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SUSTAINABILITY IMPACT ASSESSMENT: THE USE OF COMPUTABLE GENERAL EQUILIBRIUM MODELS

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ABSTRACT. This paper advocates computable general equilibrium (CGE) models as an analytical framework that is suitable for assessing the impacts of policy interference on the three dimensions of *Sustainable Development*, i.e. environmental quality, economic performance and equity. Methodological extensions of standard CGE models are illustrated that may strengthen the role of CGE models in measuring policies against key criteria of *Sustainable Development*. These developments include (i) decomposition procedures of general equilibrium effects that deliver a better understanding of key determinants for policy effects, (ii) the embedding of large-scale general equilibrium models in an optimal policy framework that considerably widens the scope of policy analysis, and (iii) systematic sensitivity analysis to test the robustness of model results with respect to uncertainties in the model's parameterization space.

JEL Classification: C68; D58; D61; F17; Q50.
Keywords: Sustainable Development; Sustainability Impact Assessment; Trade Policy; Computable and Other Applied General Equilibrium Models.

RÉSUMÉ. Cet article démontre que les modèles d'équilibre général calculable (MEGC) fournissent un cadre d'analyse fiable pour étudier les effets croisés des politiques relatives aux trois piliers sur lesquels repose le développement durable : la qualité de l'environnement, la croissance économique et l'équité. Il propose des extensions méthodologiques des MEGC standards susceptibles de renforcer leur rôle dans l'évaluation des politiques au regard des critères du développement durable. Ces apports consistent en (i) une possibilité de décomposer les effets de l'équilibre général ce qui améliore la compréhension des déterminants influant sur l'impact des politiques, (ii) un ancrage des modèles d'équilibre général à grande échelle dans un cadre politique optimal ce qui élargit sensiblement l'horizon de l'analyse et (iii) une analyse systématique de sensibilité afin de tester la robustesse des résultats compte tenu des incertitudes qui pèsent sur les paramètres des modèles.

Classification *JEL* : C68 ; D58 ; D61 ; F17 ; Q50.
Mots-clefs : Développement durable ; évaluation d'impact en termes de durabilité ; politique commerciale ; modèles d'équilibre général calculable et autres modèles appliqués.

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In 1987, the report of the World Commission on Environment and Development (WCED or Brundtland Commission) defined *Sustainable Development* as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs". In June 1992, the Rio Earth Summit concluded that "the right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations." *Sustainable Development* has meanwhile become one of the most prominent catchwords on the world political agenda. Nearly all governments and multinational firms have committed themselves to the overall concept of *Sustainable Development*. As prime example, the European Union meanwhile requires a *Sustainability Impact Assessment* of all larger policy proposals that must include estimates of policy-induced economic, environmental and societal impacts inside and outside the European Union (EC, 2001).

Yet, *Sustainable Development*, which is not just about the environment, but about the economy and our society, has proven hard to define. One reason for this is that *Sustainable Development* explicitly incorporates a (normative) equity dimension, which is *"so hopelessly subjective that it cannot be analyzed scientifically"* (Young, 1994). Another reason is that the scope of the concept seems prohibitively comprehensive to make it operational in concrete practice.

Nonetheless, societal policy is challenged to come up with pragmatic approaches to *Sustainable Development* and – to this end – requires robust advice from the scientific community. Inherently, the three dimensions of *Sustainable Development*, i.e. environmental quality, economic performance (gross efficiency) and equity concerns are intertwined and subject to tradeoffs. Accomplishing one objective frequently means backpedaling on another. Since economics is the study of tradeoff, this means that there is plenty for economists to contribute in order to make the concept of *Sustainable Development* operational. One important contribution over the last years has been the assessment of external costs as a prerequisite towards "getting the prices right". Given full information on external costs, two aspects of *Sustainable Development*, namely economic performance (gross efficiency) and the environmental quality, can be merged to a comprehensive net efficiency dimension. Furthermore, while economics has little to say on equity *per se*, the sound economic quantification of distributional effects for different agents and tradeoffs between equity and efficiency objectives is a prerequisite for any rational policy debate.

The quantification of tradeoffs requires the use of numerical model techniques. There is simply no other way to think systematically and rigorously about the interaction of the many forces that interact in the economy affecting potential indicators of *Sustainable Development*. Compared to stylized analytical models, the numerical approach facilitates the analysis of complex non-linear system interactions and the impact assessment of structural policy changes. In the end, the decisions how to resolve potential tradeoffs must be taken on the basis of societal values and judgements. However, model-based analysis puts decision making on an informed basis rather than on fuzzy or contradictory hunches.

Given the broad agenda of *Sustainable Development*, the objective of this paper is to advocate computable general equilibrium (CGE) models as an analytical framework that is suitable for assessing the impacts of policy interference on environmental quality, economic performance and equity. Methodological extensions of standard CGE models are illustrated that may strengthen the role of CGE models in *Sustainability Impact Assessment*. These developments include (i) decomposition procedures of general equilibrium effects that deliver a better understanding of key determinants for policy effects, (ii) the embedding of large-scale general equilibrium models in an optimal policy framework that considerably widens the scope of policy analysis, and (iii) systematic sensitivity analysis to test the robustness of model results with respect to uncertainties in the model's parameterization space.

It should be noted that the focus on CGE models and specific methodological extensions is very selective. Obviously, there is a wide range of alternative quantitative approaches for assessing the causal chains between a proposed policy change and its potential economic, environmental and social impacts. No specific modeling framework could fit all requirements for comprehensive *Sustainability Impact Assessment* – there is rather the need for a package of models (or methods) depending on the policy measure or issue to be assessed and the availability of data.

The structure of the paper is as follows. I start with a brief appraisal of the CGE approach and sketch the generic structure of a multi-sector, multi-region CGE model for applied policy analysis. Next, I describe recent methodological developments and illustrate their policy usefulness in the context of concrete policy simulations. Finally, I conclude.

THE GENERIC CGE APPROACH TO (SUSTAINABLE) IMPACT ANALYSIS

The general equilibrium approach is an established analytical framework for evaluating the economic implications of policy intervention on resource allocation and incomes of agents. Its main virtue is the micro-consistent representation of the direct effects as well as indirect feed-backs and spillovers induced by exogenous policy changes. The simultaneous explanation of the origin and spending of the agents' income makes it possible to address both economy-wide efficiency as well as equity impacts of policy interference.

Theoretical general equilibrium analysis provides important qualitative insights into the driving forces of adjustment reactions by economic agents to exogenous policy constraints. However, its contribution to actual policy analysis remains limited. The reason is that theoretical models are highly stylized to keep analytical tractability. As soon as certain real-world complexities are taken into account, e.g. a more detailed production structure, analytical solutions are no longer available and numerical solutions methods are required. In this context, computable general equilibrium (CGE) models have become a standard tool for applied analysis of measures in various policy domains including fiscal policy, trade policy, and environmental policy[2]. These models incorporate lots of details and come up with concrete numbers on policy-induced economic and environmental effects. Moreover, CGE models provide an open framework for the incorporation of new economic research strings such as the new growth and trade theory or important relationships to other disciplines adopting an integrated assessment approach (see Conrad, 1999, 2001 for surveys on recent developments). This flexibility makes CGE models a useful tool for *Sustainability Impact Assessment*.

Ultimately, *Sustainability Impact Assessment* requires a global and intertemporal perspective. Not only is there a need of assessing policy impacts across regions but also across generations. An intertemporal, multi-region perspective is state-of-the-art in applied CGE analysis; there are also various examples of models with overlapping generations (OLG). However, an OLG framework with multiple regions and sectors still poses considerable computational challenge and requires severe tradeoffs with the level of details that can be captured in the model.

This paper focuses on standard multi-region, multi-sector CGE models of global trade and energy use. The multi-region multi-sector framework seems indispensable for *Sustainability Impact Assessment* of major policy initiatives in a world that is increasingly integrated through trade. Such CGE trade models are meanwhile employed by many international institutions, research centers, universities and consultancies. One prominent example is the GEM-E3 model system (see e.g. Capros *et al.*, 1999; Böhringer and Löschel, 2004) that has been developed and applied since the early 1990ies under the auspices of the European Commission.

FIGURE 1 provides a diagrammatic structure of a standard (one-period) CGE model as often used for comparative-static analysis of trade and environmental policies. Primary factors of region *r* include labor $\bar{L}_r$, capital $\bar{K}_r$ and resources $\bar{Q}_{ff,r}$ of fossil fuels *ff* (crude oil, coal, and gas). A specific resource is used in the production of crude oil, coal and gas, resulting in upward sloping supply schedules.

Production Y_{ir} of commodities *i* in region *r*, other than primary fossil fuels, is captured by aggregate production functions which characterize technology through substitution possibilities between various inputs[3]. Nested constant elasticity of substitution (CES) cost functions with several levels are employed to specify the KLEM substitution possibilities in domestic production between capital (*K*), labor (*L*), energy (*E*) and non-energy intermediate inputs, i.e. material (*M*). Final demand C_r in each region is determined by a representative agent RA_r, who maximizes utility subject to a budget constraint. Total income of the representative agent consists of factor income and transfers. Final demand of the representative agent is

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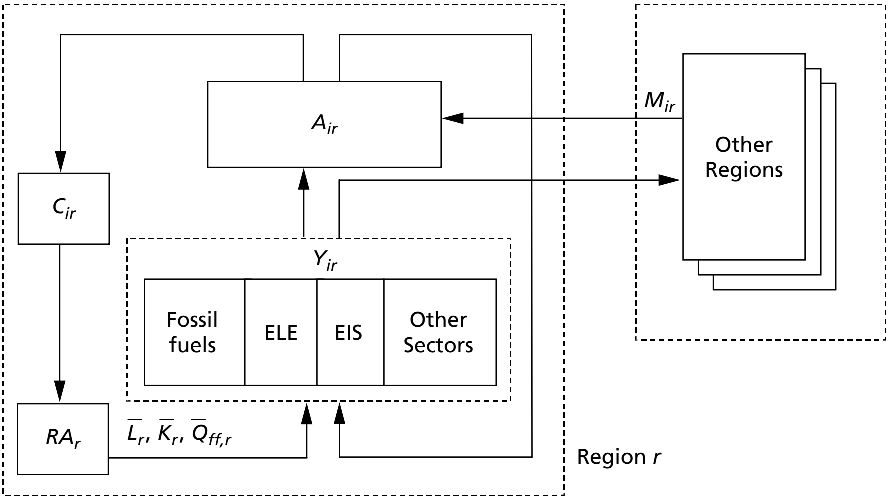
[2] See e.g. Shoven and Whalley (1984, 1992) ; Piggot and Whalley (1985) ; Borges (1986) ; Pereira and Shoven (1988) ; Bergman (1990) ; Kehoe and Kehoe (1994) ; Klepper *et al.* (1995), and Bhattacharyya (1996).

[3] In FIGURE 1, the break-down of the production block illustrates a typical sectoral disaggregation with respect to energy or climate policy analysis featuring fossil fuels (coal, oil, gas), electricity generation (*ELE*), an energy-intensive aggregate *EIS*, and *Other Sectors*.

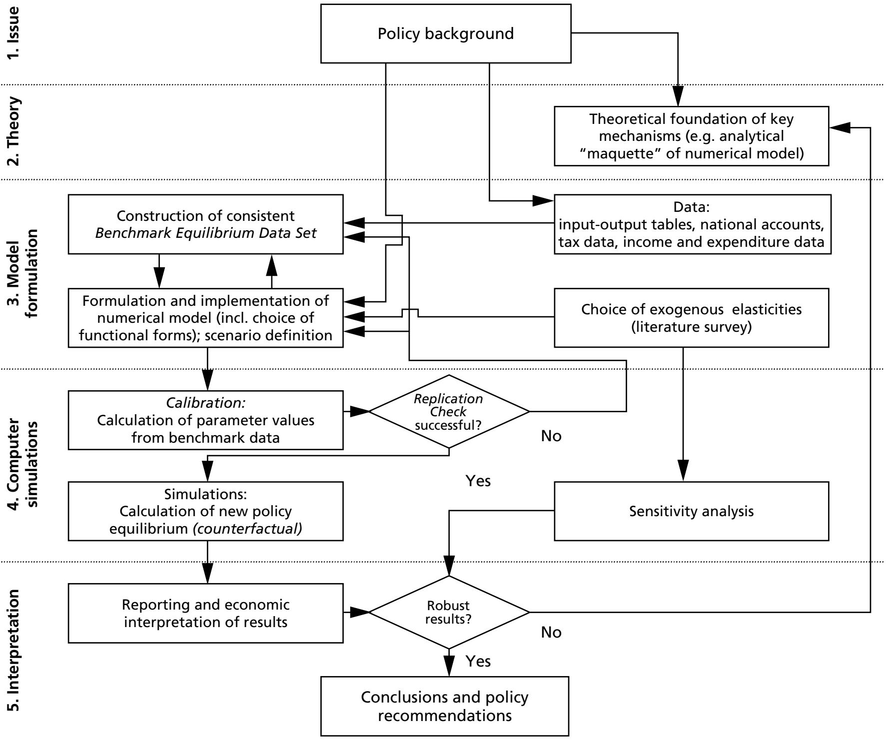
Figure 1 - Diagrammatic structure of a generic multi-sector, multi-region computable general equilibrium model



given as a CES composite which combines consumption of an energy aggregate with a non-energy consumption bundle. The substitution patterns within the non-energy consumption bundle as well as the energy aggregate are described by nested CES functions. All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{ir} of the domestically produced variety and a CES import aggregate M_{ir} of the same variety from the other regions (the so-called Armington good). Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions. A governmental sector collects taxes (e.g. production taxes or subsidies, intermediate taxes, consumption taxes, tariffs, or environmental taxes such as carbon taxes) which are used to finance the public good provision and public transfers.

The five main steps involved in constructing and using CGE models for applied policy analysis are summarized in FIGURE 2. Initially, the policy issue must be carefully studied to decide on the appropriate model design as well as the required data. The second step involves the use of economic theory (at best, the draft of a simple analytical maquette model) in order to lay out key economic mechanisms that drive the results in the more complex numerical model. Data work, model formulation and implementation then delivers the framework for numerical policy analysis. This step also involves the set-up of alternative policy instruments and strategies that induce changes vis-à-vis the reference situation (scenario definition). In determining results of policy simulation, the choice and parameterization of functional forms are crucial. The procedure most commonly used to select parameter values is known as calibration (see Mansur and Whalley, 1984). Calibration of the free parameters of functional forms requires a

Figure 2 - Steps in computable general equilibrium analysis (Böhringer, 1996)



consistent one year's data (or a single observation represented as an average over a number of years), together with exogenous elasticities that are usually taken from literature surveys[4].

The calibration is a deterministic procedure and does not allow for statistical test of the model specification. The one consistency check that must necessarily hold before one can proceed with policy analysis is the replication of the initial benchmark: the calibrated model must be capable of generating the base-year (benchmark) equilibrium as a model solution without computational work. Within the policy simulations single parameters or exogenous variables are changed and a new (counterfactual) equilibrium is computed. Comparison of the counterfactual and the benchmark equilibrium then provides information on the policy-induced changes of economic variables such as employment, production, consumption, relative prices, etc. Finally, the model results must be interpreted based on sound economic theory. Due to the reliance on exogenous elasticity values and a single base-year observation, compre-

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[4] Benchmark data is typically delivered in value terms. In order to obtain separate price and quantity observations, the common convenient procedure is to choose units for goods and factors so that they have a price of unity in the benchmark equilibrium.

hensive sensitivity analysis on key elasticities (and possibly alternative assumptions on economic incentives) should be performed before concrete policy recommendations are derived.

All in all, the typical CGE approach to policy analysis can be understood as theory with numbers, where a theoretical model is calibrated to observed statistics and then used for policy simulations.

TABLE 1 provides a selection of typical indicators in standard CGE models of global trade and energy use that could be used for quantitative tradeoff analysis along the three dimensions of *Sustainable Development*.

Table 1 - Sustainability themes and model indicators

Sustainability themes	Examples of possible core indicators in CGE models
Economic aspects	
Economic development and growth	GDP (GDP per capita)
Produced assets	Net savings
...	
Social aspects	
Employment	Unemployment rate
Income	Household final consumption expenditure
....	
Environmental aspects	
Air quality	Intensity / Total of SO_x and NO_x emissions
Climate change	Intensity / Total of CO_2 emissions
....	

METHODOLOCIGAL EXTENSIONS

Compared to analytical general equilibrium models, the numerical CGE approach accommodates the analysis of complex economic interactions and the impact assessment of structural policy changes. However, this advantage can easily turn into a disadvantage when simulation results come as black box and are not explained on the basis of rigorous economic theory. Often, the interpretation of general equilibrium effects as the total of several partial equilibrium effects is difficult, particularly if the latter can work in opposite directions. Therefore, one challenge of general equilibrium modeling is to provide decomposition methods that facilitate the isolated investigation of various partial effects contributing to the total policy impact. Below, I present two alternative decomposition techniques that can be very helpful in diagnosing the channels through which international trade transmits policy impacts between countries.

Another important extension to the standard CGE framework is the specification of optimal policy problems. This renders a *M*athematical *P*rogram with *E*quilibrium Constraints (MPEC), a new class of mathematical programs introduced by Luo, Pang and Ralph (1996). The MPEC problem class permits a formal characterization of instrument design within which the objective function depends on the instrument (e.g. tax rates), i.e. policy variables that are exogenously specified in a conventional application. With respect to *Sustainability Impact Assessment*, the MPEC framework allows to address key policy questions such as "what is the optimal tax policy to maximize economic performance given minimum constraints on the level of environmental quality or distributional concerns".

Due to lack of data, CGE models are typically not econometrically estimated, but calibrated to a single benchmark equilibrium. Apart from the benchmark statistics and assumptions about the incentives of economic agents, the effects of policy interference then depend crucially on the choice of values adopted for elasticities. Extensive sensitivity analysis must be performed to test the robustness of "central case" model results before any firm policy conclusions can be drawn. A deliberate sensitivity analysis helps to identify robust insights on the complex relationships between assumptions (inputs) and results (outputs), i.e. sort out the relative importance of a priori uncertainties. In this context, I illustrate a systematic approach to sensitivity analysis.

Decomposition techniques

Policy interventions in large open economies do not only affect the allocation of domestic resources but also change international market prices. The change in international prices implies an indirect (*secondary*) effect for *all* trading countries. This secondary terms-of-trade effect may have important policy implications. For example, international environmental agreements should account for induced changes in terms of trade when searching for "fair" burden sharing schemes. Against this background, I present a decomposition that splits the total effect or policy changes on individual countries into a *domestic market effect* holding international prices constant and an *international market effect* as a result of changes in international prices. Splitting the total effect into these components conveys important economic information as to why a country will benefit or lose from adjustments in domestic and international markets.

In applied policy analysis, it is often relevant to link changes in endogenous variables (e.g. regions' welfare or emissions) to changes in the policy instruments (e.g. tariff rates). Such a decomposition of the total policy effect could, for example, be used to evaluate induced gains or losses from multilateral trade liberalization at the bilateral level and set up transfer or compensation systems. I therefore describe another decomposition technique (originated by Harrison *et al.*, 2000) to measure bilateral spillovers from policy interference.

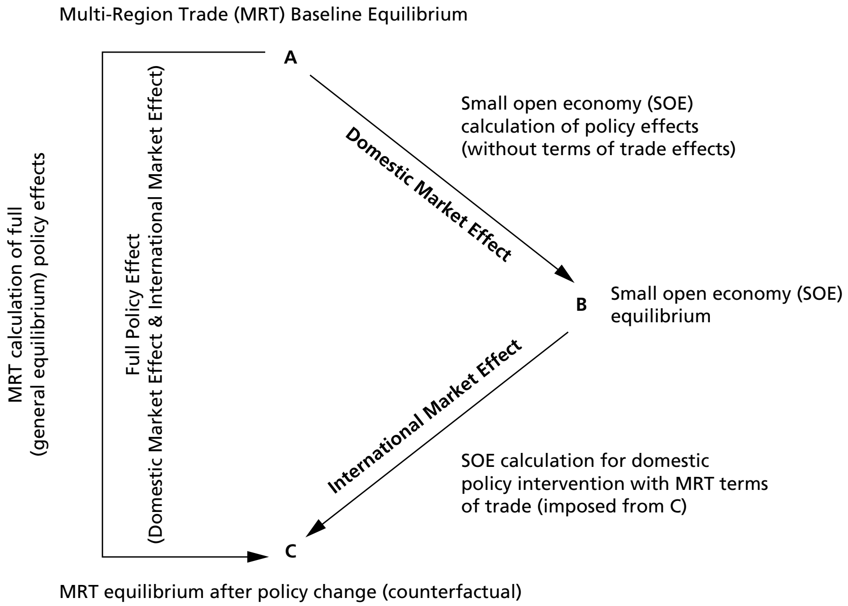
I highlight the relevance of the decomposition techniques for *Sustainability Impact Assessment* by means of an concrete application to climate change policy. The numerical simulations refer to a situation where industrialized countries apply domestic carbon taxes to meet their emission targets under the Kyoto Protocol (UNFCCC, 1997).

Decomposing international spillovers

The effects of policy intervention in large open economies can be broken down into a *domestic market effect*, assuming that international prices remain constant, and an *international market effect* as a result of changes in international prices. The key idea with respect to applied model analysis is that each region of a multi-region trade model (MRT) can be represented as a small open economy (SOE) in order to separate the domestic policy effect under fixed terms of trade. Policy induced changes in international prices from the multi-region model can then be imposed parametrically on the small open economy to measure the international market effect commodity by commodity (Böhringer and Rutherford, 2002a).

FIGURE 3 illustrates the steps involved in the decomposition procedure. Computation of the domestic market effect simply requires to keep international prices at the benchmark (reference) level and then impose the domestic policy change on the specific country. Hence, for the intermediate SOE equilibrium calculation (A→B), changes on the domestic market have no effect on international prices. The spillover effect for any economic or environmental activity of a specific country is then simply the residual between the SOE equilibrium solution at benchmark terms-of-trade and the full MRT solution for the specific country (C)[5].

Figure 3 - The MRT-SOE decomposition (Böhringer and Rutherford, 2002a)



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[5] A simple consistency check for the decomposition is as follows: Imposing the changes in international prices which are delivered by the MRT solution (A→C), one should be able to reproduce exactly the MRT solution from the SOE perspective (B→C).

Böhringer and Rutherford (2002a) illustrate the decomposition method for the case of carbon abatement policies of industrialized countries under the Kyoto Protocol. Tax-induced reallocation of resources due to emission constraints (e.g. fuel shifting or energy savings) causes substantial adjustment costs for OECD countries. Furthermore, there are considerable international spillover effects from abating industrialized countries to countries without binding emission constraint: Adjustments on international markets induce welfare losses for the Former Soviet Union as well as oil-exporting countries whereas other non-abating countries such as China, India or Brazil benefit to varying degrees from the changes in international prices associated with emission abatement in OECD countries.

Application of the decomposition method allows to gain insights into the different sources of welfare changes across regions. Obviously, the international spillover effect is identical to the total policy effect for those countries which do not undertake domestic abatement, i.e. countries whose domestic market effect is zero. As to abating countries, the decomposition provides information on the sign and relative magnitude of the primary domestic and the secondary international impacts. Regarding international spillovers, most important are the adjustments on international coal and crude oil markets. The cutback in demands for fossil fuels from abating OECD countries depresses the international prices for oil and coal. As a consequence, countries which are net importers of coal and crude oil gain, whereas net exporting countries lose. For countries which are net importer of one fossil fuel *and* net exporter of the other, the aggregate effect depends on export and import quantities as well as the relative changes in international coal and crude oil prices. As to international price changes on non-energy markets where traded goods are differentiated by region of origin, developing countries typically face adverse spillover effects. Apart from higher export prices of developed countries, developing countries suffer from a scale effect as economic activity and hence import demand by developed countries decline. On the other hand, this effect can be (partially) offset by an opposite substitution effect. Developing countries gain market shares in abating OECD countries because their exports become more competitive. The same mechanisms apply to trade between abating countries with large differences in imposed carbon taxes.

Decomposing bilateral spillovers

Harrison, Horridge, and Pearson (HHP) propose a generic linear decomposition methodology for calculating the contributions of multiple exogenous policy instruments to the resulting changes in individual endogenous variables (Harrison *et al.*, 2000). The HHP method can be explained along a simplified example in which an *endogenous* variable Z is expressed as an explicit function of a vector of *exogenous* variables $\vec{X}$ (the policy instruments):

$$Z = F(\vec{X}) = F(x_1, x_2, \ldots, x_n). \tag{1}$$

A change in the exogenous policy instruments $\vec{X}$ induces an endogenous change ΔZ in Z. For policy analysis, it is often useful to attribute changes in the endogenous variable to changes in the policy instruments. One way of decomposing the total change ΔZ in the endogenous variable with respect to the individual contributions from exogenous variables would be a sequential approximation of the impacts of *one* exogenous variable while keeping *all others* constant. Assuming that F is differentiable, the contribution of a change in the i-th exogenous variable to ΔZ (as x_i moves from the initial value x_i^0 to the new value x_i^1) can then be computed as the line integral:

$$\Delta Z\big|_{x_i} = \int_{x_i^0}^{x_i^1} \frac{\partial F}{\partial x_i} dx_i \tag{2}$$

For the numerical computation, the total change in the exogenous variable Δx_i is divided into sufficiently small steps to approximate the line integral through linearization.

When F is nonlinear, the total change from shocks in exogenous variables can not be decomposed in additive line-integrals for each exogenous variable starting from the initial value Z^0. The impact of a change in an exogenous variable must be calculated, taking into account the contributions of *previous* changes in other exogenous variables. This implies that the decomposition is potentially sensitive to the sequential ordering of changes in the exogenous policy variables. As there are *n!* ways of sequential ordering of n exogenous variables, one quickly ends up with a large number of (possibly) different decompositions for relatively small-scale policy experiments. For many policy packages (including multilateral emission abatement contracts, such as the Kyoto Protocol) no one sequential decomposition might be obviously more plausible than any other. HHP therefore suggest an order-independent "natural" way of calculating contributions. On the "natural" path, the exogenous variables move *together at the same rate* towards their final value along a straight line between their starting values $\vec{X}^0$ and the final values $\vec{X}^1$. The straight line between these points is obtained by changing the elements of $\vec{X}$ as a differentiable function H of some parameter t holding the rate of change in the exogenous variables constant along the path (where $\vec{X}^0 = H(t = t^0), \vec{X}^1 = H(t = t^1)$).

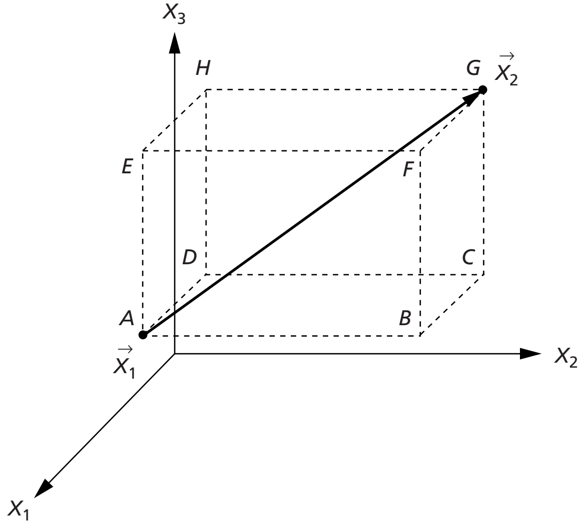
FIGURE 4 illustrates the difference between the sequential method of decomposition and the HHP approach. In contrast to moving along the *edges* of the policy cube, the HPP method follows a straight line between the pre- and post-simulation values.

For n exogenous variables, the total change in the endogenous variable is equal to:

$$\Delta Z = \sum_{i=1}^{n} \int_{t=t^0}^{t=t^1} \frac{\partial F}{\partial x_i} \frac{dx_i}{dt} dt \tag{3}$$

This concept is easily generalized to the case where the relationship between exogenous and endogenous variables is implicit, which is typically the case for computable general equilibrium models used for the economic analysis. As HHP point out, it is possible to calculate numerical values for the gradients $\frac{\partial F}{\partial x_i}\frac{dx_i}{dt}$ at all points of the "natural" path by solving a

Figure 4 - Sequential ordering *versus* "natural" path (Böhringer and Rutherford, 2004)



system of linear equations. The individual contributions of changes in policy instruments x_i can then be approximated through linearization of the respective line integral which involves solving a system of linear equations R times, where R renders a sufficiently small step-size $\Delta t/R$ (with $\Delta t = t^1 - t^0$).

Böhringer and Rutherford (2004) apply the HHP decomposition to climate change policies in order to come up with concrete estimates for bilateral spillovers that might be useful for the delicate policy issue of who should pay for adverse international spillovers to developing countries[6]. The HHP procedure avoids arbitrariness in the calculation of spillovers as compared to any sequential ordering of abatement policies in industrialized countries. In their analysis, Böhringer and Rutherford (2004) find that abatement actions by the United States produce by far the largest spillovers to other countries. The main source for these spillovers are larger adjustments on the international fossil fuel markets due to the substantial cutbacks in US fossil energy demands. Emission constraints in the United States account for the bigger part of the decline in fossil fuel producer prices following multilateral abatement under the Kyoto Protocol. This produces positive bilateral spillovers to fuel importers such as EU countries, Japan, or India and negative spillovers to fuel exporters such as OPEC. The decomposition analysis reveals fundamental problems underlying the issue of compensation to

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[6] The United Nations Framework Convention on Climate Change (UNFCCC, 1992) guarantees compensation from industrialized countries to the developing world for adverse spillovers from emission abatement in the industrialized world (Articles 4.8 and 4.9).

developing countries for induced economic costs of carbon abatement in the industrialized world. A developing region may benefit from abatement in one industrialized country, but suffer from abatement in other industrialized regions. This raises the question of whether developing countries that are compensated for adverse spillovers on the one hand should pay for positive spillovers on the other hand. To put it differently, industrialized countries that compensate for adverse spillovers to some developing countries may well claim transfers from those developing countries which benefit from their abatement policy.

The MPEC framework

A relatively new research area in applied general equilibrium analysis is based on *M*athematical *P*rograms with *E*quilibrium *C*onstraints (MPEC), a new class of mathematical programs introduced by Luo, Pang and Ralph (1996). The MPEC problem class permits a formal characterization of optimal policies within which the objective function depends on policy variables (e.g. tax rates – see example below) that would be exogenously specified in a conventional CGE application. This opens up a variety of policy applications in the field of *Sustainability Impact Assessment*.

In formal terms, the optimal policy problems in CGE models can be expressed as a specific case of the general MPEC formulation:

$$\max_{t} f(z;t) \tag{4}$$

s.t. z solves the equilibrium constraints $F(z;t)$

where:

$t \in R^m$ is a vector of policy (instrument) variables which are the choice variables for the problem,

$z \in R^n$ is a vector of endogenous variables that is determined by the equilibrium problem, i.e. $z = \begin{pmatrix} p \\ y \end{pmatrix}$, where p are prices and y are activity levels,

$F(z;\, t)$ is a system of equations which represents market equilibrium conditions, and

$f{:}R^{n+m} \rightarrow R^1$ is the objective function.

Böhringer and Rutherford (2002b) provide a large-scale MPEC application to design optimal carbon tax programs in a static multi-region, multi-sector general equilibrium model of global trade and energy use. In their case, the constraints *F(z; t)* describe the equilibrium conditions of a standard multi-sector, multi-region computable general equilibrium (CGE) model of global trade and energy use. *F(z; t)* includes an emission reduction constraint for an open economy that can be achieved through the use of (endogenous) emission taxes. The taxes correspond to the set of choice variables *t* in the optimal taxation problem and can be differentiated across different segments of the economy to maximize an objective such as overall real consumption. Böhringer and Rutherford (2002b) use the optimal tax framework to assess the relative importance of four alternative arguments that might justify the common policy practice of environmental tax differentiation: initial tax distortions, distributional concerns, leakage motives or international market power. Simulation results for the European and U.S. economies suggest that there is little economic rationale for the common policy practice to discriminate strongly in favor of heavy industries. Among the four motives for tax differentiation examined, only very specific concerns about job layoffs give reasons for tax exemptions to energy-intensive industries. Concerns about global environmental effectiveness provide some justification for tax discrimination in favor of energy- and export-intensive industries although leakage must be very high to make the case for substantial tax reductions. Tax interaction with initial fiscal energy taxes, broader-ranged concerns about factor incomes, as well as strategic international tax burden shifting can hardly rationalize the current practice in OECD countries to have only very low environmental taxes on energy-intensive industries or even exempt them.

Systematic sensitivity analysis

A wide-spread criticism to CGE analysis is the deterministic calibration approach to specify parameters of functional forms. Clearly, a stochastic estimation of parameters would be preferable. However, a (complete) econometric estimation of large-scale general equilibrium systems is typically doomed to failure due to severe data problems. The simultaneous estimation of all parameters would either require unrealistically large numbers of observations or overly severe identifying restrictions. The pragmatic way is to stick with the calibration approach and to check the sensitivity of central model results with respect to uncertainties in the elasticity space.

One approach to systematic sensitivity analysis is to conduct Monte Carlo simulations where values for key elasticties (e.g. trade elasticities, energy demand elasticities and fossil fuel supply elasticities) are drawn e.g. from uniform probability distributions around the model central values. TABLE 2 provides an illustrative statistical summary of results for CGE policy simulations on the economic effects of the Kyoto Protocol for the case that the original Kyoto emission reduction targets are achieved by industrialized countries using domestic carbon taxes (see Böhringer and Vogt, 2003). The summary includes the core (central case) values together with the mean and the median as well as the 5 % quantile and 95 % quantile. Such statistics provide useful insights into the robustness of model results[7].

An alternative to the Monte Carlo approach for systematic sensitivity analysis is Gaussian quadrature, especially if evaluations of large-scale models are time-consuming. Compared with Monte Carlo, Gaussian quadratures provide good approximations of means of model results and associated standard deviations while using substantially fewer model evaluations (see Arndt, 1996) for a detailed description). Hertel *et al.* (2003) apply this technique to the analysis of the Free Trade Agreement of the Americas (FTAA) based on the GTAP computable general equilibrium model of global trade (Hertel, 1997).

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[7] In our concrete case the robustness of results is conditional on the underlying assumption that the key elasticities are independent, i.e. the covariance between elasticity values is zero.

Table 2 - Results of Monte Carlo simulations on Kyoto Protocol (Böhringer and Vogt, 2003)

Scenario:	Implementation of original Kyoto reduction targets by domestic carbon taxes of industrialized countries as listed in Annex-B of the Kyoto Protocol				
	core value	mean	median	5% quantile	95% quantile
	Consumption change in % from business-as-usual				
OOE	–1.18	–1.16	–1.14	–1.38	–1.01
CAN	–1.48	–1.43	–1.42	–1.59	–1.31
EUR	–0.17	–0.19	–0.20	–0.23	–0.14
JPN	–0.26	–0.31	–0.31	–0.38	–0.21
CEA	0.49	0.50	0.50	0.29	0.73
FSU	–0.93	–0.88	–0.87	–1.04	–0.74
USA	–0.51	–0.56	–0.53	–0.78	–0.42
GLOBAL	–0.24	–0.25	–0.25	–0.31	–0.21
	Marginal abatement costs in USD_{97} per ton of carbon				
OOE	126	135	124	92	207
CAN	145	154	145	112	222
EUR	111	114	110	88	149
JPN	183	191	181	139	270
CEA	0	0	0	0	0
FSU	0	0	0	0	0
USA	156	170	156	114	271
	Consumption change in USD_{97} per capita				
OOE	–114	–113	–110	–134	–99
CAN	–162	–155	–153	–174	–141
EUR	–23	–25	–26	–31	–18
JPN	–53	–61	–61	–76	–43
CEA	8	8	8	5	12
FSU	–12	–11	–11	–13	–9
USA	–92	–102	–96	–142	–76
	Global emission reduction in % from business-as-usual				
TOTAL	9.60	9.51	9.50	9.00	10.00

Key: OOE - Other OECD (Australia and New Zealand), CAN - Canada, EUR - Europe (EU15 and EFTA), JPN - Japan, CEA - Central European Associates, FSU - Former Soviet Union (Russian Federation and Ukraine), USA - United States.

CONCLUSIONS

Computable general equilibrium (CGE) models provide a flexible quantitative framework for *Sustainability Impact Assessment*. These models can incorporate various sustainability (meta) indicators in a single consistent framework and allow for a systematic quantitative tradeoff analysis along the three dimensions of sustainability. Decomposition methods can be employed to better understand the complex adjustment mechanisms triggered by exogenous policy changes. The decomposition of general equilibrium results may also deliver valuable information for the proper design of policies. Furthermore, recent computational developments permit the formulation of optimal policy problems within large-scale CGE models. This class of models then can help to determine *optimal* policy choices for *Sustainable Development*.

Inherently, the strength of rather aggregate, economy-wide CGE models in capturing sustainability effects of policy initiatives at the level of different regions, sectors and households cause deficiencies when more specific impact analysis is required. There are many complementary quantitative models that feature substantially more details of technological conditions (e.g. engineering bottom-up energy system models), socio-economic household behaviour (e.g. micro-simulation models) or natural science relationships (e.g. climate models, water stress models, spatial land-use models). Complementary model information that can be linked to CGE models may substantially improve the applicability of the CGE approach for problem-tailored *Sustainability Impact Assessment*[8].

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