, more than 800 individuals have been through GTAP short courses, and these have been held around the world. Since 1998, these courses have also had an increasingly important online, web-based component. This has greatly improved learning outcomes and these course offerings have clearly done a great deal to enhance the growth of the network. Of course one risk with such widespread courses is that unqualified users will generate misleading results. However, the GTAP philosophy has been to allow widespread access to modeling tools and rely on subsequent peer-review to “sort the wheat from the chaff.”

Conferences were introduced later, in 1998, in response to interest on the part of course participants to return to Purdue University and present their own work. Subsequent conferences have been held in Europe, Asia, Australia, Africa, South America and North America. These events typically attract about 250 participants, and provide an excellent venue for researchers and policy advisors to exchange ideas. Papers cover a variety of topics, ranging from applied theory, to economic modeling, econometrics, data issues and policy analysis.

While courses and conferences facilitate face to face interactions, the vast majority of GTAP networking occurs over the internet, either through the website (www.gtap.org) or via email communications. GTAP came into being with the advent of the worldwide web and it was one of the early projects to take full advantage of this new technology. Over the past two decades, the website has undergone many upgrades. It now attracts more than 100,000 visits per year and more than a half million annual page views. Throughout this period it has been primarily focused on supporting the network. Individual members are profiled on the website, along with their publications and conference papers, and every two weeks a new set of members are highlighted on the

GTAP home page. Peer-reviewed *GTAP Technical Papers* document new innovations in theory, parameters, data and software for users. Working Papers and Research Memoranda are also posted. Figure 12.1(d) plots the growth in GTAP web-based resources (e.g. papers, research memoranda, documentation) over the past decade. The number of resources on the GTAP website now exceeds 2600. And the cumulative number of times these resources have been accessed over the past decade is approaching 2 million. Indeed, the website is the lubricant that allows the GTAP network engine to function.

One of the challenges posed by the rapidly growing GTAP network is the tension between openness, on the one hand, and quality control, on the other. Indeed, this tension is characteristic of any network (Shapiro and Varian, 1998). The idea of a publicly available CGE model is not new – the ORANI model of the Australian economy has been widely used by individuals in academia and government agencies in that country since the beginning of the 1980s (Dixon *et al.*, 1982; Powell and Snape, 1993). However, the global coverage of GTAP, coupled with the opportunities for costless dissemination via the Worldwide Web, have taken this idea to a new – and some would say dangerous – level. There is clearly great scope for abuse of any model and GTAP is no exception. Early on in the project there were calls for more quality control – with some even suggesting that all GTAP applications should be screened by staff at Purdue University. However, these pressures were resisted. We argued that it is instead up to the consumers of model results to discriminate between abuses of the framework and high-quality applications of the model. As the novelty of being able to generate thousands of numbers from global economic scenarios has worn off, it appears that we are settling into a state of affairs where more is being expected of the economists using the GTAP framework and peer review is playing its proper role in "sorting the wheat from the chaff."

One of the other factors driving the growth and prosperity of the GTAP network is economists' newfound appreciation for collaboration – across fields in economics, across disciplines and across national borders. Whereas experiments in high-energy physics – an undertaking which I would argue is of similar complexity, challenge and expense to that of modeling the global economy – often have hundreds of collaborators; economists have tended historically to work alone or in small groups. Yet such an approach is ill-suited to global economic analysis. As Alan Powell writes in his Foreword to the 1997 book documenting the GTAP framework:

> *Given that a practical AGE model involves a very heavy investment of intellectual effort and data-garnering, it would be amazing if economists did not recognize the potential for economies of scale and scope. The realization of such economies requires the proprietor of a model building effort to see most of the model's core ingredients – such as its standard or default equation listing, database, and parameter file – as public goods. Around such publicly (or semipublicly) available tools, we would expect a community of modelers to develop. Yet such has tended to be the exception rather than the rule.* (Powell, 1997, *pp. xiii–xiv*)

Finally, I would argue that an important element of GTAP's success in building this global network of researchers is the prominent position given to the individuals creating databases employed by network members. Unlike most gatherings of economists, at GTAP events database experts have something akin to "rock star status," being featured in special talks as well as sought out for collaboration and advice. A prominent subset of the GTAP Research Fellow Awards, given out each year at the Annual Conference, recognizes contributions to the GTAP database. By highlighting the importance of these fundamental contributions, the network ensures that its lifeblood continues to flow. And with this, we turn to a discussion of the GTAP database as a key resource.

12.1.3 GTAP as a database

By definition, this global economic database endeavors to record annual flows of goods and services for the entire world economy in the benchmark year. By targeting each region's GDP in the database construction process, aggregated GDP equals global GDP as reported by the World Bank. Construction of the database begins with the assembly of input-output tables (or condensed social accounting matrices) for a large number of economies (93 at the time of this writing – covering about 97% of global GDP). Where these are not available, the structure of the national economy is inferred from a similar economy.[6] With these interindustry relationships firmly in hand, each regional economy is "fitted" to macroeconomic data for the benchmark year, including private consumption, government consumption, investment, exports and imports (James and McDougall, 1993). "Savings" in the standard database is a residual category used to balance the macroeconomy and absorb a host of omissions, including foreign income payments.

The most fundamental problem in constructing this global database rests in reconciling the bilateral trade and service flows amongst the national economies. It is widely known that countries do not agree on these flows. Indeed, disagreements about the magnitude of bilateral trade between China and the US are a frequent source of political tension. Differences in valuation of imports [f.o.b. (free on board) versus c.i.f. (cost, insurance and freight)], differences in reporting years, errors in recording trade flows, smuggling and the treatment of re-exports are but a few of the reasons for discrepancies between the exports reported from one country and the imports reported by another. Unlike national trade statistics, GTAP cannot live with such discrepancies. The current approach to reconciliation of merchandise trade flows is based on reliability indexes that indicate which reporter is more likely to be accurate for any given bilateral flow in a particular commodity category (Gehlhar, 2000). The approach to services trade reconciliation is more

[6] The biggest economy currently mimicked in this way is Saudi Arabia.

mechanical, since the availability of bilateral trade flows are much more limited (Lejour *et al.*, 2010).

Given its early emphasis on analyzing multilateral trade liberalization, the GTAP community has invested a great deal of effort in obtaining accurate estimates of border protection measures. As a result, this aspect of the database has matured tremendously since the Project's inception. Protection estimates for the first GTAP database were copied by hand out of the WTO's *Trade Policy Reviews.* This was possible due to the fact that there were fewer sectors and only a dozen regions in the database, and no attempt was made to distinguish bilateral differences in rates of protection. Once GTAP-based models began to be used in high-profile policy debates, this simple approach was no longer acceptable. The majority of the Uruguay Round evaluations published in the volume edited by Martin and Winters (1996) were based on GTAP data and utilized protection data obtained through collaboration between the World Bank and the UN Conference on Trade and Development (UNCTAD). These were the result of careful processing of the protection data, starting with the tariff line (Martin *et al.*, 1997). Such processing was critical for capturing the effects of the final trade agreement, which entailed a complicated set of liberalization rules, implemented at the tariff line.

The current version of the GTAP tariff database (version seven at the time of writing) is far more sophisticated (Bouët *et al.*, 2004; Laborde, 2010). It represents joint work by researchers at the Centre d'Etudes Prospectives et d'Information Internationales (CEPII), the International Trade Centre in Geneva, the International Food Policy Research Institute (IFPRI), UNCTAD and the WTO – all of whom are GTAP consortium members. This database offers full treatment of bilateral trade preferences, which have proliferated in recent years. Tariff rate quotas are also accounted for, and distinctions are made between *ad valorem* and specific tariffs. When combined with data on bound tariff rates, this permits extremely sophisticated analyses of multilateral trade reforms such as those undertaken by Bouët *et al.* (2005) Jean *et al.* (2006) and Bouët and Laborde (2010a). Recently developed software (TASTE) has put this tariff line analytic capability in the hands of the entire network (Horridge and Laborde, 2010).

The tariff example underscores a key part of the GTAP database philosophy, which is: "Find the best person/institution in the world to do the job and convince them to become a database contributor." The measurement, assembly, processing and analysis of protection data is highly sophisticated and entails specialized skills. By drawing into the Consortium the world's leading institutions working on border protection, GTAP has been able to greatly enhance the quality of information used for the analysis of complex bilateral and multilateral trade agreements.

The other types of "protection" that have received considerable attention in the GTAP database are agricultural support and export subsidies. These have been important, since the WTO negotiations have included agricultural subsidies as part of the multilateral trade negotiations and they have been a highly contentious part of these deliberations. Fortunately, we have been able to draw on the excellent work of the Agricultural Directorate of the Organization for Economic Cooperation and Development (OECD) for internationally comparable estimates of domestic support (Huang, 2009). Translating these measures of support into model-based distortions has presented a challenge, particularly since the conditions for receiving such support are continually evolving. Over time, there has been a strong trend towards the decoupling of agricultural support from production decisions. As a consequence some of these payments are now treated as being capitalized into the value of agricultural land. For subsidies that are fully decoupled, the rate of subsidization for a given factor must be equal across sectors and therefore non-distorting in the comparative static, deterministic modeling context.

There are many extensions of the GTAP database that have been undertaken over the past decade. Most of these are one-off exercises, funded by specific research projects. Sometimes these efforts are eventually folded into the standard database. This was the case with an energy database project funded by the US Department of Energy in the 1990s. Energy volumes associated with fossil fuels combustion are now part of the standard release GTAP database, permitting calculation of the resulting greenhouse gas emissions.[7] A more recent example of a major database extension is a five-year, US Environmental Protection Agency (EPA) project aimed at improving capacity for analyzing land-based greenhouse gas mitigation policies. This resulted in a new land-use database for agriculture and forestry which draws on spatially explicit, subnational databases. These grid cell data are subsequently aggregated to the level of relatively homogeneous "agro-ecological zones" (AEZs) for incorporation into the GTAP model. The EPA project also developed a non-CO_2 greenhouse gas emissions database, the majority of these greenhouse gases are emitted from agriculture. This work is documented, along with various applications, most of which are based on the GTAP data, in Hertel *et al.* (2009). This more detailed treatment of land as well as non-CO_2 emissions has not yet been folded into the standard database build stream, so updates occur on a sporadic basis, as resources and time permit.

Other major extensions to the GTAP database which have been undertaken on a satellite basis relate to global migration (Walmsley *et al.*, 2007a) biofuels (Taheripour *et al.*, 2007) and electric power (Babiker *et al.*, 2001). Domestic taxes have also begun to attract more interest. Presently the domestic commodity tax structure in GTAP is largely inherited from the domestic databases, where the treatment is quite uneven. Primary

7 While incorporating energy volumes into the GTAP database may seem like a trivial exercise, it is in fact quite complex. The reason is that once you have a value, and a corresponding volume flow, you have an implied price. And that price can be quite important if you are applying a specific tax (e.g. a carbon price) to the volume flow. Therefore, values and volumes must be rendered consistent if the resulting prices are to make sense. Since volume data typically come from commodity data sources and value data from industry sources, large discrepancies often exist, even for reliable data sources.

factor taxes are dealt with in a standardized fashion, but they have been the subject of considerable criticism with regard to the treatment of capital income taxation (Gurgel *et al.*, 2006). The explosion of GTAP applications and possible extensions has vastly outstripped the capacity of the small core staff at the Center to respond to these many potential areas of application. This has led to proposals by the Center to move to an open-sourcing mode, wherein individuals in the network would contribute database modules. Thus far we have not been able to secure funding for such a move – it would require considerable resources: (i) for rewriting many of the database programs so they could be operated by those outside the Center and (ii) to offset the effect of lost sales revenue. However, the open-sourcing vision has been present with the Center for the past 10 years (Hertel, 1999) and it remains a central feature of our long run strategic plan (Center for Global Trade Analysis, 2008).

One modest step towards an open-sourcing model of database construction has been taken in the area of sector disaggregation. This is an area where there is nearly infinite demand for data work. Policy makers considering a new problem will inevitably ask for additional breakout of sectors and/or commodities. Yet such disaggregation is very costly in a global framework. Whereas adding another country simply requires development of a new domestic database that conforms with the GTAP standards (Huff *et al.*, 2000) followed by a reaggregation of the remaining countries in the composite region from which it was obtained, disaggregating sectors requires revisiting each and every one of the more than 100 input-output tables underpinning the GTAP database. In many cases this additional detail was not available in the original submission, so that further data must be gathered to permit such a split to be undertaken. In short, this is not a task that the staff at the Center would take lightly.

Partly as a result of the challenges posed by sector disaggregation, the original GTAP database simply adopted the same sector breakdown used for the SALTER Project (Jomini *et al.*, 1994). Indeed, the original national databases were all inherited from SALTER. In response to strong interest in agricultural trade amongst many of the GTAP consortium members in the wake of the Uruguay Round of WTO negotiations, the farm and food sectors were further disaggregated in the version four database (McDougall *et al.*, 1998). Since many input-output tables are limited in their agricultural detail, the Center has relied increasingly on Everett Peterson's (2002) methodologies for disaggregation of agriculture using data from the UN Food and Agricultural Organization (another GTAP Consortium member).

Disaggregation of agriculture was followed by a disaggregation of service sectors in the GTAP version five database (Dimaranan and McDougall, 2002) in order to better match up with WTO negotiations on cross-border provision of services. From the point of view of international trade, the disaggregation of trade and transport services into air, sea and ground was also an important advance, permitting differences in transport margins, not only by commodity and route, but also by mode of transport. This brought the total number of sectors to 57 and there has not been further disaggregation of sectors in the standard GTAP database since that time.

While there is considerable pressure to disaggregate further, the demand for such disaggregation is not concentrated in any particular areas of the economy. Indeed, a recent survey of GTAP users produced a nearly uniform distribution across the 57 extant sectors, when participants were asked where they would like to see additional disaggregation. In an effort to better meet the needs of the policy-oriented users of GTAP, Mark Horridge at the Centre of Policy Studies produced an extremely useful utility for disaggregating sectors in GTAP, nicknamed SPLITCOM (Horridge, 2005). This allows users to specify information on cost shares and sales shares for the subsectors in all regions, thereupon producing an internally consistent GTAP database with the additional sectoral detail. It is now routinely used by members of the GTAP community.

12.1.4 GTAP as an economic model

Since the GTAP database was designed explicitly for use in global, AGE analysis, it must satisfy many consistency requirements that are not exhibited in most global databases. As noted above, what one country exports, another country must import. Regional economies must be on their budget constraint – once international income payments and capital flows are accounted for. Sectors must earn zero profits. Global savings must equal global net investment. And the exports of global transport services from individual countries must equal the demand for these same services, as evidenced in the international margins applied to merchandise trade flows between countries. The dataset must also be accompanied by behavioral parameters if users are to be able to specify a full general equilibrium model and these parameters depend on the data structure, as well as the underlying model. For this reason, there must be a standard GTAP model. Section 12.2 focuses on the structure of the standard GTAP model, after which we will turn to important extensions and future areas of research.

12.2 DESIGN OF THE STANDARD GTAP MODELING FRAMEWORK

12.2.1 Guiding principles

There were three guiding principles behind formulation of the standard GTAP framework. First of all, the vision was *not* one of building the definitive model for analyzing international trade. Rather the standard model was designed to be flexible, robust and readily modified to meet specific needs. In general, the GTAP philosophy has been "one database, many models." Indeed, as the *GTAP Technical Paper* series illustrates, there are many extensions to the standard model that have been made available to the network, including: imperfect competition and scale economies, capital accumulation, endogenous technology spillovers, energy substitution, dynamics and international capital mobility, structural issues specific to agriculture, poverty analysis, international migration, and nested tariff line modeling of competition between highly disaggregated products. The standard model's design features of robustness and ease of use have been a key to the success and longevity of the project. At this point, the majority of the GTAP consortium members have their own, in-house models. In some cases, these are modifications of the standard model; in other cases, they are wholly distinct models, implemented in different software environments, and so on. However, all of these models have common elements – a point which brings us to the second guiding principle behind the standard model's design.

The standard model has been designed to run with no additional data or parameters beyond those provided in the GTAP database. Since there are some significant gaps in that database, the model had to be adapted to overcome these limitations. A good example is the global trade and transport sector discussed in more detail below. Since data are not available on which countries actually supply the international shipping services used on particular routes for particular commodities, it was necessary to specify an international trade and transport sector that absorbs all the international freight and insurance services supplied by individual countries, and that supplies all of the international margins services demanded worldwide. Another such example is offered by the Global Bank (see below). This is also the case with the so-called "regional household," the expenditure function of which is used to determine the equivalent variation in regional welfare associated with a given policy. These are all modeling decisions which were dictated by the need to overcome data limitations, while retaining a theoretically consistent global modeling framework.

The final guiding principle behind the standard GTAP model has been that of symmetric treatment of production and utility functions across regions. At the time the GTAP model was being constructed, there were examples of global models that were fully symmetric (e.g., Whalley, 1985) and those that were asymmetric (Fischer *et al.*, 1988). The argument behind allowing model specifications to vary by region is compelling – each country has distinguishing features which need to be handled differently. It can be readily argued that it is better to leave these design decisions to the local experts, as opposed to insisting that they all conform to a highly stylized format. However, in practical terms, the asymmetric approach has never really worked in the global modeling context. Problems of model solution, and even greater problems of model debugging, interpretation and analysis become overwhelming when working with a global model in which the component parts have been designed in fundamentally different ways. GTAP also faced the constraint of having a single, global database, which also dictates a symmetric model structure. As a result, the only differences in regional behavior in the GTAP model are those that arise from differences in the relative importance of economic flows (e.g., cost and revenue shares), differences in model parameters (but only in the case of consumer demand in the standard model) and differences in model closure at the discretion of the user (e.g. unemployment, fixed trade balance, etc.).

12.2.2 Regional household

The GTAP model is designed to assess the *inter-regional* incidence of economic policies. As such, it is important to have a unique measure of regional welfare. Towards this end, a regional household must be specified. The use of a regional household, maximizing welfare from current consumption, future consumption and the provision of public goods, is arguably one of the more useful, but also more frequently misinterpreted, elements of the standard GTAP model. Rather than modeling the separate elements of final demand as being derived from distinct entities, the GTAP model incorporates private consumption, government spending and savings directly into the regional household's utility function. Therefore, regional welfare might fall, even when private consumption rises, if government consumption and/or savings are adversely affected by a given policy. In short, in the standard closure, private spending, government spending and savings are all determined as part of a single utility maximization problem undertaken by the *regional household*.

This is a controversial approach as it is common in CGE models to fix real government spending, and possibly also investment, focusing on private consumption as the relevant welfare metric. However, in many countries, private consumption is less than half of GDP — in some cases less than 40% (e.g. China). Indeed, globally private consumption accounts for just 60% of GDP. Therefore, exogenously fixing government consumption and investment or savings may result in missing a large part of the macroeconomic story associated with, for example, trade reforms. By including this in the regional household's utility optimization, we can obtain a more complete picture of the potential adjustments and the aggregate regional welfare changes in the wake of economy-wide shocks. However, this begs the question — how can you incorporate government spending and savings into a static welfare maximization framework?

The motivation for including savings in this static utility function derives from the work of Howe (1975) who showed that the intertemporal, extended linear expenditure system (ELES) could be derived from an equivalent, static maximization problem, in which savings enters the utility function. Specifically, Howe begins with a Stone—Geary utility function, thereupon imposing the restriction that the subsistence budget share for savings is zero. This gives rise to a set of expenditure equations for current consumption that are equivalent to those flowing from Lluch's (1973) intertemporal optimization problem, thereby justifying the static representation of savings in the utility function as a proxy for future consumption. In other words, even without explicitly modeling future consumption decisions, the inclusion of savings in the utility function allows us to capture the tradeoff between present and future consumption in a static model. At the top level of the GTAP model's regional household demand system we employ a special case of the Stone–Geary utility function in which all subsistence shares (not only for savings) are equal to zero. This reduces to the Cobb–Douglas utility function.

The other feature of the standard GTAP model's regional household utility function requiring some explanation is the use of an index of current government expenditure to proxy the welfare derived from the government's provision of public goods and services to private households in the region. Here, we draw on the work of Keller (1980, Chapter 8), who demonstrates that if: (i) Preferences for public goods are separable from preferences for private goods and (ii) the utility function for public goods is identical across households within the regional economy, then we can derive a public utility function. The aggregation of this index with private utility in order to make inferences about regional welfare requires the further assumption that: (iii) The level of public goods provided in the initial equilibrium is optimal. Users who do not wish to invoke this assumption can employ an alternative closure, such as fixing the level of aggregate government utility while letting private consumption adjust to exhaust regional income on expenditures. However, doing so destroys the appealing welfare properties of the regional household utility function.

There is an important complication which arises in the GTAP model due to the fact that private consumption is non-homothetic. Therefore, the usual conditions for multistage optimization do not apply. This led to an inconsistency in the original GTAP model that evidenced itself in the welfare decomposition (see below). The problem was fixed by McDougall (2002) who developed a new theory of multistage optimization in the presence of non-homothetic subaggregates. The trick is to recognize that the "cost" of private utility varies with the level of private consumption expenditure. This, in turn, alters the nature of the top-level utility maximization problem, since the regional household must take account of the fact that the "price" of private utility is no longer constant. In the revised model, McDougall shows that the optimal expenditure shares derived from the regional household's Cobb–Douglas utility function are no longer constant; rather they vary with changes in the cost of private utility. In general, given the current representation of private consumption behavior in the model (see below), this means that, as countries become richer, utility from private consumption becomes more costly and the regional household tends to spend more of its income on public goods and savings. Such a change seems plausible and there is some empirical support for this. In particular, in their cross-section analysis of national final demands, Reimer and Hertel (2004) find that private consumption shares fall, while national public consumption generally rises with increases in *per capita* income. However, the rate at which these changes occur in the GTAP model have not yet been calibrated to reproduce this empirical evidence, so this feature cannot yet be counted as a strength of the modeling framework.

12.2.3 Modeling private consumption behavior

Considerable thought went into the modeling of private consumption behavior in the standard GTAP model. This is because it was recognized that the ensuing price and income elasticities of demand could play a significant role in determining the incidence of policies as well as the pattern of sector growth over time. In the end, the choice was made to use the constant difference of elasticities (CDE) minimum expenditure function initially proposed by Hanoch (1975) in response to the flurry of work occurring at that time involving second-order flexible functional forms (e.g. the translog). He accurately foresaw the need for intermediate functional forms, more flexible than the directly additive ones such as the linear expenditure system (LES) and constant elasticity of substitution (CES) function, but more parsimonious in parameters than the so-called, fully flexible forms, and also globally well-behaved. He achieves this middle ground by imposing *implicit additivity* on the underlying preferences. In particular, the expenditure function is additive in normalized prices, whereby the normalization factor is minimum total expenditure, which in turn depends on prices and utility. Since the exponent on each of these price terms differs by commodity, it is not possible to isolate expenditure on the left-hand side of the CDE's defining equation and it is therefore an *implicit* expenditure function.

The beauty of the CDE is that there are just enough free parameters to permit its calibration to two vectors of own-price and income elasticities of demand. Indeed the N substitution parameters in the CDE show a natural relationship to the N compensated own-price elasticities of demand and, once these N parameters have been obtained, the $N-1$ expansion parameters may be shown to be closely related to the individual income elasticities of demand (Hertel *et al.*, 1991). Of course, this does not ensure that the resulting CDE parameters satisfy the necessary regularity conditions for use in a CGE model, and in practice calibration requires the solution of a constrained optimization problem in which the parameters are chosen in order to minimize the deviation between the estimated and the calibrated elasticities, subject to the regularity constraints (Hertel *et al.*, 1991).

An important limitation of the CDE is that commodities that are luxuries in initial equilibrium will remain luxuries in the future, regardless of how rich the household may become – and similarly for necessities (Yu *et al.*, 2004). However, such is not always the case empirically. A good counter-example is offered by consumers' preferences for meat products. At very low income levels, meat products have been shown to be a luxury good (Cranfield *et al.*, 2003). However, as *per capita* income rises the income elasticity of demand for meats falls below one, following the path of other food commodities until, at very high income levels, the marginal budget share for food is nearly zero. As Yu *et al.* (2004) demonstrate, this causes a considerable problem when undertaking long-run projections for an economy that is relatively poor (e.g. China prior to 2000) but which is experiencing rapid growth. In such cases, the projected rate of growth in food consumption can be explosive.

The problem of accurately capturing the evolution of households' expenditure patterns over long periods of time with significant income growth was addressed squarely in the work of Rimmer and Powell (1996) who proposed a new functional form for final demand – inspired in part by Hanoch's idea of implicit additivity. Dubbed "An Implicitly Additive Demand System" (AIDADS), their new functional form contains $3N-2$ estimable parameters, all of which are focused on characterizing the expansion path for consumer goods as incomes rise. Like the LES, AIDADS includes a subsistence parameter for each of the N goods. This defines the level of consumption below which a household may not fall. Therefore, this portion of demand is insensitive to prices and incomes. There are also $N-1$ parameters governing the marginal budget shares by commodity at very low levels of income (subsistence expenditure). These two sets of parameters allow the model to capture the evolution of spending patterns amongst poor countries/households. The final set of $N-1$ estimable parameters describes the commodity marginal budget shares at very high income levels. When these are combined with the foregoing parameters describing behavior at low income levels, AIDADS can capture the phenomenon described above for meat consumption, wherein the household budget share devoted to this commodity rises at low levels of income and then proceeds to fall as income continues to rise. Yu *et al*. (2004) show that incorporating AIDADS into the GTAP model can generate much more sensible patterns of consumption and sector evolution as economic growth takes place. Unfortunately, AIDADS is not very flexible in price space and since it is the price elasticities of demand which are foremost in many of the comparative static GTAP policy simulations – wherein income changes very little, but prices may change a great deal – this limitation has precluded replacing the CDE with AIDADS in the standard GTAP model.

12.2.4 Measurement and decomposition of regional welfare

Regional welfare in the standard GTAP model is reported as the percentage change in regional utility, or, alternatively, as the associated equivalent variation. Most policy-oriented studies report the latter, as policy makers prefer to think about the value-based welfare change associated with a given policy. However, in a model with vastly different sized regional economies, expressing equivalent variation as a percentage of initial period expenditure, or equivalently, reporting the percentage change in utility is preferred for inter-regional comparisons. Small percentage changes in welfare in large regional economies can dwarf proportionately more important changes in the welfare of smaller economies.

The most difficult aspect of general equilibrium policy analysis is that of explaining the results, particularly the welfare results. In the standard GTAP model, these are a function of terms of trade changes (inter-regional shifting of welfare) and allocative efficiency changes (i.e. changes in production or consumption efficiency due to the presence of distortions). In many simulations, authors also vary technology and possibly endowments. These may vary endogenously via closure changes (e.g. unemployment, technological spillovers, etc.) or they may be determined exogenously (they may simply assume that "something good happens" due to a policy reform, e.g. improved productivity). Disentangling all of these factors affecting regional welfare is a very difficult task indeed. Fortunately, we have developed an analytical decomposition that permits a breakdown of the sources of welfare gain to be undertaken. The decomposition is documented in Huff and Hertel (1996) and involves a rather lengthy set of algebraic substitutions and simplifications, resulting in an expression for regional equivalent variation that, instead of being based on the regional household's expenditure function, is based instead on the various sources of efficiency and terms-of-trade changes.[8]

Huff and Hertel (1996) begin this decomposition with the total differential of the model equation that computes regional income as a function of payments to endowments (net of depreciation), plus tax revenue, less subsidies paid. Into this income change equation they substitute the linearized zero-profit conditions for each sector, the linearized market-clearing conditions for traded goods and endowments, and the price-linkage equations. The change in income on the left-hand side of this expression is next deflated by the change in the regional household price index and this is also subtracted from the right-hand side of the expression. Through a series of algebraic simplifications, an expression is obtained which gives the change in real *per capita* expenditure as a function of changes in endowments and taxes interacting with quantity changes. Appropriate scaling converts the real income change into the regional equivalent variation and we obtain Equation (12.1):

$$EV_s = (\Psi_s)\left\{\begin{array}{l} \sum_{i=1}^{N}\sum_{r=1}^{R}(\tau_{\mathrm{M}irs}PCIF_{irs}dQMS_{irs}) \\ +\sum_{i=1}^{N}(\tau_{\mathrm{CD}is}PD_{is}dQD_{is}) \\ +\sum_{i=1}^{N}(\tau_{\mathrm{CM}is}PM_{is}dQM_{is}) \\ +\sum_{i=1}^{N}(\tau_{\mathrm{O}is}PD_{is}dQO_{is}) \\ +\sum_{i=1}^{N}\sum_{r=1}^{R}(QMS_{irs}dPFOB_{irs}) \\ -\sum_{i=1}^{N}\sum_{r=1}^{R}(QMS_{irs}dPCIF_{irs}) \end{array}\right\} \tag{12.1}$$

[8] Baldwin and Venables (1995) independently developed a theoretical decomposition in the context of the gains from regional trade agreements which is similar in spirit.

This particular decomposition of equivalent variation EV for the household in region s is written on the assumption that the only policy distortions are tariffs and commodity taxes; it also holds technology, population and endowments fixed. (In the full GTAP decomposition, factor market distortions and variations in the other determinants of regional welfare are also permitted.) Here, subscript i is indexed over the traded commodities, r denotes exporter region and s refers to the importing region. Ψ_s is a scaling factor which is normalized to one initially, but changes as a function of the marginal cost of utility in the presence of non-homothetic preferences (McDougall, 2002).

The first four summations on the right-hand side of (1) measure the changes in efficiency of resource utilization in region s. These involve the interaction of tax/subsidy distortions with the change in associated quantities. Consider what happens when we eliminate the bilateral tariff on imports into region s of commodity i from trading partner r. The relevant term appears in the first summation:

$$EV_s(\tau_{Mirs}) = \Psi_s(\tau_{Mirs} PCIF_{irs} dQMS_{irs}). \tag{12.2}$$

Here, $(\tau_{Mirs} PCIF_{irs})$ is the per unit tariff revenue on imports of good i from r into s, associated with the *ad valorem* tariff rate τ_{Mirs}. This is multiplied by the change in the volume of imports of i from r into s: $dQMS_{irs}$. The "Harberger triangle" that we are measuring with this term may be seen in Figure 12.2. In order to evaluate the area of this triangle as the tariff is eliminated, we must consider both the "base" $(\tau_{Mirs} PCIF_{irs})$ and the "height" $(dQMS_{irs})$.[9] By continually reevaluating the base of this triangle as the tariff is eliminated, we track the diminishing gap between $PCIF$ and PMS. In this way, we are able to accurately measure its area, which is then added to the aggregate welfare measure.

In order to properly perform the numerical integration depicted in Figure 12.2, the welfare decomposition equations must be solved in conjunction with the CGE model, using appropriate solution procedures. We use the GEMPACK software suite developed by Harrison and Pearson (2002) which is ideally suited to this problem, as it solves the non-linear CGE model using a linearized version of the behavioral equations, coupled with updating equations that link the change, in this case $dQMS_{irs}$, with the levels variables, QMS_{irs}. Standard extrapolation techniques can be used to obtain arbitrarily accurate solutions to any well-posed non-linear problem (Harrison and Pearson, 1996).

Note from Equation (12.1) that, in addition to tariffs, we consider volume interactions with consumption taxes on household purchases of both domestic goods (τ_{CDis}) and imported goods (τ_{CMis}). Taxes (or subsidies) on output also play a role. If $\tau_{Ois} < 0$, then the production of commodity i in region s is subsidized and an expansion of output $(dQO_{is} > 0)$ will contribute negatively to efficiency and hence to equivalent variation.

9 For those accustomed to computing "Harberger triangles" as ½ base * height, it may appear that we need a ½ premultiplying the right-hand side of Equation (12.2). However, this is not required. The numerical integration procedure facilitated by GEMPACK continually re-evaluates the base of the "triangle" (Harrison and Pearson, 2002).

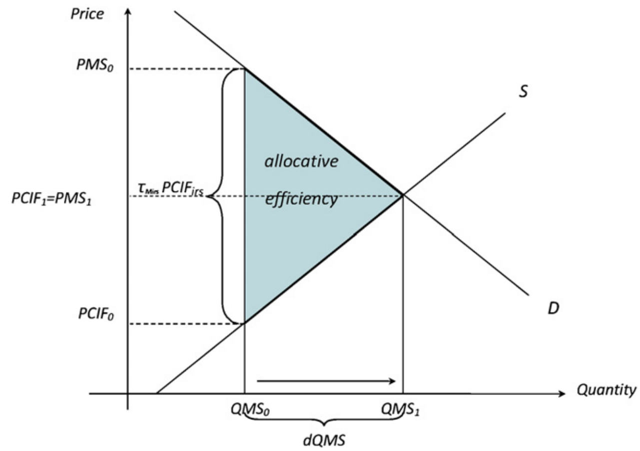

Figure 12.2 Allocative efficiency gains from tariff elimination.

The absence of terms associated with income, export and input taxes, is due to the fact that we are assuming these taxes are zero in this stylized example. In normal GTAP simulations, these distortions are also present and their interactions with policy impacts are taken into account.

The final two terms on the right-hand side of Equation (12.1) refer to the terms-of-trade effects for region *s*. These determine how the global efficiency gains are shared amongst regions. If region *s*'s export-weighted f.o.b. prices rise, relative to her import-weighted c.i.f. prices, then the terms of trade will improve. Since one region's export prices (inclusive of international transport services exports) are another region's import prices, the improved terms of trade for region *s* translates into a terms-of-trade deterioration in the rest of the world (taken as a group).

As noted above, Equation (12.1) permits an exhaustive decomposition of each region's equivalent variation. By comparing this alternative method of computing equivalent variation to the equivalent variation computed directly from the regional household's expenditure function, users of the GTAP model also obtain a useful consistency check on the model. Since the equivalence of these two measures relies on all of the equilibrium conditions holding, any data or model inconsistencies will show up in a discrepancy between equivalent variation computed from the consumption side and equivalent variation computed from the sources side, using (12.1).

Of course, as with other general equilibrium models, the GTAP model also offers a consistency check in the form of Walras' law. In the standard model, an endogenous slack variable is included in the expression equating global savings and global net investment. If this variable is equal to zero in the model solution, then Walras' law holds, and the user can be assured that the theoretical integrity of the model (as well as the integrity of the associated GTAP database) is intact. If this does not hold, then there is a problem and the model user needs to retreat to the standard model/database and revisit any modifications that have been subsequently undertaken.

12.2.5 Global Bank

The next topic considered in this overview of novel features introduced by the standard GTAP model is the *Global Bank*. As with the regional household, this is a response to a data deficiency. In particular, we do not have a comprehensive global database on bilateral investment flows and ownership of capital stocks. Yet savings and investment flows are an integral part of the GTAP database. Whalley's (1985) solution to this problem involved rebalancing the database to enforce equality between regional savings and investment, and hence exports equal imports at the regional level. He then merged investment activity with consumption and allowed the regional household to "eat the capital goods." This eliminates a whole host of problems that arise with savings and investment in a global model. However, it also radically alters the global economic landscape in a way that would have been unacceptable to most GTAP users.

An alternative approach taken in designing the GTAP model was to introduce another fictitious entity, the Global Bank, in order to mediate between global savings, on the one hand, and investment, on the other. As noted above, regional households demand savings as a proxy for future consumption, while regional investment is a component of the final demand for goods and services in the regional economy. As with other static CGE models, current period investment raises end-of-period capital stock, but does not affect current period productive capacity. The Global Bank uses receipts from the sale of the homogeneous savings commodity to the individual regional households in order to purchase shares in a portfolio of regional investment goods. The size of this portfolio adjusts to accommodate changes in global savings. Therefore, the *global closure* in this model is neoclassical, with savings driving investment. However, on a regional basis, adjustment in the allocation of global investment is permitted, in response to changes in the expected rate of return on investments made in each regional economy. This adds another dimension to the determination of investment in the model.

The expected rate of return on investment is a function of the current rate of return in the model, adjusted for changes in current period investment. If the latter is extremely large, then investors discount the current rate of return somewhat. Following an approach originally developed by Dixon *et al.* (1982) for the determination of sectoral investment in the ORANI model, we introduce a *flexibility* of the expected rate of return with respect to changes in the regional capital stock. The larger is this flexibility (in absolute value), the stronger the response of the expected rate of return to a given change in investment. In equilibrium, expected rates of return are equalized across regions. Hence a large flexibility translates into a more limited portfolio response to a change in current rates of return across regions.

Malcolm (1998) tests this general approach to the determination of regional investment against historical experience. In particular, he introduces an exogenous risk premium into this formulation and then proceeds to examine the impact of shocks to the regional risk premium facing South Africa in the wake of apartheid's abolition. Given observed reductions in the bond market premium facing South Africa in the wake of these reforms, the model does a reasonable job predicting the increased capital inflow into the region between the 1991–1993 and 1995–1997 periods, using the default value for this flexibility (10.0). Further empirical investigation of this key parameter is certainly warranted.

12.2.6 Global trade and transport sector

The final fictional sector which had to be invented in order to enable global economic modeling with the GTAP database is the global trade and transport sector. In practice, the global shipment of goods and services is supplied by firms based in specific countries and these services accrue to those countries in the form of services exports. However, in the GTAP database, as constructed from the best available statistics, we only have an estimate of national exports of trade and transport services. We do not know where these services were employed. On the other hand, we also have an estimate of the global demand for international shipping services, which is implicit in the difference between the f.o.b. and c.i.f. prices for merchandise trade. The global transport sector mediates between these two elements of the database, ensuring that the supply of services to this sector from individual regions is sufficient to cover the observed trade margins.

As previously noted, with the introduction of different modes of transport into the GTAP version five database, there are now separate transportation margins exports and demands for each of the modes: air, sea and other (i.e. land) transport. In the standard model, the global trade and transport sector produces global services from regionally differentiated services exports with a unitary elasticity of substitution in production. The demand for a given type of transport service, along any given route, for a given commodity, is assumed to vary in fixed proportion to the merchandise trade volume. However, Avetisyan (2011) has recently introduced modal substitution into a revised GTAP model. His econometric estimates of this modal substitution elasticity (e.g. between sea and air transport) suggest values typically ranging between 1 and 2.5, with considerable variation across commodities, as might be expected.

12.2.7 Treatment of imports

The treatment of imports, particularly the resolution with which they are tracked from producer to consumer, is partly determined by the type of model being employed. Models of firm-level product differentiation, which have dominated the empirical trade literature over the past 20 years, require the sourcing of imports by individual agent in the economy. In the standard, Dixit–Stiglitz–Krugman, love of variety (LoV) model, added product variety provided to US consumers of say, automobiles, or to industrial consumers of steel, will lower the cost of attaining a given level of utility or production. In order to track the change in variety embodied in imports from, say Japan, it is necessary to know the change in number of firms operating in that sector. Since different sectors have differing patterns of import sourcing, this requires tracking imports of each commodity, bilaterally, by agent and destination region. This entails a four-dimensional array that greatly expands the dimensions of the model. It also exceeds the resolution of most international datasets, which only track bilateral imports between countries. One exception is the regional database maintained by the Institute for Developing Economies (IDE) with a focus on East Asia. The IDE supplements national input-output tables with surveys that allow it to estimate the sourcing of imports by sector in the economy. However, this entails substantial additional expenditure; as a result, the IDE datasets lag other sources by a considerable margin and they only cover a limited number of countries in the Asia—Pacific region.

The standard GTAP model belongs in the class of so-called "Armington" models (Armington, 1969), with imports being differentiated by source country. Furthermore, unlike the models of product differentiation by firm, this differentiation is exogenous. Extensions of the standard model to deal with endogenous, firm-level differentiation are discussed below and are documented in the *GTAP Technical Paper* series. In light of the use of the Armington specification, it is less critical to track imports bilaterally to individual uses within the destination economy. In order to limit the size of the resulting numerical model, and in keeping with the concept of matching the standard model with global data availability, the standard model aggregates bilateral imports at the border. However, unlike many global CGE models built on the Armington approach, the substitution of imports for domestic goods is something that occurs at the level of individual sectors in the standard model.

Hertel *et al.* (1997) emphasize the importance of sourcing aggregated imports by agent in their GTAP-based analysis of the impact of the Uruguay Round on the Korean economy. First, they note the very substantial differences in import intensity across the Korean economy, where the average import intensity of household consumption is just 4%, whereas the average import intensity in the extractive and manufacturing industries is between 35 and 40%. Investment goods are also relatively import intensive (17%) in their analysis of the Korean data. As a consequence, the main impact of tariff reductions in their model is to lower firms' intermediate input costs, as well as boosting the rate of return on investment. The direct impact on consumers is relatively modest. They point out that their results would have been quite different had they aggregated imports at the border, as is more commonly done in such studies.

As global trade in intermediate inputs becomes more important and trade theory continues to place greater emphasis on firm-level outcomes, there will be a greater demand for sourcing trade bilaterally by agent. This is also the direction of projects aiming to build

World Input-Output Databases. While these efforts have not been able to overcome the limitations inherent in current bilateral trade databases, they have made some progress simply by classifying highly disaggregated goods as either producer or consumer goods and then aggregating them accordingly. This, in turn, has permitted some rather sophisticated analyses of global supply chains (Bénassy-Quéré *et al.*, 2009; Koopman *et al.*, 2010; Miroudot *et al.*, 2011).

12.3 MODEL VALIDATION AND SYSTEMATIC SENSITIVITY ANALYSIS

12.3.1 Validation of CGE models

Despite their widespread use in policy analysis, CGE models are often criticized for having uncertain empirical foundations and for being insufficiently validated (Jorgenson, 1984; Kehoe *et al.*, 1995).[10] The problem of endowing large CGE models with numerical parameter values is formidable and numerous choices also have to be made about model structure. In many cases the trustworthiness of a model may be based largely on the assertions of the model developer. As decision makers increasingly become aware of the critical dependence of policy results key parameters and closures, they are demanding more attention to the issues of parameter estimation and model validation. Unfortunately, it is much harder to validate an existing model than to build a new model with some exciting new features – and the publication potential of the latter research effort is also typically greater. Thus, the effort devoted to model estimation and validation is far too little, given its importance to this field of research. Fortunately, several chapters in this volume are devoted to these issues. Accordingly, I will focus my discussion here on the work that is pertinent to the GTAP model and closely related efforts.

Gass (1983) provides a useful starting point for discussion of the validation of simulation models. He stresses the need for credibility in policy related simulations, but suggests that such models can never be truly validated. However, by subjecting a simulation model to *invalidation* tests we can become more confident that the model is *not invalid*, thereby improving its credibility. Gass argues that the central concern of policy models should be *replicative validity*, as opposed, for example, to a singular focus on a model's underlying theoretical assumptions. Replicative validity essentially means that a model's simulated outcomes match historical outcomes over some appropriately chosen period of time. This process facilitates: (i) understanding of the model by potential users, (ii) exposition of the strengths and weaknesses, (iii) an assessment of the model's limitations in a predictive capacity and (iv) information on the proper level of confidence to attach to results. McCarl (1984) adds that validation can point the way for adaptations that produce better predictions in an area where a model was previously limited.

10 Parts of this section draw heavily on the paper by Valenzuela *et al.* (2007).

While the operations research literature continues to devote considerable attention to the validation of simulation models (Kleijnen, 1999) there are few cases of CGE models being tested against the historical record. We rarely have the kind of natural experiment that is needed to validate a large-scale partial or general equilibrium global model. For instance, in the case of multilateral trade liberalization, the policy changes are usually very modest and are phased in over a long period of time, particularly when compared to the other short-term factors perturbing the world economy, such as wars, currency crises, and trade embargoes. By focusing on a single regional economy, Kehoe *et al.* (1995) are able to validate a CGE model of the Spanish economy in terms of its predictions of the impacts of tax reform. Their experiment deals with shocks to a single, *national* economy, making the process of isolating events (e.g. a severe drought in the same year), and exogenously introducing their impacts into the model, considerably more straightforwardly than for a *global* model.

Fox (2004) follows Kehoe *et al.*'s lead in developing summary goodness-of-fit measures to assess the North American Free Trade Agreement (NAFTA) predictions of Brown *et al.* (1992b), using the global Michigan Model of Production and Trade. In implementing shocks to capital and labor endowments, and allowing for international capital mobility, he finds that the model does a good job in capturing the qualitative pattern of trade changes. However, it fails to simulate the large magnitude of trade changes in certain sectors. He suggests this may be due to the low magnitude of the elasticities used in the model and the CES representation of trade. Of course, this work is still subject to the criticism that NAFTA was not the only event occurring over this time period and it is next to impossible to account for all the other changes that took place, (see Dixon and Rimmer (2002) for a more detailed discussion of this point).

Gehlhar (1997) also encounters such difficulties when seeking to validate the GTAP model using policy shocks. He uses a backcasting simulation to evaluate the validity of model results versus observed outcomes concerning East Asian economic growth in the 1980s. Accordingly, he focuses on changes in trade shares rather than levels, hoping to lessen the importance of macroeconomic factors in his analysis. He finds that the model performs adequately with respect to the direction of change in trade shares over this historical period, but is otherwise weak in terms of predictive power. He then alters the model, separating labor inputs into skilled and unskilled components, and increases the trade elasticities by 20% from their base values. These alterations significantly improve the validation results in the particular case of East Asian growth, and these findings led to a labor force disaggregation in the standard GTAP database.

Liu *et al.* (2004) formalize the approach of Gehlhar (1997) by developing an approximate likelihood function to assess the quality of the GTAP model's performance over the (backcasting) period of 1986—1992. Rather than focusing on model validation *per se*, these authors use this as an environment for hypothesis testing. Since the historical pattern of trade flows in the East Asia region depend critically on the trade elasticities, they test the widely maintained hypothesis known as the "Rule of Two," whereby the import/import substitution elasticities are twice as large as the import/domestic elasticities for comparable goods (Corado and de Melo, 1983). The authors fail to reject this hypothesis, thereby lending further support to its use in the parameterization of the standard GTAP model.

Valenzuela *et al.* (2007) follow the lead of the "real business cycle" literature, which aims to develop models that are capable of mimicking correlations and volatility among consumption, output, investment and labor in time-series data (e.g. Kydland and Prescott, 1982). However, Valenzuela *et al.* (2007) focus on the GTAP model's performance with respect to a single sector – in this case wheat, arguing that the weather-induced supply variation in agricultural commodity markets translates into a series of natural historical experiments. They incorporate this supply-side variation into the GTAP model as technology shocks at the individual sector level and ask whether the model can reproduce the observed variance of national commodity prices. They find that the model performs quite well for some countries. However, their most interesting finding relates to the pattern by which the model *fails* to replicate observed behavior in other markets. In particular, it tends to overstate price volatility in the major net importing markets, while understating price volatility in major exporting regions. They conclude that this arises from the tendency for countries to insulate domestic markets from world prices. To account for the incomplete transmission of world prices, they modify the standard GTAP model to introduce econometrically estimated market insulation by importers. Once this modification is undertaken, the model is again evaluated relative to the same metric – predicted versus observed price volatility. The richer formulation improves model performance but also suggests a truly satisfactory reconciliation of observed and predicted outcomes can only come through explicit modeling of the key policies in individual markets.

Beckman *et al.* (2011) extend the Valenzuela *et al.* approach to model validation to petroleum markets, where both demand and supply-side shocks are important. They undertake time-series analysis of the underlying drivers of demand (GDP) and supply-side (oil supply) shocks to create probability distributions for random shocks to the underlying supply and demand schedules for petroleum. They utilize the GTAP-E (E for Energy) model (Burniaux and Truong, 2002) to simulate endogenous oil price distributions which may be compared with observed price distributions This test of the model's ability to replicate historical price volatility hinges on the specification of key energy parameters as they characterize agents' behavior in the CGE model. If they are incorrectly specified, estimated volatility will not be representative of historical volatility and thus any estimates from the CGE model will be suspect. They find that, in the words of Gass (1983) the model is *invalid* for analysis of oil markets. In particular, the GTAP-E energy substitution and demand elasticity parameters appear to be much too large. They then turn to the more recent econometric literature and respecify the demand elasticities in the GTAP-E model. The authors redo the historical validation analysis and find that the resulting model performs much better. This is an excellent illustration of the

Gass/McCarl idea of using model validation to uncover ways in which a model fails, thereupon using these as a basis for future improvements.

12.3.2 Systematic sensitivity analysis

Based on the foregoing discussion, it is clear that we are unlikely to have access to a fully validated, global CGE model in the near future. A more modest goal is to provide sufficient robustness checks to assure policy makers that key findings are not simply a function of certain arbitrary (or worse yet, strategically selected) parameter settings. This leads to the topic of systematic sensitivity analysis (SSA) — a tool that has been widely employed in the GTAP community to explore the sensitivity of model results to parametric uncertainty. The basic idea is to sample from a set of parameter distributions, each time re-solving the model and saving the results. After completion of the SSA, the user can compute standard statistics — most commonly the mean and variance of model results, thereupon providing model consumers with appropriately constructed confidence intervals. Thus, it should be possible to say, for example: "Given the overall structure of the GTAP model, we are 95% confident that this policy will improve regional welfare." Of course, the only sources of uncertainty are the parameters and the policy shocks, which can be varied separately and/or together according to a specified covariance matrix (Horridge and Pearson, 2011).

There is now a long history of CGE studies utilizing SSA (for early contributions to this literature, see Pagan and Shannon, 1987; Wigle, 1991; Harrison and Vinod, 1992; Harrison *et al.*, 1993). The fundamental problem with SSA in a large-scale CGE model is that the individual model solutions can be quite time-consuming, even with modern computational facilities. This may preclude solving the model 10,000 times, as might be desirable from the point of view of Monte Carlo Analysis. Fortunately, other methods have been developed that appear to perform quite well in the context of standard CGE models. In particular, DeVuyst and Preckel (1997) show that a modest number of solutions via Gaussian Quadrature can approximate the true mean and variance of model results quite well for a simple, global CGE model. The Gaussian Quadrature approach has been tailored for use in GTAP through a series of *GTAP Technical Papers* (Arndt, 1996; Pearson and Arndt, 2000; Horridge and Pearson, 2011). Indeed, the tools for implementing SSA in RunGTAP make it difficult for any author to excuse themselves from providing such robustness checks on their results and journal reviewers are increasingly insisting on SSA as part of the peer-review process.

Of course, none of the foregoing discussion touches on the question of how to specify the parameter distributions and these are central in determining the distributions of model results. Some authors have taken the approach of surveying the literature, treating each estimate of a given parameter as a draw from the underlying distribution (Harrison *et al.*, 1993). The problem with this approach is that there is a limited pool of published studies and many of them make different assumptions in their estimation approaches. In addition, the process of peer review has a tendency to lead to overly narrow parameter distributions, with so-called "unreasonable" values being ruled out *a priori* during the peer-review process. A more common approach to SSA is to simply specify a uniform or a triangular distribution with a lower endpoint of zero (for non-negative elasticity values). This reassures the reader that the author is being suitable conservative by specifying a generous variance in the underlying distribution. However, none of this is really satisfactory. It would be far preferable to actually estimate the relevant parameters and the associated distributions and use these directly in the SSA.

This led Hertel *et al.* (2003) to undertake such an exercise in the context of their analysis of the proposed Free Trade Area of the Americas (FTAA). Following earlier work by Hummels,[11] their econometric work focuses on the estimation of a particular parameter, the elasticity of substitution among imports from different countries, which is central to any evaluation of a discriminatory trade agreement such as the FTAA. They match the data in the econometric exercise (from North and South America) to the policy experiment at hand, and employ both point estimates and the associated standard errors in a policy analysis which takes explicit account of the degree of uncertainty in the underlying parameters. In particular, they sample from the distribution of parameter values given by their econometric estimates in order to generate a distribution of model results from which they then construct confidence intervals. These authors find that imports increase in all regions of the world as a result of the FTAA, and this outcome is robust to variation in the trade elasticities. Nine of the 13 FTAA regions experience a welfare gain in which they are more than 95% confident. The authors conclude that there is great potential for combining econometric work with CGE-based policy analysis in order to produce a richer set of results that are likely to prove more satisfying to the sophisticated policy maker.

12.4 SOFTWARE AND IMPLEMENTATION ISSUES[12]

First of all, let me note that there is an entire chapter in this Handbook (Chapter 20 by Horridge, Rutherford *et al.*) devoted to the issue of software for CGE modeling.

11 Readers are referred to Hillberry and Hummels in Chapter 18 of this Handbook for an extended discussion of the issues underpinning estimation of trade elasticities for use in CGE models.

12 In my view, CGE modelers spend far too much time arguing about which particular software package is best for modeling purposes. The fact is that there is a menu of alternatives available, and users should choose the tool that is best suited to their particular needs and fits within their available resource constraints. Often the most important resource constraint is not financial, but rather access to human capital. If there is an expert in a particular software factor down the hall from you, this can be the determining factor. The key thing is to be able to get the job done, which means successfully coding the model, debugging it, solving it and providing a complete analysis of the results. Of course, as discussed in the text, the choice of software environment is likely to affect one's ability to accomplish these tasks.

In this section, I merely discuss how software and model implementation issues have shaped — and been shaped by — the GTAP model, short courses and network. Amongst the many persistent myths in CGE modeling, one of the most irritating is the idea that implementing a non-linear model via a linearized representation, as is typically the case with GEMPACK, will yield different answer than would be obtained by implementing the very same model via a levels representation in a software package such as GAMS. The potential for eliminating any linearization errors from the linearized implementation of a well-specified CGE model was addressed on both theoretical and empirical grounds in the original ORANI book by Dixon *et al.* (1982, section 35). However, this myth persists and it was perhaps abetted by the frequent use of linear approximations in practical implementations of the ORANI model. This led to a subsequent paper by Hertel *et al.* (1992) who implemented a global CGE model in both GEMPACK and GAMS, and demonstrated that the two solutions were identical, provided the linearized model is solved using appropriate non-linear methods. They titled their paper "Mending the family tree: a reconciliation of the linearization of levels schools of applied general equilibrium modeling" and devoted most of the paper to a detailed comparison of the two model implementations. They conclude that the ideal CGE model (at least from the point of view of ease of interpretation and analysis) would be a mixed, linearized/levels model in which the behavioral equations are implemented in linearized form, thereby capitalizing on the intuitive expressions of supply and demand in terms of elasticities and shares, while the equilibrium conditions (market clearing, zero profits, budget constraints) are most naturally written in levels form.

The standard GTAP model maintained by the Center for Global Trade Analysis is implemented in GEMPACK. No doubt this has much to do with the fact that the GTAP effort was greatly inspired by the "Australian School" of CGE modeling led by Peter Dixon and his colleagues. As noted above, the SALTER model, developed at the Australian Productivity Commission (Dee, 2005; Jomini *et al.*, 1994) and heavily influenced by ORANI (Dixon *et al.*, 1982) was the source of the GTAP database as well as many ideas for equation implementation. A number of key staff members at the Center also trace their roots back to the "Australian School." The GTAP—GEMPACK marriage has proven particularly effective due to the strong involvement of GEMPACK developers (first Ken Pearson and then Mark Horridge) in the GTAP short courses. Many of the software innovations that have driven growth in the community of GTAP users have been born in these courses. RunGTAP, for example, is a "wrapper" that presents GTAP users with key modeling decisions, including choice of version/aggregation, model closure, shocks and solution method, through a graphical user interface. This was originally developed by Mark Horridge in the context of the first African GTAP short course in 1997, and it has gone on to dramatically alter the way in which the GTAP short course is taught, as well as providing an excellent structure for archiving, sharing and replicating GTAP model simulations. In short, these software developments have greatly enhanced the productivity of members of the GTAP network.

Another reason for the close ties between GTAP and GEMPACK is the strong emphasis placed on equation-by-equation analysis as well as the decomposition of model results. Linearization of the model greatly facilitates such decomposition and analysis. Indeed, the welfare decomposition presented above in Equation (12.1) is fundamentally tied to this linearization. All of this analysis has been greatly facilitated by a tool called AnalyseGE, developed by Ken Pearson, with the idea once again born in a GTAP short course. This software permits the user to bring up their model equations on the screen, with data (typically initial equilibrium flows and shares), parameters and solution values lurking behind their respective on-screen symbols. Using the mouse, and invoking a series of right- and left-clicks, the user is able to quickly decompose a given equation, thereby ascertaining, e.g. in the context of Equation (12.1), that the increase in welfare associated with a tariff increase in a given region was due to the interaction of a rise in output with a pre-existing output tax (or perhaps due to a change in the terms of trade, and so on). This is a remarkably powerful tool that, when combined with appropriate model implementation and decomposition equations, greatly enhances the effectiveness of members of the GTAP community in delivering sophisticated policy analysis in a timely fashion.

However, this is not to say that GTAP-based models are exclusively implemented in GEMPACK. Indeed, the group of GAMS-based modelers in the GTAP community is very large and growing rapidly. They have historically been serviced by Thomas Rutherford's GTAP-in-GAMS package (Rutherford, 2005) which offers a slightly modified version of the standard GTAP model within the GAMS environment. More recently, the MIRAGE[13] and GLOBE[14] models have emerged as additional alternatives for those interested in GAMS-based global modeling with the GTAP database. Of course there are many in-house models, implemented in GAMS and drawing on the GTAP database. One of the most prominent among these is the OECD—World Bank LINKAGE model, which subsequently evolved into the ENVISAGE model and which is documented by Dominique van der Mensbrugghe in Chapter 14 of this Handbook. Because GAMS is a general purpose, optimization-oriented software package, it is frequently licensed to institutions for other reasons (e.g. for use in a non-linear optimization course). It is quite versatile and well-suited to data balancing, model calibration and model linkage, among other things. As such, it has a large user community and it is often utilized due to its ready availability and the familiarity of users with its syntax.

In wrapping up this discussion of software, it is worth noting that the rapid growth in the GTAP-based global CGE modeling network has provided a great

13 http://www.mirage-model.eu/.
14 http://ideas.repec.org/p/usn/usnawp/14.html.

stimulus for software development. The recent emergence of special purpose software for disaggregating GTAP sectors (SPLITCOM: Horridge, 2005) and for creating tariff-line-driven GTAP liberalization scenarios (TASTE: Horridge and Laborde, 2010) are just a few examples of the growing value of this network for the global economic modeling community. As the GTAP community becomes more sophisticated in its analyses, these special purpose tools will continue to increase in importance.

12.5 GTAP-BASED ANALYSIS OF GLOBAL ECONOMIC INTEGRATION

By far the most widespread use of GTAP-based models to date has been for analysis of economic integration, including reductions in trade costs, liberalization of domestic support for agriculture and industry, and the cross-border flow of people and capital, as well as technology (e.g. van Meijl and van Tongeren, 1999). Within this broad area of application, the vast majority of studies have focused on the liberalization of merchandise trade. This is partly due to the historical emphasis of trade negotiations on this area of global economic integration and partly due to the fact that this is where the GTAP database is richest in its representation of the global economy. As noted previously, the GTAP project came of age with the Uruguay Round of multilateral trade negotiations sponsored by the General Agreement on Tariffs and Trade (GATT)/WTO. Indeed, four of the five global CGE assessments of this multilateral trade agreement in the synthesis volume edited by Martin and Winters (1996) were based on the GTAP database. (The fifth group subsequently shifted to using the GTAP database as well.) By using a common database, as well as a common set of policy scenarios, the results from these diverse studies, each emphasizing different sectors and making quite different modeling assumptions, showed a far greater level of agreement than earlier assessments.

Subsequent improvements in the underlying database, particularly the detailed treatment of trade preferences, in conjunction with supplementary data on bound tariffs, as well as the development of new models based on the core database, positioned GTAP to be extremely influential in the context of the debate over the Doha Development Agenda (DDA). The DDA was launched in 2001 and was intended to deliver poverty reductions in the developing world, among other benefits. Accordingly, virtually all the global quantitative analyses of the DDA were based on variants of the GTAP database (e.g. Francois *et al.*, 2005) as well as studies in the volumes edited by Kuha-Gasnobis (2004) Anderson and Martin (2006) and Hertel and Winters (2006).

An unintended side-effect of this improved accuracy in the characterization of WTO agreements was that it became more difficult to “sell” such agreements to the general public. The fact is, large efficiency gains typically involve adjustment costs and the latter are something that trade negotiators typically seek to minimize. In a series of important GTAP-based studies, authors showed that the DDA, as proposed was far less promising than initially believed to be the case. For example, Bouët *et al.* (2005) showed that prior assessments of the DDA that had neglected preferential agreements and the binding overhang (both in tariffs as well as domestic support – such that bound rates could be cut without affect applied protection) had been excessively optimistic about the actual benefits of multilateral trade liberalization. Fontagné *et al.* (2005) found that excluding tariff peaks (typically the most sensitive sectors) halved the expected trade and welfare gains. Jean *et al.* (2006) found that allowing just 2% of the tariff lines in rich countries (and 4% in developing countries) to be exempt from the DDAs deepest cuts on sensitive products grounds would reduce the overall applied tariff cut in agriculture by 80%. Bouët *et al.* (2006) emphasized the fact that exemption of the 3% of the most sensitive tariff lines from inclusion in the proposed Duty Free Quota Regime would largely eliminate the benefits for least-developed countries. Hertel *et al.* (2009) highlighted the disconnection between the declared objectives of the DDA and the actual impacts of the proposed agreement. They show that the reforms left out of the DDA (most important is the omission of tariff cuts on food in the least developed countries) were more poverty friendly than the cuts that were actually included under the Agreement.

In summary, it seems that the more closely GTAP-based studies looked at this prospective WTO agreement, the smaller were the gains. All of this made it difficult to sell the agreement to an already skeptical developing world, particularly in light of the stiff opposition to deeper cuts by agricultural interests in the rich countries. With agriculture at an impasse, manufacturing tariffs already reduced to modest levels in most major sectors/markets, and services and intellectual property negotiations proving difficult to tackle on a multilateral basis, the DDA negotiations stalled. Momentum shifted to the bilateral trade agreements and this is where the bulk of GTAP-based analyses of trade policy have been undertaken since 2006.

Before turning to the plethora of studies on FTAs, it is important to consider the possibility that most of the GTAP applications of the DDA have been asking the wrong question. The issue is not whether a DDA agreement will bring large gains, relative to the present state of the world. Rather, the question is whether a WTO-bound world would be significantly better off than the world that is likely to prevail in its absence. In this case, WTO disciplines on tariffs might vanish or tariffs might rise to the level dictated by bound tariffs established under the previous Uruguay Round Agreement. Bouët and Laborde (2010a) take this alternate view of the appropriate counterfactual state of the world. They find that the economic cost of a failed DDA could be much larger than hitherto estimated. Those authors assess the scope for the DDA to curb future trends in protectionism and suggest that, by reducing bound duties, the DDA could prevent the potential reduction of US$809 billion of world trade.

In light of the limited progress in trade reforms at the multilateral level, hundreds of bilateral trade agreements have been concluded over the past decade and dozens more are currently under negotiation. This has translated into a very strong demand for GTAP-based analyses, as the agreements are fundamentally about preferential treatment of trade within the region, and for this, one requires a modeling framework with explicit treatment of bilateral trade flows and bilateral policies — precisely the area of primary expertise in the GTAP network.

One of the most striking examples of the switch from staunch multilateralism to aggressive bilateralism is that of the Japanese government which has been an active user of GTAP-based analysis since the late 1990s when GTAP was first used to analyze the impact of Asia Pacific Economic Cooperation (APEC, 1997). Subsequently it has been used by the Japanese government to analyze prospective FTAs with Mexico, Korea, Malaysia, Philippines, Thailand, Indonesia, Australia, Chile, Switzerland, Canada and the EU. This widespread use of GTAP-based models in Japan was facilitated by Kenichi Kawasaki, a leading member of the GTAP network, who published a Japanese language version of GTAP, along with several applications of GTAP to Japanese policy issues (Kawasaki, 1999). Japanese interest in FTAs has also spilled over to the Asian Development Bank which also commissioned a GTAP-based study of Asian free trade agreements (Francois and Wignaraja, 2008) which found that the gains from a pan-Asian FTA hinge critically on the participation of India in such an agreement.

The US government is also an active user of GTAP-based models. The Economic Research Service of the US Department of Agriculture (USDA) — one of the original GTAP Consortium members — has recently used GTAP to examine how recently concluded FTAs with ASEAN, China, Australia and New Zealand are likely to affect US agricultural trade. They conclude these agreements may reduce US agricultural exports. However, these reductions are dwarfed by prospective increases in farm exports under the pending US—Korea and US—Colombia trade agreements (Wainio *et al.*, 2011). The Office of Economics in the US International Trade Commission (ITC), under the leadership of Robert Koopman, has also undertaken numerous studies of prospective FTAs using the GTAP database and related models. Unlike USDA, their focus is on the economy-wide impacts of such agreements. The ITC website (http://www.usitc.gov/publications/332/pub3949.pdf, pub3896.pdf, pub3855.pdf, pub3717.pdf, pub3704.pdf, pub3697.pdf, pub3605.pdf and pub3603.pdf.) reports GTAP-based studies of eight prospective and completed FTAs, including those with Korea, Colombia, Peru, Central America, Morocco, Australia, Chile and Singapore. The study of the US—Korea FTA had to come to grips with differences between US and Korean safety and emission standards for passenger cars that were believed act as an implicit barrier on US exports to Korea. The original 2007 US—Korea FTA exempted a certain level of US passenger cars from Korean standards. In December 2010, changes to certain FTA provisions raised the level of excepted US passenger cars. An analysis of the 2010 passenger car amendments relied on a modified GTAP framework that modeled the sourcing of imported products at the industry and consumer level (ITC, March 2011). This feature of the model allowed for a more precise specification of the simulated removal of Korean NTMs on US passenger cars.[15]

One of the most important global economic developments over the past decade has been the enlargement of the EU, which grew from 15 to 25 members. This economic integration has been much more significant FTAs, since it involved harmonization of external barriers, as well as the extension of domestic support to the new entrants and integration of regulatory and governance structures. In so doing, the EU significantly reconfigured its demand for imports and supply of exports, with potentially very important implications for international trade. In an early and highly influential study published in *Economic Policy*, Baldwin *et al.* (1997) utilize a modified GTAP model and conclude (p. 126): "The bottom line is unambiguous and strongly positive: enlargement is a very good deal for both the EU incumbents and the new members." A novel feature of their analysis is their incorporation of a reduction in the risk premium on investment in the Eastern European countries. This generates a significant investment inflow in their analysis of enlargement, which, when coupled with a steady-state closure under which capital stock is allowed to expand,[16] generates significant economic growth − nearly 20% expansion of GDP in the seven prospective Central European entrant economies. Subsequently, GTAP-based models (MIRAGE in this case) have been widely employed to analyze a large number of FTAs, including those with India (Decreux and Mitaritonna, 2007), ASEAN (Boumellassa *et al.*, 2006) and Korea (Decreux *et al.*, 2010). The EU Commission has also commissioned scoping exercises using GTAP-based models to investigate the potential gains from closer trade relations with Canada (European Commission, 2010) and South Korea (Francois, 2007). Finally, the OECD has undertaken a GTAP-based study of trade liberalization and economic growth amongst the G20 economies (Dee *et al.*, 2011).

In the context of the economic and financial crisis that started in 2008, the OECD (2010) has used GTAP to analyze a wide variety of trade instruments and behind-the border measures, such as subsidies with buy-local provisions, which countries have undertaken to counter the adverse domestic impacts of the economic downturn. The study investigates the negative economic spillovers on other countries of such policies and highlights the value of coordinating "rescue packages." Other OECD studies have

15 Assuming that imported passenger cars in Korea are destined for final demand and that they are not used as intermediate inputs, the simulation can focus on Korean demand for US passenger cars even though, in the model's database, passenger cars are aggregated with other products in the GTAP sector "MVH," which represents motor vehicles and parts.

16 See Francois and MacDonald (1996) for details regarding the capital accumulation closure.

used GTAP to decompose the trade drop that occurred during the financial crisis in order to understand the relative contributions of product composition, changing policies and demand shortfalls. Still another OECD study has brought increased attention to the importance of export taxes, particularly in the context of food security (Bouët and Laborde, 2010b).

There have also been quite a few GTAP-based studies of unilateral trade reforms. To the extent that the GTAP framework is handy and readily available for many researchers, it often provides a convenient starting point for such analyses. However, in my view, studies of unilateral reform are likely to be more effective when undertaken in a single-region modeling framework, as this permits closer attention to the specific features of the economy in question. This volume provides numerous examples of such models that often offer much greater disaggregation, improved parametric specifications, as well as more refined treatment of domestic institutions and constraints.

Another type of study that deserves mention here is the combination global/national model linkage effort wherein results from a global model, such as GTAP, are passed on to a detailed national model to elicit more nuanced national impacts. The volume edited by Hertel and Winters (2006) actively employs this approach in an attempt to understand the potential national poverty impacts of a proposed WTO agreement. The methodology is laid out in Horridge and Zhai (2007) and involves first solving the GTAP model to assess the (nearly) global impacts of the WTO reforms. I say "nearly global" since the reforms undertaken by the individual focus country (e.g. Brazil), are omitted from this GTAP-based simulation. The resulting global model solution describes how the import supply and export demand schedules facing Brazil are likely to shift as a result of other countries' actions. These shifts are then incorporated into a national model simulation in which Brazilian reforms are also undertaken and the detailed poverty impacts are assessed. The chapter by Ferreira-Filho and Horridge (2006) in that same volume illustrates how this is done. Those authors modify their national model in order to render the import supply and export demand schedules consistent with those in the GTAP model. In this case, their multimodel analysis was rewarded with an important new insight – namely that WTO agricultural reforms would actually reduce poverty in Brazil. This finding stood in sharp contrast to popular wisdom at the time of the study, which presumed that all the benefits would accrue to wealthy landowners in Brazil. The Ferreira-Filho and Horridge study did not refute the strong gains to landowners, but they also found that a substantial poverty reduction was likely due to the unskilled labor intensity of agriculture in Brazil and the relatively high rate of unemployment amongst that segment of the population.

The idea of linking GTAP-based global models with other models in order to provide additional insights for policy makers considering trade reforms is quite a common one. Another example is offered by Jean and Laborde (2004) who link the MIRAGE model to the DREAM regional CGE model of the EU in order to generate estimates of the regional impact of EU trade policies at the level of 119 "NUTS" (nomenclature d'unités territoriales statistiques) regions within Europe. Another very interesting margin for exploring such model linkages involves the so-called PE-GE approach to trade policy analysis wherein a highly disaggregated, partial equilibrium model is nested within the global CGE model. Grant *et al.* (2009) develop such a model, building on the GTAP-in-GAMS CGE model developed by Rutherford (2005).[17] They subsequently disaggregate the dairy products sector, since the level and composition of protection varies greatly across the more than 20 tariff lines embedded in the single GTAP dairy products sector. The authors focus on the tariff rate quotas (TRQs) that apply to many of the dairy tariff lines in the case of US imports. Since these are not always binding, it is impossible to accurately aggregate these protection measures to the sector level. Appropriate modeling of the impact of proposed reform on these TRQs necessarily entails disaggregation, and the authors achieve this by specifying a nested CES demand function and a constant elasticity of transformation (CET) supply function over disaggregated dairy products, within each regional economy. This makes it possible to consider the impacts of tariff line competition between imports and domestic products within the context of the global CGE model. Using a mixed complementarity formulation for the TRQs to permit regime changes as quotas are expanded, the authors demonstrate that the production, consumption and welfare impacts depend critically on whether the reforms entail bilateral quota expansions, or multilateral expansions, or simple out-of-quota tariff cuts.

The ITC often uses the GTAP database to evaluate potential impacts of trade policies. In addition to careful modeling of changes in tariffs and tariff-rate quotas, the ITC has worked at improving the measurement of the impacts of non-tariff measures (NTMs) and at quantifying the sensitivity of simulated effects to certain assumptions and parameters. As with TRQs, NTMs vary considerably in their impacts and do not typically lend themselves to convenient aggregation, so the PE-GE approach is quite attractive. The ITC (2008) has linked a partial equilibrium model of 12 HS (Harmonized System) six-digit beef products to the GTAP model to capture variation in import restrictions from beef product to beef product. This permitted analysis of the general equilibrium impacts of BSE[18]-related import restrictions imposed on US and Canadian beef products in 2004.

The approach of nesting a PE model within a GE model permits economists to address two important goals of quantitative trade policy analysis that arise in virtually all

17 The PE-GE model is solved using the sequential calibration approach developed by Böhringer and Rutherford (2005).

18 Bovine spongiform encephalopathy.

trade negotiations. The first is to offer an overall assessment of the value of a trade agreement to a member country. Is this worth pursuing? The second goal is to devote special attention to sectors which emerge as particularly sensitive over the course of the negotiations, and which therefore require more detailed attention. For those wishing to undertake such PE-GE, nested analyses with the standard GTAP model, Narayanan *et al*. (2010) have developed a special module which may be appended to the bottom of the standard GTAP model. Such extensions of the standard model to the tariff line is greatly facilitated by the TASTE software package discussed earlier (Horridge and Laborde, 2010). However, authors must still obtain disaggregated consumption and production data, which is often challenging.

In all of the multiregion, CGE work on trade liberalization, the most controversial issue has been the size of the terms-of-trade effects associated with trade reforms. A good example is offered by the debate over the Australia—US Free Trade Agreement (AUSFTA) in which two contradictory estimates of the welfare gain to Australia were presented. The first, prepared by the Centre for International Economics (2001, 2004) estimated substantial potential benefits from the AUSFTA. In contrast, ACIL Consulting (2003) found that an AUSFTA would actually make Australia worse off, starting a debate on the likely benefits of the agreement for Australia. The differences in results were found to hinge critically on the assumed Armington elasticities, with the Centre for International Economics assuming larger values and therefore obtaining smaller terms-of-trade effects flowing from the reforms.[19]

The underlying economic mechanism driving the large terms-of-trade effects in GTAP is quite straightforward: tariff reductions lead to increased imports; assuming little change in the country's trade balance, exports are required to increase; in order to increase exports, prices must fall; this increase in international competitiveness is achieved via a real depreciation that, in turn lowers the prices of all exports, and raises import costs, sufficiently to restore external balance. At modest levels of tariffs (as is the case in most countries today), the regional welfare impact of this terms-of-trade effect often dominates the efficiency gains generated by tariff reductions (recall the decomposition in Equation (12.1); therefore model-estimated aggregate regional welfare falls as a result of trade liberalization. This is just another way of saying that the optimal tariff in the GTAP model is quite high, since the export demand elasticities facing individual countries are largely determined by the size of the Armington elasticities of substitution amongst imports. Increasing the size of the trade elasticities is one way of lessening this problem, as larger elasticities of substitution increase the size of the allocative efficiency gains and reduce the size of the price decline required to restore external balance in the wake of a unilateral tariff cut. However, larger substitution elasticities also result in larger output and employment adjustments and it is generally the case that substitution elasticities that

[19] The Centre for International Economics study also assumed greater benefits from services liberalization.

are large enough to moderate the terms-of-trade effects tend to result in excessive specialization following tariff cuts.[20]

The problem of dominant terms-of-trade effects in global CGE models has been explored in detail by many authors. Drusilla Brown was one of the first to address this in a rigorous fashion. Lloyd and Zhang (2006) highlight the many ways in which the introduction of Armington preferences alters the properties of a general equilibrium trade model. An empirical critique of the mechanism by which this occurs is offered by Hummels and Klenow (2005) who compare the relative importance of the two margins along which countries typically expand trade. They find that only 40% is at the intensive margin, through movement down demand curve for a given product. The remaining 60% of the increased exports from large economies is due to expansion of product variety — a phenomenon which does not entail a reduction in price and which therefore does not threaten the gains from trade. To address this issue, it is necessary to explicitly incorporate so-called "LoV" into global CGE models (Brown *et al.*, 1992a, 1992b; Francois 1998). While initially introduced into consumer demand by Dixit and Stiglitz (1997) and Ethier (1984) suggested using this specification for modeling firms' derived demands, and the cost reductions from added variety subsequently became a key element of the gains from trade liberalization (Romer, 1994).

However, the extension of LoV to firms' cost structures led to a major problem in CGE models. When confronted with real-world data, in which the vast majority of trade is in intermediate inputs, the standard CES LoV cost function led to extreme model instability. Consider the case of a reduction in tariffs on intermediate inputs utilized in a domestic industry. In the absence of LoV, this leads to a cost reduction and expansion of the industry, but this expansion is curtailed by rising factor prices and the model finds a new equilibrium at a higher level of output. However, when firm-level product differentiation and LoV are added to this picture, the reduction in costs also leads to firm entry. When such entry occurs in input-supplying industries, this expanded product variety contributes to further cost reductions, which leads to additional entry, and so on. For this reason CGE models with the CES LoV specification have been shown to be prone to far greater specialization than observed in reality (Brown *et al.*, 1995).

20 Single-region CGE models such as the ORANI model (Dixon *et al.*, 1982) have avoided this problem in one of two ways. The first involves by having an asymmetric treatment of import—domestic substitution elasticities (typically small) and export demand elasticities (typically large). [This approach has subsequently been modified in the case of the MONASH model in recognition of the increased differentiation of Australian products (Dixon and Rimmer, 2010).] Of course, in a multiregion model, one region's export demand elasticities are a function of the other regions' import substitution elasticities, so the multiregion modeler is more tightly constrained in this matter. Large export demand elasticities typically translate into large import—domestic substitution elasticities. The other approach to reducing the size of the terms-of-trade effects in CGE models is to constrain the national export supply response by introducing imperfect transformation possibilities between sales to domestic and export markets (Dervis *et al.*, 1982). This can have its own drawbacks in the long run by making the economic structure excessively rigid.

The problem relates back to the fact that the standard LoV specification puts a great burden on the CES in that function, for it must determine both the price elasticity of demand — and hence the optimal markup — as well as consumers' LoV and therefore the gains from product proliferation. Given the relatively greater availability of information on markups, the usual approach to specifying the CES parameter is to choose a value which gives the desired markup — regardless of the implied LoV. The undesirable feature of determining these two separate effects with a single parameter led Alan Deardorff to propose a modification of the standard Spence—Dixit—Stiglitz CES specification in which another parameter is introduced explicitly governing agents' LoV. This parameter, let us call it β, is bounded between zero and one, and produces both the Krugman-style trade model ($\beta = 1$) and the Armington model (no LoV) ($\beta = 0$) as special cases.

Of course, the addition of a new LoV parameter requires that it be assigned a value. Lacking empirical evidence, Deardorff proposed assigning it the value of 0.5 — precisely halfway between the Armington structure and the traditional LoV model (Brown *et al.*, 1995). This proved to be a shrewd choice. Subsequent empirical work by Ardelean ("How strong is the love of variety?" unpublished), utilizing approaches to variety measurement pioneered by Feenstra (1994) results in a global, trade-weighted mean estimate of $\beta = 0.54$ (with a standard deviation of 0.13). Of course this parameter varies widely across sectors and importing regions. While Ardelean's work has yet to be widely adopted in the CGE literature, it does offer strong empirical support for a modified LoV formulation of trade in global CGE models in which variety effects are weaker than originally posited in the Dixit—Stiglitz model.

A fully general treatment of the LoV model is more challenging than the CGE-based research to date would lead one to believe. Proper implementation requires tracking sales from individual firms to individual agents in the importing regions.[21] Such data are not available in the GTAP database; if they were, the model dimensions would explode.[22] Therefore, simplifying assumptions (e.g. symmetric firms and possibly aggregation of variety at the border) are often used. Another challenging issue is the separation of inputs into fixed and variable categories. In a standard model of monopolistic competition, the only mechanism for generating changes in output per firm is through a divergence in fixed and variable costs. Indeed, the combination of entry/exit leading to zero profits and the optimal markup condition in this model means that output per firm is proportional

21 Under certain assumptions on the cost side, these models may be viewed as relatively simple extensions of the standard GTAP model. Indeed Francois (1998) shows how clever "variety scaling" of outputs in the monopolistically competitive sectors may be used to incorporate LoV via the addition of just a few equations and a closure change.

22 A final observation about product differentiation has to do with the mapping of firms to individual countries given the current GTAP database structure. However, in practice, expansion of Toyota exports from Japan will depress prices for Toyotas produced around the world — thereby sharing the impact of the terms-of-trade effect. To capture this, we need trade and production data by firm. That is likely to be a long time coming!

to the ratio of fixed to variable costs (Hertel and McCorriston, 1999). Now consider what happens in the face of trade liberalization. If intermediate goods are incorporated into variable costs, but not fixed costs, then tariff liberalization which lowers the cost of intermediates (either by reducing price, or adding variety) will raise the ratio of fixed to variable costs, thereby raising output per firm. This can be a very powerful mechanism for generating gains from trade. However, it is a direct consequence of the initial assumption about the composition of fixed versus variable costs – something that is not well supported in most studies to date.

Recent work by Feenstra and Weinstein (2010) has also challenged the large size of the LoV effect in international trade. By adopting a different functional form (the translog), with a variable elasticity of substitution and a finite reservation price for individual varieties, they are able to obtain a more satisfying estimate of the welfare gains due to increased merchandise imports into the US over the 1992–2005 period. They find that these imports contributed to a 5.4% cumulative price decline, of which 3.7% is due to variety expansion and 1.7% is due to the disciplinary effect of imports on domestic markups. The latter component was not possible in the CES LoV monopolistic competition framework since the optimal markups by domestic firms were constant.[23] Overall, they find comparable gains from trade to previous studies. However, the introduction of this more general specification diminishes the contribution from added variety.

Perhaps the most important recent development in trade theory, from the perspective of global CGE modeling, is the line of work initiated by Marc Melitz (2003) that incorporates the idea of firm heterogeneity into a general equilibrium trade framework. In equilibrium, the most productive firms are the exporters and the least productive firms do not produce. Other firms produce solely for the domestic market. Therefore, anything that stimulates trade tends to raise average industry productivity, by shifting more resources and production to the most productive firms. This also conforms to the empirical observation that relatively few firms tend to dominate exports and they account for a large share of total industry production in many countries (Bernard *et al.*, 2007). Incorporating these new theories into a global CGE model offers an endogenous mechanism by which trade reform can boost productivity and economic growth – an area often considered by CGE models to represent the "holy grail" as it addresses the frequently voiced frustration that the estimated gains from trade are must smaller than those believed to be present in reality. Recently, there has been increasing interest in incorporating firm heterogeneity into GTAP data-based CGE models. Since there is an entire chapter in this Handbook (Chapter 23 by Balistreri and Rutherford) devoted to this work (see also Balistreri *et al.*

[23] It is, however, possible to capture these procompetitive effects in a CES model if there are a small number of firms. Francois (1998) demonstrates how to treat this case within the GTAP framework, and Elbehri and Hertel (2006) apply this approach to their analysis of Morocco's FTA with the EU in which they find that these precompetitive effects do indeed play an important role due to Morocco's highly concentrated manufacturing sector.

2011), I will simply draw on the recent the findings of Zhai (2008) who shows how a simplified version of the Melitz model can be readily implemented in a modified multiregion CGE framework, using a modest amount of supplementary information on industry markups, variable and fixed costs, and the relative importance of the extensive margin for industry expansion. In a comparison of the gains from 50% tariff cuts worldwide, he finds that the use of the Melitz specification generates gains roughly double those from a standard Armington model (Zhai, 2008). Since fixed costs — both for production and for entry into export markets — play such an important role in determining which firms are active in the Melitz-type framework, this new interest in Melitz-type models has heightened interest in the topic of trade facilitation and the role of non-tariff trade costs in limiting promoting trade — a topic to which we next turn.

12.5.1 Trade facilitation

In an influential study of the cost of time delays at the border, Hummels (2001) estimates the economic value of timeliness by comparing the willingness to pay for the relatively more-expensive air cargo versus the less-expensive ocean shipping services. Using data of US imports of manufacturing goods from the rest of the world, he finds that each additional day spent on transportation corresponds to an *ad valorem* tariff equivalent of 0.8% on manufactured goods and reduces the probability that the US will import from a country by 1—1.5%. In light of the fact that poor trade facilitation can easily delay shipments by 10 days, these are large numbers.

Hertel *et al.* (2001) use Hummels' estimates of the value of time in trade to analyze the economic impact of the Japan—Singapore Free Trade Agreement. This FTA was notable in that one of the partners (Singapore) had almost no tariffs. The bulk of the agreement focused on trade facilitation and improved movement of people and investment. The authors estimate that the expansion of e-business and automation of customs procedures between Japan and Singapore under this FTA were likely to greatly expand bilateral trade between these countries as well as their trade with the rest of the world. The latter result stems from the fact that improved customs procedures benefit imports from — and exports to — all countries, not just the FTA partners. Therefore the authors conclude that such reforms are more consistent with "open-regionalism" than are preferential tariff cuts, which tend to promote the diversion of trade from the rest of the world to FTA trading partners.

Walkenhorst and Yasui (2003) undertook a global study at the OECD using the GTAP framework in which they decompose the costs of border barriers into direct and indirect costs, where direct costs measure the logistic barriers of moving goods across borders, such as efficiency of customs services, transparency and integrity of administrative processes, and indirect costs measures the cost to firms due to delays in freight movement, border waiting times, and so on. Since the indirect cost measures timeliness and increases with waiting time, it is modeled using the iceberg approach, whereas direct costs are modeled as taxes since they generate revenue for private and public firms that provide customs facilities, shipping services, amongst others. Incorporating these into the CGE model the authors simulate the effect of reducing border-related transaction costs. They find that a reduction these transactions costs equal to 1% of world trade generates about $40 billion in welfare gains.

In many cases, these non-tariff barriers to trade dominate the impact of traditional tariffs on trade flows. Mirza (2009) utilizes a variant of the GTAP model — supplemented by econometric results relating trade facilitation to trade volume changes — in order to compare the likely impacts of tariff and trade facilitation reforms in South Asia. She finds that modest improvements in trade facilitation — measured either through a reduction in number of days delay in international shipments or through improvements as measured by the World Bank's Logistics Perception Index — offer a much more powerful stimulus to trade in this region of the world than do tariff reforms. For example, Bangladeshi exports increase by more than $3 billion under the envisioned trade facilitation reforms, whereas full tariff removal in the region boosts trade by less than half that amount.[24]

Many non-tariff barriers to trade arise from domestic regulations put in place to address issues such a product safety, consumer health and environmental quality. Regulatory heterogeneity across countries in these areas often leads to trade frictions, as imports are forced to comply with new domestic requirements. At what point non-tariff measures become trade barriers is conceptually and empirically difficult to ascertain. Unlike for tariffs, "reduction to zero" of these regulatory measures is not an option. So the estimation of trade and welfare effects depends crucially of an intelligent design of scenarios (Dee *et al.*, 2011).

12.5.2 Globalization of factor markets

While globalization in product markets has received the bulk of the attention in the GTAP-based literature, one could argue that the barriers to factor mobility are much larger and hence factor market liberalization holds the potential for much greater welfare gains. This point has been driven home by Walmsley and Winters (2005) who used the GTAP-extended, GMig Database (Walmsley *et al.*, 2007a, 2007b) and estimate that liberalization of quotas on the flows of both skilled and unskilled labor from developing to developed nations equivalent to 3% of the latter's labor force would yield a global welfare gain of $150 billion at 1997 prices — a figure that rivals in magnitude the global welfare gains from merchandise trade reform using that same period/model. The World Bank (2006) used the GTAP-extended, GMig Database with a modified version of the World

24 Of course, this does not account for the cost of investment in improved physical infrastructure and customs clearance technologies. Mirza (2009) modifies the GTAP model to account for these investment costs and finds that the returns from investment in trade facilitation are still substantial, even after the associated costs are taken into account.

Bank's recursive-dynamic general equilibrium model (LINKAGE: see van der Mensbrugghe in Chapter 14 of this Handbook) to estimate a global welfare gain of $674 billion in 2025 (in 2001 US$) compared to their baseline. This is obtained following a 3% increase in the labor force of high-income countries, with the developing world supplying the additional workers. More recently, migration has been included in the Dynamic GTAP (G-Dyn) model (Aguiar and Walmsley, 2010) which has been used to examine changes in migration policy in North America, and to examine whether migration could be used to overcome the effect of projected declining populations in Japan, Singapore, Hong Kong, China and Thailand over the next 20 years in Asia (Walmsley *et al.*, 2011).

As with migration, serious analysis of international capital mobility requires supplementary data. In an ideal world, this would include a global bilateral array of capital ownership, by sector, source and destination region, in addition to current period investment flows. In practice, these data do not exist and they must either be estimated or the model must be simplified. The first effort to extend GTAP in the direction of including endogenous FDI flows as the FTAP model, developed at the Australian Productivity Commission with the explicit goal of incorporating foreign direct investment and barriers to trade in services at a relatively aggregate level (Hanslow *et al.*, 2000; Verikios and Zhang 2001). Using FTAP, Dee and Hanslow (2000) estimated that the complete liberalization of international trade in services would make the world as a whole better off by about $130 billion annually, compared with about $50 billion and $80 billion estimated gains from full agricultural and manufacturing liberalization, respectively.

The CEPII has recently developed a more detailed foreign direct investment (FDI) database for use with the GTAP framework. Their approach builds detailed data available for the EU from EUROSTAT. They use these data to estimate a "gravity" model in which FDI by sector, time period, source and destination, is a function of GDP in the two regions, GDP/capita, sector, distance, language, etc. Using this, they are able to fill in the missing cells[25] for in the global FDI matrix, thereupon balancing this matrix using entropy methods (Boumellassa *et al.*, 2007; see also Lakatos and Walmsley, 2010). There is also a problem of adjusting capital stocks to match these flows. With these new data in hand, authors are now in a position to begin to examine the impacts of relaxing restrictions on FDI flows (Berisha-Krasniqi *et al.*, 2011; Decreux and Chapuis, 2011).

The greatest difficulty with modeling international capital mobility lies in determining the degree of such mobility. While easy to implement, the extreme cases of perfect capital mobility (one rate of return, worldwide) and no capital mobility across regions (the static GTAP approach – at least from the perspective of capacity), these rarely appear appropriate. In practice, the truth lies somewhere in between. Ianchovichina and McDougall

[25] They also have unilateral data on sectoral FDI for some countries/regions as well as bilateral data at the national level for the OECD member countries.

(2000) seek to handle this in the dynamic GTAP model (G-Dyn) by introducing a partial adjustment mechanism whereby risk adjusted net rates of return on capital converge, but only gradually. In this way, the G-Dyn model allows for limited capital mobility in the short run, and perfect mobility in the long run. Golub (2006) estimates these rates of convergence using data from OECD countries and incorporates them into the G-Dyn model in order to project the long-run evolution of the global economy. Other applications of this model have looked at the implications of the East Asian Financial crisis (Ianchovichina *et al.*, 1999) and the impact of China's accession to the WTO on foreign investment in that country (Walmsley and Hertel, 2001). Full documentation along with a set of applications is available in the volume edited by Ianchovichina and Walmsley (2011).

12.6 CGE MODELING OF GLOBAL ENVIRONMENTAL ISSUES

While the GTAP project was initially conceived as a vehicle for delivering quantitative analysis of global trade policy issues (hence the project name), the fastest growing area of application presently involves analysis of global environmental issues. I refer to these as GTAP/CGE expansions at the *extensive margin*, since much of this work involves extending the – reach – of global CGE analysis into new areas of application. Working at this extensive margin typically requires some sort of interdisciplinary collaboration in which knowledge from other fields is obtained and organized into a format suitable for incorporation into a CGE model. Success in this area of work may or may not hinge on new theoretical developments, but it inevitably requires the authors to master new datasets and wrestle with ways to make these supplementary data consistent with the rest of the CGE modeling framework. Often a bit of modeling innovation is also required to make the bridge between the core model and the satellite analysis. I begin this section by discussing the more mainstream applications of global CGE analysis to the analysis of carbon taxes or "emissions caps" and then move into areas that are relatively newer to CGE analysis.

12.6.1 Analysis of fossil fuel-based climate policy

Some of the earliest global CGE modeling work on CO_2 mitigation policy was undertaken at the OECD, led by Jean-Marc Burniaux and nicknamed the GREEN model (Burniaux *et al.*, 1992). This predated the GTAP project and GREEN-based estimates of the cost of curbing CO_2 emissions were influential in the early debate over climate policy. Burniaux's early work was also influential in the subsequent modeling work (LINKAGE) carried forward at the OECD Development Center and subsequently at the World Bank. The successor to LINKAGE, named ENVISAGE, is the subject of Chapter 14 of this Handbook by Dominique van der Mensbrugghe. Burniaux also spent a sabbatical at Purdue University during which time he coauthored an energy-oriented version of the GTAP model, nicknamed GTAP-E (Burniaux and Truong, 2002). The latter a common platform for those developing energy-environment oriented applications with the standard GTAP model. It features extensive nesting of production functions in order to capture the possibilities for interfuel substitution as well as links between energy prices and the demand for capital and labor. It also has a flexible structure for tracking greenhouse gas emissions and allowing alternative emissions trading schemes.

At the forefront of recent climate policy analyses building on the GTAP database is the work of the MIT Joint Program on the Science and Policy of Global Change, nicknamed the EPPA model (Babiker *et al.*, 2001). Early work with this model focused on the economic impacts of fossil fuel-based carbon policies – particularly the Kyoto Protocol. Babiker *et al.* (2000) analyzed the impact on non-participating economies of Kyoto Protocol implementation in developed countries. Paltsev *et al.* (2008) use the EPPA model to assess specific US proposals to implement a cap-and-trade system for carbon reductions, while Babiker *et al.* (2003) and Paltsev *et al.* (2007) emphasize the interactions between such climate policies and pre-existing distortions. The former study examines the question of whether climate policy as envisioned under the Kyoto Protocol would offer a "double-dividend" by which use of the revenue generated to lower distorting taxes would provide an extra boost to welfare. They find little evidence to support this. In the latter study, the authors use the EPPA model to show that pre-existing distortions, when coupled with international price changes, can even result in reduced welfare when moving from a regional to a global emissions trading regime.

Another early GTAP-based contributor to the climate change policy debate was the GTEM model (and its predecessor: MEGABARE) (Tulpulé *et al.*, 1998). These models were developed at the Australian Bureau of Agricultural and Resource Economics (ABARE) with the aim of contributing to the climate policy debate. This framework has been used to analyze the benefits of an emission trading scheme (Tulpulé *et al.*, 1998; Jotzo *et al.*, 1999) as well as the role of a potential Clean Development Mechanism for assisting developing countries in achieving low cost abatement. More recently, the *Garnaut Climate Change Review* (Garnaut, 2008) and the Australian Treasury (Australian Government, 2008) have used GTEM in conjunction with the MONASH Multi-Regional Forecasting (MMRF) model of the Australian economy and a Global Integrated Assessment Model to estimate the impacts of climate change under mitigation and no-mitigation scenarios. The *Review* focused on the costs and benefits to Australia and Australia's role in mitigation in a global context. The Treasury's analysis has sought to estimate the impact of market-based mitigation policies on the Australian economy, at the national, sectoral and household levels (Australian Government, 2008).

12.6.2 Land use in CGE analyses of climate policy[26]

Nearly one-third of global greenhouse gas emissions may be tracked to land-use activities (agriculture and forestry), yet, until recently, the representation of land in GTAP has been limited and the treatment of the associated greenhouse gas emissions has been non-existent. The non-climate implications of such policies are also important and they are inherently general equilibrium in nature, including impacts on food security and poverty, access to water, and aggregate economic welfare. In addition to this contribution to climate change mitigation, agriculture and forestry are two of the sectors most susceptible to climate change impacts, as the relative productivity of lands change with changes in plant productivity, weather variability, and disturbances (Intergovernmental Panel on Climate Change, 2007). For all these reasons, the modeling of land use in GTAP has received increasing attention in recent years. Recent development of global land-use and emissions data, as well as new mitigation cost data, have provided a solid foundation for advancing global economic land modeling (Hertel *et al.*, 2009).

The first global CGE model with land use disaggregated by physical characteristics was the GTAP-based, FARM model by Darwin *et al.* (1995). Land, typically treated as a non-tradable endowment in CGE models, was split into a number of different land categories, distinguished by length of growing period. Land endowment by category was an aggregate taken from a spatially explicit bioclimatic model. The model was used to estimate the impacts of climate change (Darwin *et al.*, 1995) of sea level rise (Darwin and Tol, 2001) and of nature conservation (Darwin *et al.*, 1996) – each of which changes the relative land endowments in various regions of the world. More recently, versions of the GTAP model have been used to assess the impacts of climate change on poverty (Ahmed *et al.*, 2009, 2010; Hertel *et al.*, 2010).

As noted previously in this chapter, the spatial dimension is at the very heart of land-use modeling. With introduction of a GTAP compatible, global land use dataset at the 0.5° grid cell level (Monfreda *et al.*, 2008, 2009) there is ample scope for dramatically increasing the dimensions of any global model. If such a model also endeavors to cover *all* economic activity, not just agriculture or just forestry, then the data and modeling requirements become truly overwhelming at this level of resolution. As a consequence, the GTAP-AEZ model (Hertel *et al.*, 2009) follows the lead of Darwin *et al.* (1995) and aggregates land endowments into AEZs – in this case, there are 18 potential AEZs within each country. The LEITAP model, a land-use-oriented extension of the GTAP model, treats land use at the national scale and focuses on the scope for expanding agricultural land use at the extensive margin (Eickout *et al.*, 2009).

Closely related to the spatial dimension is the issue of the homogeneity of land and its potential mobility across uses. If the unit of observation is small enough so that, for all

[26] This section draws heavily on Chapter 1 of Hertel *et al.* (2009).

practical purposes, the land is perfectly homogeneous, then we would expect rental rates on all land within that unit to be equalized. In the absence of risk and uncertainty, and in the absence of technological interdependence amongst the crops (e.g. benefits from crop rotation or the sharing of common inputs), we would expect farms to specialize in the crop with the highest return, net of non-land input costs. However, farms are often diversified and certainly most of the larger units of observation (e.g. grid cells or AEZs) exhibit diversification of production. Explaining this diversification therefore presents the CGE modeler with a challenge. Several different approaches have been taken to reconciling this puzzle. The first approach is to appeal to risk considerations. This is the approach taken in KLUM (Ronneberger *et al.*, 2009) where risk averse producers maximize expected utility and returns to different crops are uncertain. This combination of factors leads farmers to diversify production. Those authors use half the data in their time series from the UN Food and Agriculture Organization to calibrate the risk aversion and cost parameters for their model. They reserve the second half of the data series for model validation and find that the model performs reasonably well in this out-of-sample test.

Of course, risk aversion is a producer-level issue, not a market-level issue. So when we move to the level of regions, or indeed countries, the appeal of a risk-based approach to model calibration is somewhat lessened. For example, it may be attractive to, for example, grow certain crops in the valley and others on the hillside. Thus, physical heterogeneity is a reason why we might observe diversification in crops within a given AEZ. Hertel and Tsigas (1988) employ a simple CET function to allow the imperfect transformation of the land endowment into alternative uses. This approach is also in the GTAP-AEZ and LEITAP models. The problem with the CET approach is that the "transformation" of land from one use to another destroys the ability to track the allocation of hectares across agricultural activities. Instead of constraining the sum of hectares across uses to equal the total availability of hectares in a given AEZ or country, the CET function constrains the land rental share-weighted sum of hectares to equal the total endowment of land. In this framework, differential land rents reflect differences in the *effective* productivity of a given hectare of land across uses and it is these *effective* hectares that are constrained in the aggregate. Also, given the lack of an explicit link to yields and the underlying heterogeneity of land, this model is difficult to validate against the observed data. In short, while it is an extremely versatile approach to limiting factor mobility across uses, the CET function "covers a multitude of sins." A more explicit approach to handling land heterogeneity would be desirable.

The AgLU model developed by Sands and Kim (2009) also reflects land heterogeneity in its attempt to reproduce a diversified mix of output in a given AEZ (or in their case, a watershed). Their methodology, developed by Sands and Leimbach (2003) and inspired by the work of Clarke and Edmonds (1993) is isomorphic to the CET approach in its representation of maximum profits and supply response. However, unlike the CET function, their framework is based on an explicit model of yield heterogeneity. Indeed, in this model, the variance parameter (possibly adjusted for the correlation of yields across crops), determines the extent of the supply response (see the appendix in Sands and Leimbach, 2003). It can also be shown that there is a direct mapping from these parameters to the transformation parameter in the CET function. Of course, as with any practical approach to modeling complex phenomena, this one involves some restrictive assumptions, in particular the form of the underlying yield distribution (log-Gumbel). The supply function also implies that, at the margin, land rents (profits in their terminology) are equated across uses. This is a testable hypothesis that warrants econometric investigation.

One of the most difficult challenges faced by authors wrestling with global CGE modeling in the context of climate policy is the treatment of forestry. This sector is critical, as the release of carbon from deforested lands accounts for a large share of global emissions and curbing such deforestation appears to be one of the lowest cost options for mitigation (Sohngen, 2010). Sohngen *et al.* (2009) outline the problems and challenges of adequately representing forestry in economic models of land use and land-use change. Unlike most other production processes in the economy, which can be adjusted within a matter of a few years, it takes decades to grow a new forest. Furthermore, growth in the forest stock, as well as sequestration potential, depends critically on the vintage and type of forest. There are very few global forestry models that handle all these aspects well in partial equilibrium. Thus, expecting proper treatment within general equilibrium in the near future is probably asking too much. For example, Sands and Kim (2009) derive a steady-state condition for the determination of optimal forest rotation and embed this in their CGE model of the US economy. This has the virtue of capturing the impact of carbon sequestration subsidies on the optimal timber rotation; however, in so-doing, they ignore the issues of vintages and optimal adjustment paths. Golub *et al.* (2009b) calibrate their a modified GTAP model to mimic the behavior, over a fixed time period, of the Sohngen and Mendelsohn (2007) forestry model on the intensive (more carbon/hectare) and the extensive (more hectares) margins, without explicitly modeling the temporal production process.

A critical issue in modeling the long-run supply of land to different activities in agriculture and forestry is the availability of new lands that might be brought into production. The simplest way to handle this problem is to construct a land supply schedule in which rising land rents causes additional land to be brought under cultivation. This is the approach adopted by Eickhout *et al.* (2009) who estimate the slope of this schedule based on the physical productivity of marginal lands in each region. Golub *et al.* (2009) focus on the potential for expansion of commercial lands into inaccessible forests, offering a model new investment subject to access costs. Here, the access of new lands requires real resources. These authors find that adding the inaccessible lands makes a sizable difference in the long run scarcity of land in some regions of the world.

Most of the work on global land use in GTAP-based CGE models to date has studiously avoided dealing with demands for land by the non-primary sectors, i.e. commercial, residential, recreational uses. Yet in some parts of the world, these represent the main area of future growth in land use and they often dictate land values, and hence the opportunity cost of land-use expansion. The first step in incorporating non-primary demands for land in CGE models involves identifying its importance in the other sectors' production functions. A natural place to start would be the residential and commercial sectors, which are typically broken out in CGE models and which are clearly land-intensive. In the long run the demand for land in parks for recreation and the preservation of ecological diversity is likely to be very important. However, these sectors have not yet been well-developed in global CGE models. Improving their specification, as well as estimating how the demand for their services is likely to grow with higher incomes, will be an important undertaking (Antoine *et al.*, 2008).

Finally, without water, agricultural land is of little use. Indeed residential and commercial lands also depend heavily on water availability. Therefore, incorporating water into the GTAP framework would seem to be a high priority for those interested in global land use, environmental sustainability and climate change. Berrittella *et al.* (2007) have developed a water-extended version of GTAP which they use to examine the role of water resources and scarcity in global trade, analyzing the impact of scarcity on international trade flows as well as welfare.

12.6.3 Bioenergy[27]

Higher fossil fuel prices, concerns about energy security and global warming have all contributed to greater interest in bioenergy over the past decade — particularly in Europe and the US. (Brazil has been a large producer and consumer of ethanol for 30 years.) Early assessments emphasized the potential benefits of displacing fossil fuels with renewable energy (Farrell *et al.*, 2006). However, since publication of a high-profile paper in *Science* by Searchinger *et al.* (2008) concerns about indirect land-use change leading to additional greenhouse gas emissions and higher food prices have moved to the forefront and enthusiasm for bioenergy crops has been tempered. Additional constraints have been placed on biofuel policies — including the need to assess the likely impacts on global land-use change (e.g. California Air Resources Board, 2009). This, in turn, has led to great interest in global economic models capable of eliciting the impact of biofuels subsidies and mandates on land use, food prices, global trade and economic welfare. Equipped with a fairly well-developed description of energy—agriculture—economy interactions, as well as explicit competition for land between sectors, the GTAP-based CGE community has begun contributing to this literature in a significant way (Kretschmer and Peterson, 2010).

Part of the problem in the early days of US biofuel policy formation was that more comprehensive models were not used in the environmental assessment of the US ethanol program. Initial estimates of the greenhouse gas emissions impacts of ethanol were based

[27] This section draws heavily on Golub *et al.* (2010) and Golub and Hertel (2011).

solely on commodity-specific, partial equilibrium analysis. These studies (e.g. Farrell *et al*., 2006) highlighted the greenhouse gas emissions reductions likely to ensue if ethanol produced from corn were used to replace petroleum in the liquid fuel economy. It was on this basis that the US renewable fuel mandate for corn ethanol was proposed, assuming that it would benefit the environment, while reducing dependence on imported oil and boosting farm incomes. Only when more comprehensive economic modeling was undertaken did the phenomenon of indirect land use enter the debate. This turned out to reverse the conclusions. Therefore it is clearly important to include competing land using activities in any biofuels policy model – specifically livestock pasture and forestry.

There are additional, important linkages which must also be taken into account in order to obtain an accurate assessment of biofuels policies. For example, the demand for ethanol in the US depends critically on the overall demand for liquid fuels in transportation. Due to engineering limitations with the US auto fleet, once ethanol use reaches a predefined percentage of total fuel demand, a "blend wall" becomes binding and more ethanol cannot be absorbed, regardless of price. Thus, it is important to model aggregate liquid fuel demand explicitly. This is not the end of the story when it comes to expanding the model. In the case of ethanol – about 16.5% of industry revenue comes from byproducts (dried distiller grains with solubles (DDGS)); Taheripour *et al*. (2010). (This figure is even larger in the case of biodiesel processing.) DDGS substitute for corn in livestock feeding. In effect, the process of ethanol production does not fully exhaust the feed value of the corn. Thus, if one wants an accurate picture of the impact of ethanol production on global land use, for example, it is critical to take into account the role of byproducts in filling part of the niche vacated by the corn being diverted from the livestock sector to energy production. This entails developing a proper model of the livestock feeding decision. In short, if one were to take a partial equilibrium approach to the problem, it would be hard to know where to draw the line on which components of the economy to model and which to ignore. In the end, it is easier to take a general equilibrium approach in order to ensure that nothing important has been missed. For this reason, the GTAP-BIO model was developed (Birur, *et al*., 2007; Taheripour *et al*., 2011).

Hertel *et al*. (2010) use the GTAP-BIO model to decompose the main drivers of the US biofuel boom during 2001–2006 and find that, of the total change in ethanol growth in the US (133.5%), 64% of the total figure is attributed to a ban on the main competing additive methyl *tert*-butyl ether (MTBE), 93% is attributed to the rise in petroleum prices over this period and –23% is due to the diminishing relative importance of the $0.51/gallon blenders' subsidy. In the case of EU biodiesel growth over this same period (341%), the most important driver is the fuel tax exemptions (202%) since the *ad valorem* equivalent of the power of the EU subsidy on biodiesel rose by 81.2% over this period. This is followed by the contribution of higher oil prices (140%).

Hertel *et al*. (2010) use the GTAP-BIO-AEZ model in a study undertaken for the California Air Resources Board (2009) aimed at establishing a benchmark for the global land-use impacts of biofuel expansion. Those authors emphasize the role of market-mediated mechanisms in moderating the global land-use change. While the naïve estimate of the global land requirements needed to achieve the 15 billion gallon mandated level of corn ethanol production in the US is about 15 million hectares (starting from a 2001 base), this gross land requirement is reduced to 4.2 million hectares due to number of market-mediated effects that include: availability of coproducts, the reduction in food consumption due to higher prices and increased yields due to higher prices. Nonetheless, once the land-use changes have been converted to greenhouse gas emissions, the authors estimate that land conversion associated with a 1 MJ increase in ethanol production, results in 27 g CO_2 in added emissions. When added to the direct emissions from corn ethanol production (estimated at 65 g CO_2/MJ) are sufficient to "... nearly eliminate carbon benefit of this biofuel relative to typical gasoline (94–96 g/MJ)" (Hertel *et al.*, 2010). Since this finding had significant financial implications for the ethanol industry, the results were heavily scrutinized. Subsequent work by Tyner *et al.* (2010) suggests that these land-use-related emissions may be somewhat lower due to a revision in the assumptions about yields on the newly converted croplands.

In summary, the analysis of environmental issues in GTAP has proven to be a fruitful "extensive margin" of CGE model development and the demand for improved CGE modeling in of climate policy, biofuels, land use and climate impacts show no sign of slowing down in the future.

12.7 FUTURE DIRECTIONS FOR GTAP

Discussion of future directions for GTAP can be usefully divided into three areas: institutional considerations, database and model development. I will take these in reverse order. Given the widespread continuing use of the standard model, there would appear to be some value in giving this model an "upgrade" to reflect recent theoretical and empirical developments. Furthermore, allowing these features to apply in some sectors but not in others (or not at all) via closure changes would be particularly attractive. The most straightforward area in which this could be offered is that of Dixit–Stiglitz LoV, which could be implemented following the general methodology of Francois (1998) and modified along the lines suggested by Brown *et al.* (1995) and supported the empirical estimates provided by Ardelean (unpublished). Without the addition of an independent "LoV" parameter, this kind of extension is unlikely to be used and useful in a standard modeling platform. Adding the possibility of heterogeneous firms is more complex, but should be possible following the simplifications suggested by Zhai (2008) as well as the computational advances discussed by Balestreri and Rutherford in Chapter 23 of this volume. By allowing users to invoke these features, as appropriate, this should also stimulate the demand for additional empirical work, aimed at estimating the new parameters, and executed in a manner compatible with the GTAP sector groupings.

More sophisticated modeling of labor markets should also be a high priority in the future. Concerns about employment rank at the top of many policy makers' agendas, and devoting more serious attention to this area of the model would yield significant payoffs. Such efforts will necessarily involve further disaggregation of the labor force, as well as improved modeling of labor mobility and unemployment.

There is substantial scope for innovations that permit the GTAP model to be more coherently linked to biophysical models for purposes of analyzing environmental issues – of which climate change policies and impacts are perhaps the most prominent example. Indeed, the challenges discussed above in simply incorporating spatial explicit information on physical land area in a coherent fashion into CGE models highlight the difficulties of linking models based on economic values with those based on physical quantities. Progress in this area will require CGE modelers to "think outside the box," working closely with natural scientists to better understand the key issues that need to be captured in the economic model.

As the range and use of GTAP-based models continues to expand, there is great scope for more systematic model intercomparison exercises. These have become widespread in the climate change community, but economists have been slower to move into this area. One exception is the model comparison effort focusing on dynamic stochastic general equilibrium models discussed by Schmidt and Wieland in Chapter 22 of this Handbook. It would seem that something similar could be profitably pursued in the GTAP community, particularly since most models start with the same database. This simple fact will greatly facilitate such model intercomparison exercises in the future.

As we turn to the database front, there will continue to be tension between broadening and deepening of GTAP. Quality assurance continues to be a big issue, as each of the more than 100 national databases comprises roughly 7000 economic flows and each of these flows may potentially have a distinct tax or subsidy equivalent associated with it. This is quite apart from the bilateral trade relationships that must be tracked. However, there is much more enthusiasm (and funding) for extending the database into new areas, as opposed to improving the quality of the existing database. Fortunately, the GTAP Advisory Board has continued to advocate strongly for quality assurance.

Ever since the beginning of the GTAP effort, there has been interest in assembling a time series of GTAP databases. In addition to satisfying the interest in seeing how disaggregated linkages in the global economy have evolved over time, such time-series data would greatly enhance the potential for econometric estimation of key parameters as well as model validation. Given these compelling interests, it is perhaps surprising that such a database has been slow to be developed. The difficulties lie in two areas. First of all, the underlying source data are continually changing/being revised and updated. Therefore, the 2004 trade data used in building the version 7 GTAP database are likely to differ significantly from the 2004 trade data available in 2010 when the version 8 GTAP database was being assembled. Even in cases where the underlying source data were unchanged, incompatibilities in the time series are introduced due to changes in the methodology for processing the data. For example, the introduction of methods for measuring tariff preferences had a dramatic impact on aggregate tariffs in the GTAP database — lowering average tariffs substantially from the previous, most favored nation-based tariffs used in the database. In order to overcome these issues, and realize the benefits of a consistent time series of GTAP databases, the version 8 database is being released with two base years (2004 and 2007) both built from the same source data and database construction programs. In the future, the Center plans to rebuild the 2004 and 2007 base years with updated sources and methods, while updating the new database to 2010. In this way, the database will be carried forward as a time series.

A key area for extending the database is the development of more detailed national fiscal accounts. Without such data, it is impossible to address many important issues of public finance. The recent work by Sonmez *et al.* (2011) suggests one way forward in this important area.

There is also considerable potential for realizing network economies in the context of dynamic modeling, with a shared, GTAP-compatible baseline (Chappuis and Walmsley, 2011). The development of model consistent projections of GDP, factor endowments and total factor productivity growth is a substantial exercise, particularly if the productivity growth is to vary by sector. Adding policy projections makes such scenarios much richer, but also more complex. There is clearly much to be gained from collaboration on this front.

With the explosion of interest in global environmental, trade and economic issues, there promises to be a growing demand for GTAP data and modeling activity. A key question is whether the institutional infrastructure can continue to evolve in order to meet these needs. For the last decade, project leadership has advocated moving toward an "open-sourcing" model of operation, whereby more individuals and groups around the world become contributors of database modules. In the long run, this seems to be the only viable approach to meeting the explosion of interest in — and demands for — global economic data and analysis. However, it is not clear how to manage such a transition. Documenting and translating existing programs into a form that can be used by researchers anywhere in the world will require substantial resources. And, having done so, a new model for funding core activities will need to be invented. All of this has left the GTAP Advisory Board rather cool to the idea of open-sourcing. As the saying goes — "if it isn't broken, why fix it?". However, concentrating all database construction activities at Purdue University will constrain long term growth of its use and its extension into new areas.

The open-sourcing model also leads directly into the question of competition versus collaboration in global database construction. Economists are generally opposed to monopolies — and with good reason. There is a tendency to become complacent and innovation can suffer. At present, many groups take the core GTAP database and "add value" in various ways, thereby differentiating the final product. This has proven to be an effective means of permitting innovation at the margin. However, these groups are fundamentally constrained to working with the final GTAP product. There have also been occasional efforts to mount competing projects from the ground up. At the point of this writing, the sheer cost of assembling and maintaining a global database has prevented such competitor projects from succeeding. However, there will no doubt be new efforts in the future. An open-source approach to database construction would greatly facilitate the entry/exit of research groups at various stages of the database construction process, while avoiding wasteful expenditure on projects which never materialize. In the long run, this may be the strongest argument in favor of the open-source institutional model.

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