CHAPTER 1

Introduction

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1.1 OVERVIEW

Computable general equilibrium (CGE) modeling is a challenging field. It requires mastery of economic theory, meticulous preparation of data and familiarity with underlying accounting conventions, knowledge of econometric methods, and an understanding of solution algorithms and associated software for solving large equation systems. However, the most important requirement is the ability to communicate. CGE modeling is primarily about shedding light on real-world policy issues. For CGE analyses to be influential, modelers must explain their results in a way that is comprehensible and convincing to their fellow economist, and eventually to policy makers.

While CGE modeling is challenging, it is also rewarding. CGE models are used in almost every part of the world to generate insights into the effects of policies and other shocks in the areas of trade, taxation, public expenditure, social security, demography, immigration, technology, labor markets, environment, resources, infrastructure and major-project expenditures, natural and man-made disasters, and financial crises. CGE modeling is the only practical way of quantifying these effects on industries, occupations, regions and socioeconomic groups.

In 2010, CGE modeling had its 50th birthday, marked by a celebration in Oslo commemorating the publication in 1960 of Leif Johansen's *A Multisectoral Study of Economic Growth*.[1] In that book, Johansen describes a 22-sector model of Norway which is generally recognized as the first CGE model. What distinguishes his model from other economy-wide models of that time is the explicit identification of behavior by separate agents. In Johansen's model, households maximize utility subject to their budget constraints, industries choose their inputs to minimize the costs of producing the level of output that will satisfy demand and capitalists allocate the economy's capital stock between industries so that rates of return reflect historical relativities. The behavior of these individual agents is coordinated through prices determined by interaction of demand and supply. In contrast to Johansen's multiple-agent approach, earlier and

1 The papers presented at the celebration will be published at a special issue of the *Journal of Policy Modeling*.

Handbook of CGE Modeling - Vol. 1 SET
ISSN 2211-6885, http://dx.doi.org/10.1016/B978-0-444-59568-3.00001-8

contemporaneous economy-wide models in the 1960s [e.g. the input–output and linear programming systems of Leontief (1936, 1941), and Sandee (1960) and Manne (1963)] visualized the economy as a single agent. In those models, the *economy* produced the output vector necessary to satisfy exogenous final demands or to optimize an economy-wide welfare function.

Fifty years on, CGE modeling is an established field. It has textbooks [e.g. Dervis *et al.,* (1982), Dixon *et al.,* (1992) and Burfisher (2011)], survey articles [e.g. Shoven and Whalley (1984), Robinson (1989), Bandara (1991), and Partridge and Rickman (1998, 2010)] and conference volumes [e.g. Kelley *et al.,* (1983), Scarf and Shoven (1984), Bergman *et al.,* (1990), and Mercenier and Srinivasan (1994)]. It is the subject of many monographs and journal articles, and provides the substance of thousands of consultancy reports. So what is added by the *Handbook of Computable General Equilibrium Modeling*?

This Handbook is not a textbook, a survey or a conference volume. It is a collection of chapters setting out the experience of leading CGE modelers. Each chapter contains essential knowledge but just as importantly, each chapter points to new horizons. As evidenced in the Handbook, CGE modeling embraces new problems as they arise in a real-world context. Important current focuses are aging, greenhouse gases and global financial imbalances.

In planning the Handbook we had a four-part structure in mind: single-country models; global models; technical aspects of CGE modeling covering data, parameter estimation, computation and validation, and current cutting-edge methodological areas. Broadly, this is how things worked out; but of course chapters that were initially planned for one section describe contributions that fit into other sections as well.

1.2 SINGLE-COUNTRY MODELS

Norway and Australia are the two countries in which CGE modeling has had its highest profile in policy formation. Both these countries have long-standing CGE modeling projects with continuous histories up to the present day. In Norway, the MSG (multi-sectoral growth) project located in the Norwegian government's statistical agency (Statistics Norway) goes back to Johansen in the 1960s. In Australia, the MONASH project, currently located in Monash University's Centre of Policy Studies, goes back to the setting up in the Australian government bureaucracy of the IMPACT project in 1975. The MSG and MONASH projects are related. The MONASH project adopted and extended Johansen's techniques and carried his style of CGE modeling to the rest of the world.

As explained in Chapter 2 by Peter Dixon, Bob Koopman and Maureen Rimmer, creation of the first MONASH model, ORANI, involved a series of enhancements to Johansen's model, including: (i) a computational procedure that eliminated Johansen's linearization errors without sacrificing simplicity, (ii) endogenization of trade flows by introducing into CGE modeling imperfect substitution between imported and domestic varieties (the Armington assumption), (iii) increased dimensionality allowing for policy-relevant detail such as transport margins, (iv) flexible closures, and (v) complex functional forms to specify production technologies. ORANI was a large-scale comparative statical model used in Australia's tariff debate of the 1970s. Modern MONASH models are dynamic. They have proved remarkably flexible and operate in numerous countries on a wide variety of policy issues. As well as broad theoretical features of MONASH models, the chapter covers data preparation and introduces the GEMPACK purpose-built CGE software, discussed in detail in Chapter 20.

To a large extent MONASH models have evolved to meet the needs of clients in government and business. The models can be used for four modes of analysis: historical, decomposition, forecast and policy. Historical simulations produce up-to-date data, and estimate trends in technologies, preferences and other naturally exogenous but unobservable variables. Decomposition simulations explain historical episodes and place policy effects in historical context. Forecast simulations provide baselines using extrapolated trends from historical simulations together with specialist forecasts. Policy simulations generate the effects of policies as deviations from baselines. To emphasize the practical orientation of MONASH models, the chapter starts with a MONASH-style policy story on the effects on the US economy of restricting the number of illegal immigrants working in the US. The story is told in a way that is typical of policy briefs provided by MONASH modelers to government-sector economic advisors. It is a *quantitative* story that exposes the main mechanisms and data items that drive the results but does not require advisors to have a CGE background. Among the factors identified in the story is the Occupation-mix effect. This is the idea that a reduction in low-skilled immigrant employment creates job vacancies for legal residents at the low-skilled end of the occupational ladder, while closing off vacancies at the top end. In the long run, this causes a deterioration in the occupational mix of employment of legal US residents.

In Chapter 3, Erling Holmøy and Birger Strøm consider applications of MSG6, the most recent version of the MSG model of Norway originally developed by Leif Johansen (1960, 1974). Holmøy (2012) has traced the development of successive generations of the MSG model over the past half century. Although the different versions of MSG have common features, such as integration with the Norwegian national accounts and an emphasis on long-term trends, the current version bears relatively little resemblance to Johansen's model. In place of constant returns to scale and perfect competition for individual industries, as in Johansen's approach, individual industries in MSG6 are modeled as imperfectly competitive with increasing returns to scale. Second, the model incorporates a detailed microsimulation model for Norway in order to capture the role of changing demographics and the distributional impact of alternative policies.

Holmøy and Strøm consider applications of MSG6 to assessments of the fiscal sustainability of government tax and spending programs in Norway. Despite Norway's massive revenues from the sale of petroleum and natural gas in buoyant international markets, the Norwegian economy faces a severe problem of fiscal sustainability in the future. This can be traced to the relatively high level of government services, the aging of the Norwegian population and the eventual depletion of oil and gas resources. This finding is robust to variations in assumptions about productivity growth, the level of petroleum prices, longevity of the Norwegian population, immigration policies and health of the elderly. The authors emphasize the crucial role of general equilibrium effects in the outcomes of the policy simulations. General equilibrium modeling is particularly important for distinguishing between the transitory impact of large petroleum revenues and the long-term effects of an aging population on the Norwegian economy.

Apart from public sector institutions in Norway and Australia, another institution that has had a long-standing involvement in CGE modeling is the World Bank. Chapters 4, 5 and 6 discuss some of the Bank's current and past single-country CGE modeling. Later chapters (Chapters 13, 14 and 21) cover the Bank's contributions to global modeling.

In Chapter 4, Hans Lofgren, Martin Cicowiez and Carolina Diaz-Bonilla describe the World Bank's program to develop a standardized modeling approach for assessing progress toward the Millennium Development Goals (MDGs). These goals were established at the UN Millennium Summit in 2000, and called for halving poverty rates, achieving universal primary education, reducing under-5 and maternal mortality rates, and reducing the share of the population without access to improved sources of water and sanitation, all by 2015. In 2004 the World Bank established the MAMS (Maquette for MDG Simulations) framework for CGE modeling of the MDGs and launched a pilot project for Ethiopia. This framework has now been applied to more than 40 countries by the World Bank staff, the staff of the UN Department of Social and Economic Affairs and national researchers in emerging economies. Applications have been extended beyond the MDGs to include alternative targets, additional issues and longer time horizons.

Lofgren, Cicowiez and Diaz-Bonilla describe the MAMS framework, its implementation in the GAMS software package and the development of an Excel-based front end to make the model results accessible to a wider range of users. A major finding from cross-country comparisons is that achievement of the MDGs is heavily dependent on each country's initial situation. This leads to the conclusion that countries may be better off pursuing country-specific goals for poverty reduction and human development. A relatively balanced development program consisting of public infrastructure and human development services generates the most desirable outcomes. Second, a focus on human development programs such as education and health generates large demands for highly educated labor and undesirable distributional effects. The MAMS framework has also been used to analyze the potential for currency appreciation from foreign aid that could undermine competitiveness. The authors present a relatively detailed model for Yemen to illustrate the CGE approach and its application to development policy.

Chapter 5 is a reflective piece by Shanta Devarajan and Sherman Robinson. It draws on their long experience in applying CGE models in developing countries on behalf of the World Bank and other organizations. The chapter provides a taxonomy of CGE models (stylized versus detailed; static versus dynamic; recursive versus perfect foresight) and identifies model characteristics necessary for addressing different policy problems in developing countries. The chapter then discusses the ways in which CGE models have been used in policy formulation and the lessons learned from past experience. An interesting conclusion is that the process of policy making in many developing countries is becoming more democratic and that this should change the way in which CGE models are used. Rather than being a tool purely for government technocrats, CGE models should become relevant and accessible to different groups in the political/economic debate. This may require modelers for developing countries to broaden the range of questions they address and to rethink their communication strategies.

Chapter 6 by David Tarr describes a World Bank CGE-based study on Russian accession to the World Trade Organization (WTO). The chapter starts with a stylized model in which services in a country are produced by domestic-owned and foreign-owned firms located in the country. The foreign-owned firms have a much more efficient technology than domestic-owned firms. However, domestic-owned firms can survive because foreign-owned firms face extremely high discriminatory taxes and red-tape requirements. When discrimination is removed, foreign-owned firms drive out domestic firms. Large welfare benefits result. Having established his main ideas via the stylized model, Tarr moves on to a detailed empirical model. Simulations with the detailed model show that the major benefit of WTO accession for Russia would be liberalization of foreign direct investment, allowing highly efficient foreign service providers to dramatically expand their operations. The projected welfare gains generated from improved service provision are about 5% of GDP, with the total benefits of all aspects of WTO accession being about 7% of GDP. As with Devarajan and Robinson in Chapter 5, Tarr emphasizes the importance of effective public communication. He cites evidence of the impact of the World Bank study on moving public opinion in favor of WTO accession.

In many countries, especially federations, the regional dimension is a key aspect in the discussion of economic policies. Consequently, in countries such as Australia, Canada and the US, an early development in national CGE modeling was the creation of facilities for working out the implications of policies for states and provinces. Chapter 7 is a comprehensive introduction to and survey of regional CGE modeling. In this chapter, James Giesecke and John Madden start with a discussion of applications. They distinguish between those concerned with national shocks, such as changes in tariffs, for which top-down (national to regional) methods are adequate and those concerned with region-specific shocks, such as major events in particular states, for which bottom-up (regional to national) methods are required. Bottom-up modeling introduces theoretical and data challenges in the handling of interregional trade and factor mobility, cross-border ownership of productive assets, the regional location of margin providers, intergovernmental finances and agglomeration economies. A "typical" multiregional CGE model is set out in the chapter to explain how these challenges are being met. Throughout the chapter, Giesecke and Madden emphasize result interpretation. They demonstrate the use back-of-the-envelope (BOTE) models to explain results from regional CGE calculations and show how intuitive explanations can be deepened and checked through regression analyses.

Chapters 8 and 9 describe CGE models for the US and Australia that have been used in high profile studies of climate policies.

In Chapter 8**,** Dale Jorgenson, Richard Goettle, Mun Ho and Peter Wilcoxen present their Intertemporal General Equilibrium Model (IGEM) for analyzing energy and environmental policies in the US. This model has been employed in a series of policy studies by the US Environmental Protection Agency. A distinctive feature of the IGEM model is that the behavioral responses of producers and consumers to changes in policy are obtained from econometric estimates. The econometric methods used in IGEM are discussed in more detail in Chapter 17. Jorgenson, Goettle, Ho and Wilcoxen compare a base-case simulation of the US economy, based on no change in energy and environmental policies, with alternative cases corresponding to specific policy changes. They evaluate these policy changes by means of equivalent variations in the wealth of individual households. These are defined in terms of differences between the wealth required to achieve the time path of lifetime consumption under the policy case with the wealth required under the base case, both evaluated at prices of the base case. If the difference is positive, the policy change can be recommended for implementation; if not, the current policy is preferred and no change in policy is recommended.

Jorgenson, Goettle, Ho and Wilcoxen focus on market-based environmental policies, such as environmental taxes or tradable permits. Each policy regime corresponds to an intertemporal equilibrium of the US economy. This consists of a market equilibrium between supply and demand for commodities and factors of production achieved through the price system. Markets can be extended by incorporating environmental taxes or tradable emissions permits. Supply—demand balance in each period is linked to similar balances in future periods by arbitrage conditions that assure equality between the current price of an asset and the present value of its future services. Supply—demand balance is linked to the past through the accumulation of assets from past investments. Heterogeneity of energy producers and consumers is critical for the evaluation of energy and environmental policies. To capture this heterogeneity it is necessary to distinguish among different commodities, industries and households. Econometric methods are particularly useful for summarizing information on different industries and different consumer groups in a form suitable for policy evaluation.

In Chapter 9, Philip Adams and Brian Parmenter use a CGE model to project the effects for Australia of entering a worldwide emissions trading scheme. Their chapter emphasizes the importance in the policy process of identifying winners and losers. They achieve the required level of detail for doing this in three ways.

First, they start with a bottom-up regional model for Australia that already has an impressive level of detail: 50 industries operating in each of eight regions. This workhorse model is supplemented by a top-down facility for projecting results from the eight regions to 57 subregions and by a subsidiary dataset of carbon dioxide emissions by industry. The workhorse model generates a year-on-year baseline informed by forecasts from organizations concerned with various aspects of the economy and by trends in industry technologies, consumer tastes and world trading conditions. Policy effects are generated as deviations from the baseline. Second, they modify the workhorse model in various ways to enhance its ability to encapsulate greenhouse issues. For example, they disaggregate electricity generation into six industries defined by fuel input. Third, they make links between the workhorse model and two other models: a specialist electricity model, which provides baseline paths and policy responses for several electricity variables, and a global model, which generates projections for the world price of carbon dioxide emissions. The chapter is an example of CGE modeling at its practical best. It shows how CGE modeling can support a comprehensive study of a real-life policy issue. By embedding in their CGE framework information from specialist models, Adams and Parmenter produce analysis with high credibility and widespread acceptance in policy circles.

In Chapter 10, Dale Jorgenson and Kun-Young Yun present an intertemporal general equilibrium model of the US economy for evaluating alternative tax reforms. The model has similar features to the IGEM model described in Chapter 8, but radically simplifies the analysis of tax policy by including only a single production sector and a single representative consumer. In the US, as in many other countries, income from corporate assets is taxed at both the corporate and the individual level, income from non-corporate assets is taxed at the individual level, and income from owner-occupied housing is not taxed at all.

Differences in tax policy are incorporated in the model by distinguishing among corporate, non-corporate and household capital services. For each reform proposal an intertemporal price system clears markets for outputs of consumption and investment goods and inputs of capital and labor services. This price system links the past and the future through markets for investment goods and capital services. The government sector is coupled to the commodity markets through the tax system. Parameters that describe the economic responses of households and businesses to changes in tax policy are estimated econometrically.

Jorgenson and Yun illustrate their approach to policy evaluation by comparing proposals that would remove barriers to efficient allocation of capital and labor inputs. They have analyzed the economic impact of major US tax legislation, such as the Tax Reform Act of 1986, as well the potential impact of alternative tax reform proposals. These proposals are based on two broad approaches to reform: (i) to remove discrepancies in the tax treatment of different categories of income and (ii) to shift the tax base from income to consumption. Jorgenson and Yun identify Efficient Taxation of Income as the most effective approach to tax reform. This involves equalizing tax burdens on business and household assets, especially income on assets held in the corporate sector and the imputed income from owner-occupied housing. A second feature of Efficient Taxation of Income is that the graduated tax on labor income would be replaced by a proportional tax and equity would be preserved by imposing different tax rates on capital and labor incomes. Another effective approach would be to substitute a European-style value-added tax for the corporate and personal income taxes, but this would involve a serious loss in equity.

In Chapter 11, John Diamond and George Zodrow present their dynamic, overlapping generations (OLG) CGE model for the analysis of the economic effects of tax reforms. This model is especially well-suited to analyzing both the short-run transitional and the long-run dynamic macroeconomic effects of these reforms. These effects include changes in the time paths of labor supply, saving and investment induced by changes in tax policy, as well as the distributional effects of these reforms within and across generations. This important line of research was initiated by the seminal contribution of Auerbach and Kotlikoff (1987). This work has been extended to include multiple goods and multiple individuals by Fullerton and Rogers (1993), and now includes the analysis of open economies, human capital accumulation and economic uncertainty discussed in Chapter 27. The application of OLG models has focused on changes in capital income taxation, especially on the replacement of capital income taxes by a consumption-based tax system.

Diamond and Zodrow describe their model in considerable detail. This is characterized by 55 age cohorts with 12 income groups within each cohort. The model includes four production sectors and provides explicit calculations for changes in asset values resulting from changes in tax policy. This is particularly valuable for the analysis of the substitution of a consumption-based tax for income taxes, which could produce a substantial fall in the value of residential housing. The chapter includes numerous applications of the Diamond–Zodrow model to important issues in tax policy. Examples range from incremental reforms in specific provisions of tax law to substantial changes in tax policy, such as deficit-financed tax cuts like those instituted in the US in the early years of the George W. Bush Administration. Diamond and Zodrow analyze the effects of substituting a consumption tax for individual and corporate income taxes. They also consider the addition of a consumption-based value-added tax to the existing system of income taxes as a means of reducing government deficits and slowing or reversing the increase in US government debt.

1.3 GLOBAL MODELS

Analysis of several major contemporary issues including: climate change, multilateral and bilateral trade agreements, immigration, and international financial imbalances, can benefit from a global perspective. CGE modelers have responded over the last twenty years with several multicountry model-building projects. Chapters 12–16 describe some of these efforts.

Chapter 12 by Tom Hertel describes GTAP (Global Trade Analysis Project) run at Purdue University. This is a remarkable project operating on a small budget with limited staff. It provides a global database for 113 countries (or in some cases regions) and 57 sectors. The data include input-output tables for each country, trade flows, tariffs and tariff equivalents of other trade restrictions, immigration flows, and greenhouse gas emissions. Since the inception of the project in 1992, the number of people participating in it as users of GTAP data and models, as contributors of data, and as presenters at GTAP conferences has grown rapidly. The GTAP network now includes 10,000 people from almost every country in the world. Surely it must be the largest cooperative network of researchers ever assembled in economics. Hertel describes the profound influence that the GTAP has had on trade negotiations and policy and its spreading influence in the area of climate policy negotiations. He also describes how the GTAP data and model are being used by economists working at the cutting edge of developments in trade theory.

The obvious question is: how did GTAP happen? Hertel credits Alan Powell and his IMPACT Project in Australia as an inspirational force in the organization of GTAP. He also credits technical developments in Australia [particularly the SALTER global model, which was derived from the first MONASH-style model (see Chapter 2) and was implemented using GEMPACK software (see Chapter 20)] as giving him a great starting point. He outlines the GTAP strategy of providing a unifying database but encouraging the creation of many models that use that database. The development of these models, focusing on aspects of the world economy of interest to particular organizations and researchers, is facilitated by the provision of a generic GTAP model. Hertel and his colleagues have emphasized openness and the provision of training. They have combined this with early and effective use of the worldwide web as a communication medium.

In Chapter 13, Kym Anderson, Will Martin and Dominique van der Mensbrugghe describe their DAI (Distortions to Agricultural Incentives) database that quantifies tariffs on imports as well as subsidies and taxes on exports and production for many countries and commodities. They compare the DAI and GTAP databases on trade-distorting policies by conducting a series of simulations with LINKAGE (a global CGE model that has been used for the past decade by the World Bank in preparing growth and trade projections for the world economy, see Chapter 14). The LINKAGE results show the effects of removing distortions as represented in the two databases. The results cover a wide variety of variables including welfare and poverty effects by country and region. A striking feature of the results is the dominance of agriculture in trade distortions.

The chapter emphasizes three points regarding simulations of trade liberalization in global CGE models: (i) accurate representation of trade-distorting policies is necessary, (ii) it is important to think about where trade-distorting policies would go in the absence of trade liberalization—it is not clear that the no-change baseline assumption is appropriate and (iii) aggregation matters. Analysts using global CGE models are restricted to about 60 commodity categories within which distortions applying to subcommodities may differ widely. Anderson, Martin and van der Mensbrugghe discuss the aggregation problem and show its importance by comparing results from liberalization simulations in which category tariff rates reflect fixed import weights with simulations in which optimal variable-weight tariff rate aggregation is used.

In Chapter 14, Dominique van der Mensbrugghe presents the ENVISAGE model of the world economy. ENVISAGE is a successor of LINKAGE (see Chapter 13), which served as the macro/industry component of the World Bank's GIDD model (see Chapter 21) for analyzing the evolution of world income distribution. ENVISAGE is a recursive-dynamic CGE model, but does not generate an intertemporal equilibrium like the models discussed in Chapters 8, 10 and 11. It is calibrated to the GTAP database described in Chapter 12. The current version of this database, release 7.1, has a base year of 2004, provides 57-sector input-output tables for 113 regions/countries and contains detailed data on bilateral trade among all these regions/countries. ENVISAGE and related models have been used to analyze international trade, the Doha Development Agenda and structural change in the world economy. The model has also been employed to construct forward-looking scenarios for agriculture and energy, to analyze the regional implications of international migration, and to study climate change and its potential impacts on the world economy.

The main application described by van der Mensbrugghe in Chapter 14 is the development of forward-looking scenarios for agriculture in the light of the sharp rise in world food prices in 2007/2008 that preceded the financial and economic crisis of 2007—2009. Construction of a forward-looking scenario for world agriculture begins with world population projections prepared by the UN. These are used to project growth of the labor force for all regions/countries. Productivity growth for agriculture is based on modeling by the International Food Policy Research Institute (IFPRI). In the baseline scenario for world agriculture presented in Chapter 14, food prices rise and land use increases in response to growth in world income and changed patterns of consumption. This reverses a long-term trend toward lower food prices in inflation-adjusted terms. These conclusions are robust to changes in assumptions about population growth, land use and agricultural productivity growth. Chapter 14 concludes with a brief discussion of applications of ENVISAGE to the analysis of climate policy.

Warwick McKibbin and Peter Wilcoxen present their G-Cubed model for analyzing energy and environmental policy in Chapter 15. This is a multiregion, multicommodity, intertemporal general equilibrium model of the world economy. In each period the model links economic activity in twelve subregions of the world economy through bilateral trade flows. Like the models presented in Chapters 8, 10 and 11, the G-Cubed model contains forward-looking links among supply—demand balances at different periods of time through rational expectations about asset prices. The model also contains backward-looking links through capital accumulation resulting from past investments. From the point of view of international trade theory, an innovative feature of the model is the distinction between physical and financial capital for each region. Financial capital is perfectly mobile among regions and investment is driven by forward-looking investors who respond to arbitrage possibilities. Physical capital, by contrast, is perfectly immobile once installed. An intertemporal budget constraint is imposed on trade for each country, so that trade deficits must eventually be repaid by accumulating trade surpluses. Saving and investment in each region of G-Cubed are determined by forward-looking households that optimize intertemporal utility functions and forward-looking investors that maximize the stock market value of their equity. Another distinctive feature of G-Cubed is that parameters describing economic behavior are determined by econometric estimation rather than calibration. Finally, G-Cubed incorporates important features of macroeconomic models such as liquidity-constrained agents, a transaction-based money demand function and slow nominal wage adjustment. These features are also included in the dynamic stochastic general equilibrium (DSGE) models discussed in Chapter 22.

The G-Cubed model has been used extensively in analyzing the impacts of climate policies on the world economy. These impacts include changes in trade patterns and capital flows. McKibbin and Wilcoxen have shown that trading in global emissions permits the possibility of greenhouse gases, like those considered in the Kyoto Protocol, producing dramatic transfers in wealth among regions. These could lead to substantial capital flows as different regions react to changes in world climate policy. G-Cubed has also been used to simulate the effects on the world economy of a variety of other policies, including international trade agreements, monetary and fiscal policies, and, most recently, the impacts of financial and economic crises on subregions of the world economy and the world economy as a whole.

In Chapter 16, William Nordhaus presents integrated assessment models (IAMs) of the world economy employed for evaluating alternative climate policies. These models integrate global economic models with physical models of the global atmosphere. The two types of models interact through the generation of emissions of greenhouse gases, such as carbon dioxide, from economic activity. These emissions effect temperatures through the well-known greenhouse effect. The resulting changes in temperature and in patterns of precipitation effect future levels of economic activity. The chapter begins with a brief overview of the physical basis for climate change. This leads to a consideration of climate policies and their likely effects. These policies include two of the principal international agreements on climate change, the Kyoto Protocol, also discussed in Chapter 15, and the Copenhagen Accord of 2009. With this essential background Nordhaus turns to economic modeling of climate change using IAMs. The economic components of these models are increasingly based on CGE models with features that capture economic behavior over the time horizon relevant for the evaluation of climate policies. The physical components of IAMs are summary representations of elaborate global circulation models used for simulations of future changes in the global atmosphere.

To illustrate the construction and application of IAMs, Nordhaus provides a detailed discussion of the DICE/RICE family of models that he originated. The DICE model (Dynamic Integrated model of Climate and the Economy) is based on a neoclassical growth model with a single sector representing the world economy. Investments in capital reduce current consumption, but provide enhanced opportunities for future consumption. The novel feature of the DICE model is the incorporation of the natural capital of the climate system. By reducing emissions of greenhouse gases today, the world economy sacrifices current consumption in order to maintain future levels of consumption. Nordhaus has used this model and the closely related RICE (Regional Integrated model of Climate and the Environment) to evaluate alternative climate policies, including the Kyoto Protocol and the Copenhagen Accord. A general finding is that the range of climate policies that produce benefits that exceed the costs is relatively limited. Many climate policies actively under discussion have costs that exceed the benefits. Nordhaus has also designed optimal policies, i.e. policies that maximize an intertemporal social welfare function. He has shown how to implement these policies using a carbon tax or tradable permits for emissions of greenhouse gases. Finally, using the RICE model, Nordhaus has analyzed the likely outcomes of negotiations among subregions of the world economy to arrive at international agreements on climate policy.

1.4 TECHNICAL ASPECTS OF CGE MODELING: DATA, PARAMETER ESTIMATION, COMPUTATION AND VALIDATION

Behind any policy-relevant CGE result is an enormous amount of background work on data, estimation and computation. Ideally, the result is also supported by model validation. In the early days, each modeling group performed all this background work itself. Nowadays, modelers are often able to draw on shared resources. One such resource is the GTAP database described in Chapter 12. Chapters 17–20 discuss other background efforts required to support CGE modeling: econometric parameter estimation, validation and software creation.

Chapter 17 by Dale Jorgenson, Hui Jin, Daniel Slesnick and Peter Wilcoxen and Chapter 18 by Russell Hillberry and David Hummels are devoted to econometric methods for general equilibrium modeling. However, it must be recognized at the outset that calibration of the parameters that determine behavioral responses to economic policy changes is much more common than econometric estimation. This is due in part to the lack of suitable data for econometric modeling of production. However, this obstacle is beginning to disappear with the rapid development of comprehensive datasets for individual industries within the framework of a time series of input-output tables, so-called capital-labor-energy-materials-services (KLEMS) datasets. These are now available for more than 40 countries and many countries, including the US, have incorporated these datasets in their systems of national accounts. Another important source of data for general equilibrium modeling of preferences is cross-section and panel datasets for individual households. These datasets are particularly valuable in capturing the heterogeneity of consumer behavior that is a common finding in microeconometric research.

In Chapter 17, Jorgenson, Jin, Slesnick and Wilcoxen present econometric methods for modeling producer behavior that have been implemented from a KLEMS-type dataset for the US for the period 1960–2006. These methods facilitate the separation of substitution among inputs from technical change as sources of variations in patterns of output, input and productivity for the industrial sectors of IGEM – the model presented in Chapter 8. Technical change is separated into components associated with the rate and biases of technical change. The rate of technical change is defined as the rate of decline of the price of output, holding the prices of the inputs constant. Biases are changes in the shares of inputs in the value of output, again holding the prices of inputs constant. Jorgenson, Jin, Slesnick and Wilcoxen also present econometric methods for modeling consumer behavior. These methods incorporate demographic characteristics of households as determinants of their expenditure patterns. Aggregation over the population transforms the demographic characteristics into the relative shares of different consumer groups in determining aggregate expenditure. Additional determinants include prices and statistics that describe the distribution of total expenditure.

An important ancillary benefit of econometric methods for general equilibrium modeling is that confidence intervals for the outcomes of policy simulations can be derived from econometric estimates of parameters that describe economic behavior. These confidence intervals make it possible to formulate and test the implications of general equilibrium models as statistical hypotheses. Jorgenson, Jin, Slesnick and Wilcoxen illustrate this approach in Chapter 17 by deriving confidence intervals for the outcomes of IGEM simulations. These confidence intervals must be carefully distinguished, for the intervals describe ranges for model outcomes corresponding to different parameter values and different values of the exogenous variables. These ranges reflect the sensitivity of the model outcomes to the underlying determinants but do not involve probability statements. Confidence intervals are associated with probability statements that can be used as the basis for statistical tests and, at least potentially, can provide a powerful new methodology for testing the specifications of general equilibrium models.

In Chapter 18, Hillberry and Hummels point out that CGE models of international trade typically rely on econometrically estimated trade elasticities as model inputs. Major trade-focused CGE models draw elasticities from many different econometric studies. These econometric studies use very different data samples, response horizons and estimating techniques, and arrive at elasticities as much as an order of magnitude different from each other. There is no consensus on which elasticities to use. Hillberry and Hummels review the literature on estimating trade elasticities, focusing on several key considerations: what are the identifying assumptions used to separate supply and demand parameters? What is the nature of the shock to prices employed in the econometrics? And what is the time horizon over which trade responds to this shock? The discussion in Chapter 18 ranges from older reduced form approaches that use time-series variation in prices to more recent work that identifies demand elasticities from trade costs or uses instruments in cross-section or panel data. Hillberry and Hummels consider prominent applications that separately identify supply and demand parameters in the absence of instruments.

They also discuss recent theoretical developments from the literature on heterogeneous firms that complicate the interpretation of all the parameter estimates. They focus on Melitz (2003) who considers monopolistically competitive firms that have different levels of productivity and face fixed costs of domestic production and of exporting. The most productive firms choose to sell domestically and to export; less productive firms sell only to domestic markets and the least productive firms exit. An upward-sloping export supply curve arises through expansion of export sales via the entry of marginally less productive firms charging higher prices. Hillberry and Hummels briefly survey a literature on structural estimation and link this to recent attempts to incorporate such theories in CGE applications (see also Chapter 23). By elucidating the differences and similarities in various approaches to estimation they provide a useful guide to CGE practitioners in choosing elasticity estimates. The authors favor elasticities taken from econometric exercises that employ identifying assumptions and exploit shocks that are similar in nature to those imposed in the model experiment.

In Chapter 19, Peter Dixon and Maureen Rimmer discuss validation. This topic is a key issue for policy advisors who want to know how much reliance they can place on a particular CGE analysis. Many CGE modelers respond to the reliance question with numerical sensitivity computations. Dixon and Rimmer argue that what is really required is evidence that the analysis under consideration is based on accurate up-to-date data for the relevant part of the economy and adequately captures the crucial behavioral and institutional characteristics. They advocate the use of BOTE models. A well-designed BOTE model has two properties: (i) it reveals the roles of the major behavioral, institutional and data assumptions in causing a model to generate a given result, and (ii) it is small enough to be managed with pencil and paper (on the back of an envelope) and to be presented in a limited timeframe to policy advisors.

In addition to BOTE modeling, the chapter describes three other forms of validation. The first of these is computational validation. Dixon and Rimmer describe test simulations and demonstrate that the value of these simulations goes beyond computational checking. Test simulations are a practical way to become familiar with a model and often reveal modeling weaknesses. The second is consistency with history. Dixon and Rimmer focus on historical simulation. This is a technique whereby a CGE model is reconciled with periods of history by allowing it to determine endogenously movements in technologies, preferences and other shift variables. These implied movements can then be assessed against other information leading to a process of model improvement. The final form of validation discussed in the chapter is the testing of baseline forecasts against reality. The chapter demonstrates that CGE models can produce forecasts at a highly disaggregated level that comfortably beat non-model-based trend forecasts. It also demonstrates that there is considerable potential for more accurate CGE forecasts through conscientious data work and improved methods for projecting trends from historical simulations into forecasting simulations.

Chapter 20 describes and compares the two dominant general-purposes software platforms used for solving CGE models: GEMPACK and GAMS. These two rival platforms are represented in the authorship: Ken Pearson and Mark Horridge for the GEMPACK team and Alex Meeraus and Tom Rutherford for the GAMS team. It is to the credit of the two teams that they were able to cooperate to produce a fascinating chapter. Both GEMPACK and GAMS have made an enormous contribution to CGE modeling since the mid-1980s by largely relieving modelers of the burden of acquiring advanced computing skills and knowledge of solution algorithms. The platforms have also facilitated communication between modelers, allowing effortless transfers of models between sites.

CGE modelers are typically highly committed to their chosen platform, be it GEMPACK or GAMS. Vigorous debate with claims and counterclaims about the relative merits of the two platforms and their change or levels format are a perennial feature of CGE gatherings. This chapter will be compulsory reading for committed modelers. The chapter will also make interesting reading for non-CGE modelers who are contemplating a start in the field. To bring the chapter to life, the authors incorporated a comparison of computational speed between GEMPACK and GAMS. Both platforms were presented with a standard model. In the first comparison, the standard model was given 100 sectors and the respective platforms solved it to a required degree of accuracy. In seven more comparisons the sectoral dimension was gradually increased to 500. GEMPACK outperformed GAMS at all dimensions from 100 to 500 sectors with the time difference at high dimensions being dramatic. Of course, speed is not the only criterion for comparing software platforms. The chapter also discusses the ranges of model features (e.g. complementarity conditions) that can be handled by the two platforms and the available supplementary programs for preparing data and analyzing solutions.

1.5 CURRENT CUTTING-EDGE METHODOLOGICAL AREAS

There is a two-way flow of ideas and techniques between CGE modeling and other branches of economics. The final group of chapters in this Handbook surveys some of the areas from which CGE modeling is currently drawing inspiration, including trade theory with imperfect competition, DSGE modeling and the theory of labor markets. It also includes a pair of chapters showing how the CGE perspective, integrated with micro datasets, can contribute to the understanding of issues in income distribution, aging and social insurance.

In Chapter 21, Francois Bourguignon and Maurizio Bussolo present the World Bank's Global Income Distribution Dynamic (GIDD) model, combining a micro-simulation model with the LINKAGE CGE model of the world economy (Chapters 13 and 14). Microsimulation models are based on survey data for individual households. These models have been used for studying reforms of tax-benefit systems, the delivery of public goods like education or healthcare, or changes in the regulation of the labor markets through alterations in the retirement age and the minimum wage or other policy instruments. The GIDD model includes survey data for 132 countries, covering more than 90% of the world population. Macroeconomic models are typically used to analyze the potential impact of reforms in tax, trade, finance or monetary policies on the structure of the economy, the level of employment and wages, and their distribution by skill levels and the returns to capital. By linking this aggregate information to the distributional detail of a microsimulation model, the distribution of gains and losses from policy changes can be analyzed.

Versions of the GIDD framework have been used to study the distributional effects of trade policy reforms, financial crises, reforms of the financial sector, subsidies on agricultural production prices, workfare programs, cash transfer programs and scaling up of other poverty alleviation policies, as well as others. Bourguignon and Bussolo emphasize that different variants of the model focus on different issues, such as behavioral responses, imperfections in markets and longer-term effects. The choice of the model depends on the policy issue under consideration. For example, in analyzing the short-term impact of reductions in tariffs, a static CGE model linked to simple micro accounting may be the best methodological choice. The interaction of trade liberalization with labor markets, sectoral adjustment of the economy, and the growth and distribution effects of trade reform may require a dynamic model. Bourguignon and Bussolo illustrate the application of the GIDD model to the projection of the world distribution of income in 2030. They find that even with significant changes of within-country inequality levels, the potential reduction of global inequality can be accounted for mainly by the projected convergence in growth rates of average incomes across countries. The aggregate impact of the changes of the within-countries component of inequality appears to be minor. The main cause of changes in within-country inequality is adjustment of factor rewards.

In Chapter 22, Sebastian Schmidt and Volker Wieland present a detailed introduction to the construction and estimation of New Keynesian models and their applications in macroeconomic policy analysis. Two key ingredients of the New Keynesian model that distinguish it from traditional Keynesian models are that the decision rules of economic agents are based on optimization subject to constraints and agents' views of the future behavior of variables are formed under rational expectations. Agents' decision rules inevitably vary with changes in policy and this dependence becomes explicit in the system of reduced-form equations. The Lucas critique, named after Robert E. Lucas and formulated in Lucas (1976), criticizes policy evaluation exercises based on estimated reduced-form relationships that fail to recognize this dependence. Lucas argues that this type of econometric model is unsuitable for policy analysis because the estimated parameters are not policy-invariant. In Chapter 22, building blocks of current-generation DSGE models are discussed in detail. These models address the Lucas critique by deriving behavioral equations systematically from the optimizing and forward-looking decision making of households and firms subject to well-defined constraints. Finally, Schmidt and Wieland review a new approach to model comparison that helps to identify robust policies under model uncertainty. This comparative approach could also be of benefit to practical model-based policy making in other arenas including international trade, economic development and climate change.

In their chapter, Schmidt and Wieland present state-of-the-art methods for solving and estimating DSGE models, using standard software packages such as DYNARE. The chapter also provides a framework for model comparison along with a database that includes a wide variety of macroeconomic models. This offers a convenient approach for comparing new models to available benchmarks and for investigating whether particular policy recommendations are robust to model uncertainty. To illustrate this idea, the authors evaluate the performance of simple policy rules across a range of recently estimated models, including some with financial market imperfections. Medium- to large-scale DSGE models are routinely used by economists at central banks and international institutions to evaluate monetary and fiscal stabilization policies. In the course of the recent financial crisis commentators have criticized the DSGE approach for its failure to predict the financial turmoil and the implications for the real economy. Indeed, the type of models that were used prior to the crisis in general did not include a realistic treatment of the banking sector and the involved macroeconomic risks. In response to this criticism, proponents of the DSGE approach have started to enhance the existing benchmark models to allow for a more detailed treatment of financial market frictions and the role of the banking sector in causing and propagating shocks to the macroeconomy.

In Chapter 23, Ed Balistreri and Tom Rutherford set out the Krugman (1980) and Melitz (2003) models of international trade. These provide alternatives to the Armington (1969) specification which has been the standard in CGE models since its introduction via Australia's ORANI model in the 1970s (Dixon *et al.*, 1977, 1982). In earlier economy-wide trade-oriented models (e.g. Evans, 1972) imported and domestic varieties of a given commodity were treated as perfect substitutes. This led to "flip-flop"—import shares in domestic markets flipping between zero and one in response to seemingly minor changes in relative prices. By treating imported and domestic varieties as imperfect substitutes, the Armington specification dealt with this problem in a practical and empirically justified fashion.[2] Starting in the late 1980s, many modelers questioned the Armington specification. They were disappointed with Armington-based simulations that often show a welfare loss for a country that undertakes a unilateral reduction in tariffs, with the terms-of-trade loss outweighing the efficiency gain. Both the Krugman and Melitz specifications assume large-group monopolistic competition. This gives the potential for generating more favorable welfare results from a tariff cut than can be generated with the Armington specification. Under the Krugman specification, there are two additional sources of welfare change from a tariff cut: (i) cost reductions in the domestic economy through economies of scale and (ii) increased variety through extra imports (which may or may not be offset by a reduction in domestic varieties). Melitz adds another source of welfare change. In the Melitz model, tariff cuts can increase productivity by weeding out inefficient domestic firms.

Balistreri and Rutherford build a small-scale multicountry CGE model that incorporates the Melitz specification, with the Armington specification as a special case. Using this model, they compare results under the two specifications for the effects of tariff cuts and for climate policies. They find the use of the Melitz specification produces significantly different results from those obtained under the Armington specification. So far Melitz simulations have been conducted in small models with stylized parameter values. A major challenge remains to establish the empirical significance of the mechanisms in the Melitz approach.

Chapter 24 by Joe Francois, Miriam Manchin and Will Martin also explores imperfect competition in trade-oriented CGE modeling. In contrast to the large-group, monopolistic competition specifications of Chapter 23, Francois, Manchin and Martin focus on oligopoly specifications. For them, large-group, monopolistic competition is

2 Early econometrics estimates of Armington elasticities were obtained at a detailed level by Alaouze (1976) and used in the ORANI model.

a special case. However, unlike Chapter 23, most of the discussion in Chapter 24 concentrates on the case of symmetrical firms within an industry (the Krugman case in which each firm produces its own variety but no firm is inefficient relative to other firms). Each of the symmetric firms within an industry prices according to the Lerner rule: the markup over marginal cost as a fraction of price is the reciprocal of the magnitude of the firm's perceived elasticity of demand for its product. Calibration for CGE modeling of perceived elasticities of demand and their relationship to the number of firms in an industry is discussed in detail. The calibration of marginal costs is also discussed. Another challenge that must be met in CGE modeling with oligopoly is the determination of pure profits. The chapter discusses this issue and suggests relationships between pure profits and the number of firms in an industry.

Francois, Manchin and Martin not only present calibration hints but they also provide computational hints and a discussion of some results from imperfect competition models. A valuable computational hint for modelers wanting to try imperfect competition/ increasing returns to scale specifications is to start with a vanilla perfect competition/ constant returns to scale model and then to introduce markups as phantom indirect taxes. This is also a hint for interpreting results. Understanding the equivalence[3] between indirect taxes and markups reflecting imperfect competition is the key to understanding why procompetitive, markup-reducing policies have strong positive effects on real wages.

In Chapter 25, Elizabeth Christen, Joe Francois and Bernard Hoekman discuss the treatment of services trade in a CGE framework. Services are a rapidly increasing component of international trade, now representing more than 20% of world trade on conventional measures and a considerably higher percentage if services sales by foreign affiliates are treated as trade. While trade in goods can be visualized in terms of trucks, ships and planes moving physical items across international borders, trade in services conjures up a more complex and varied picture. As set out in the General Agreement on Trade in Services (GATS), services trade can be classified into four modes: mode 1, in which neither suppliers (exporters) nor buyers (importers) are required to change their physical locations (e.g. call-center services supplied from India to US households); mode 2, in which the buyer travels to the country of the supplier to receive the service (e.g. international tourism); mode 3, in which the supplier provides the service through an affiliate or branch office in the buyer's country (e.g. foreign airline desk services at US airports); and mode 4, in which individuals temporarily move to the buying country to provide services (e.g. consulting services provided in the US by an employee of a firm based in Australia).

In the chapter, Christen, Francois and Hoekman describe barriers to services trade, pointing out that these are often less transparent than those that restrict goods trade. They

[3] Equivalence here refers to resource allocation effects not distributional effects.

then review CGE studies of the effects of lowering barriers to services trade. Such studies show that the welfare gains from liberalizing services trade are potentially greater than those which would flow from removing the remaining barriers to goods trade. They illustrate this point with a study of Italy, which complements the study of Russia in Chapter 6. For convincing CGE analysis of issues in services trade, the chapter emphasizes the importance of: (i) mobilizing detailed and accurate data, (ii) understanding the special circumstances that apply to trade in each type of service, (iii) taking account of the market structure of service industries in importing countries and (iv) distinguishing the effects of trade liberalization on dead-weight losses from those on rents. As an interesting example of the complexities of services trade, Christen, Francois and Hoekman mention the role of health insurance: policies that require home-country treatment inhibit trade in health services.

Chapter 26 by Stefan Boeters and Luc Savard is about the labor market in CGE models. In most models, the treatment of the labor market is rudimentary: either exogenous aggregate employment with an endogenous wage or an exogenous wage with endogenous aggregate employment. As argued by Boeters and Savard, these rudimentary approaches may be adequate for analyses of many policies, but not for those that impinge directly on labor supply such as changes in marginal income tax rates and immigration.

The chapter presents a portfolio of approaches for specifying the labor market in CGE models. It organizes the literature on the topic by starting with a discussion of the various economic issues that might motivate a desire to add labor market detail to a CGE model. Methodologies for doing this are then set out in three sections: (i) labor supply, (ii) labor demand, and (iii) coordination of labor demand and supply. Among other things, these sections provide detailed discussions on: modeling labor supply via a single representative household, multiple representative households and microsimulation; modeling labor demand via cost-minimizing problems with nested production functions distinguishing labor types by characteristics such as occupation, education, gender, age and part-time/full-time; and modeling labor market coordination and involuntary unemployment via search theory, efficiency wage and collective bargaining. The chapter will be a valuable resource for CGE modelers wishing to improve their modeling of the labor market within their own models.

In Chapter 27, Hans Fehr, Sabine Jokisch, Manuel Kallweit, Fabian Kindermann and Laurence Kotlikoff examine the micro- and macroeconomic effects of polices that affect different generations differently. For this purpose they use both closed- and open-economy CGE models that incorporate an OLG model similar to that presented in Chapter 11. The models illustrate the broad array of demographic, economic and policy issues that can be simultaneously incorporated within models of economic growth. The policy issues include country-specific tax, spending, social security, healthcare and deficit policies. The demographic issues comprise age- and country-specific mortality, age-specific fertility, age-specific morbidity, lifespan uncertainty, and age- and skill-specific emigration and immigration. Finally, economic issues embrace earnings inequality driven by skill differences and idiosyncratic labor earnings uncertainty, capital adjustment costs, international trade, international capital flows, trade specialization, and trade policy.

Fehr, Jokisch, Kallweit, Kindermann and Kotlikoff begin their chapter with an exposition of the dynamic OLG model of Auerbach and Kotlikoff (1987). They present two detailed applications. The first is with a single-country, closed-economy model characterized by an intertemporal equilibrium like that of Diamond and Zodrow (Chapter 11). This single-country model is calibrated for Germany and used to analyze the consequences of alternative pension reform proposals. The simulations demonstrate that increases in the retirement age under public pension programs are an important policy instrument for distribution of resources to future cohorts. The authors then turn to an open-economy model, featuring five regions—the US, Europe, Japan and other Asian countries, China, and India, producing six goods, some of which are traded. The transition path of this global model shows that government pay-as-you-go healthcare and pension systems in the developed countries will come under increasing stress requiring extraordinary increases in tax rates unless policies are significantly changed and done so quickly. The most obvious reform to overcome the effects of population aging is a partial or complete switch to a funded pension system. This induces the strongest redistribution toward future cohorts, and induces a significant increase in retirement ages and substantial reductions in future payroll and consumption taxes. A second major message from the model is that wage inequality in developed countries will substantially increase over the course of the century. As successive cohorts of Chinese and Indian workers reach the job market with higher levels of productivity in unskilled occupations, the worldwide effective endowment of unskilled workers rises relative to that of high skilled workers. This will put downward pressure on unskilled worker wages in the developed world thanks to factor price equalization.

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