Capital mobility and spillovers within a modular approach to multi-region modeling

Marian Leimbach*, Ottmar Edenhofer

March 24, 2005

Abstract

This paper presents a novel approach to multi-region modeling. This approach is capable to reproduce the results from the traditional Negishi approach. In contrast to the latter, however, it also allows to model technological spillovers induced by foreign direct investments. The way of finding an equilibrium solution in a multiregional dynamic framework differs from existing methods. However, it resembles the solution method applied to the Arrow-Debreu type computable general equilibrium models in using an imaginary auctioneer who balances the interactions of the decentralized agents. We discuss the characteristics of the underlying tatonnement process which, in contrast to the joint maximization with the Negishi approach, is numerically implemented as decentralized optimization. Results from numerical model experiments are presented for cases with and without spillovers. According to preliminary results, it turns out that there are only small positive feedbacks from technological spillovers to the foreign direct investors (technological forerunners).

JEL classification: O41;C61;F21;F17

keywords: multi-region modeling, capital mobility, technological spillovers, decentralized optimization, integrated assessment

*PIK - Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, D-14412 Potsdam, Germany, Tel. ++49/331/288-2565, e-mail: leimbach@pik-potsdam.de

1 Introduction

This paper presents a novel approach to multi-region modeling. It originates from research in the domain of Integrated Assessment (IA) of climate change. While significant progress could be demonstrated in improving IA models in the last 15 years (Janssen, 1998; Rotmans and Dowlatabadi, 1998; Schneider, 1997), IA modeling fails to take essential interregional effects into account, in particular capital mobility. This, on the one hand, reflects general deficiencies of the economic theory in dealing with regional interactions in a dynamic framework, but is odd, on the other hand, in view of the role foreign investments play in a globalized world and may play in dealing with the climate change problem.

International experts expect investments into the climate change relevant energy systems worldwide to amount to around 16 trillion dollars over the next 30 years (IEA, 2003). 10 trillion dollars alone will be invested into the electricity sector, mainly in China, India, and Africa. For Africa these investments would consume half of the domestic savings. Hence, enormous foreign direct investments will be needed. This is also indicated by recent results from simulations with IA models (Edenhofer et al., 2005). Pursuing to restructure the energy system in a climate-friendly way results in scenarios that are dominated by investments into the renewable energy sector and other carbon-free technology options. This implies huge foreign investments, because those regions that host the innovators of, for instance, new solar energy technologies, do not correspond with those regions where the solar power plants will be build-up. Furthermore, foreign investments are linked with trade flows that influence the terms of trade especially with the developing countries. This may, with respect to the level of debts, imply opportunities as well as risks.

Within the discussion about promising climate protection strategies, technological spillovers come to the fore. Recent literature (Blomström et al., 1999; Hejazi and Safarian, 1999) identified a strong link between foreign direct investments and spillovers. Spillovers could make the difference that help investors of new energy technologies to break even and can make it profitable for single regions to become forerunners in climate policy. This paper shall provide a model framework that allows to analyze the impacts of foreign investments and spillovers on regional welfare and economic growth. This has to be considered as a preparatory step in integrating new types of regional interactions into IA models. In this paper we deal with spillovers that can be conceived as technological progress induced by foreign investments.

From an economic point of view, dealing with long-term issues like climate change require the intertemporal consistent selection of investment paths given the initial conditions that characterize the regions. Within this approach to multi-region modeling, a Ramsey type economic growth model will serve this task. Respective economic modules are embedded in a modular framework linked by a numerical coupling module. The pursued modular modeling concept is summarized in section 2 together with a discussion of competing approaches and techniques to model regional linkages. Another methodological tool, the balance of payment concept (BOP), is applied to deal with the arising accounting problems. It is described in section 3. The mathematical structure of each relevant module of the multiregional model is presented in section 4. One core element is the coupling module which is an iterative algorithm that searches for an equilibrium solution. We discuss the characteristics of the underlying tatonnement process and contrast them to the characteristics and capabilities of the Negishi approach (section 5). Before we end with some conclusions (section 7), preliminary results, depicting welfare and terms of trade implications, are presented in section 6.

2 Modular approach to multi-region modeling

Modeling capital mobility and spillovers obviously demands to distinguish different economic actors[1]. Within a global analysis these actors can be conceived as representative households of different world regions. Major inputs into the discussion of linkages between representative economic agents have been provided by the theory of international trade (cf. Neary, 1995) and the general equilibrium theory (cf. Debreu, 1996).

Several flows (e.g. goods trade, capital flows, tradeable permits, knowledge spillover) between heterogenous regions form a complex pattern of interaction. Recently, computable general equilibrium (CGE) models were developed that simultaneously balance trade flows, consider interaction between goods trade and capital mobility, and find equilibrium prices on all markets - e.g., Springer (2003).

[1]See Barro et al. (1995) for an analysis of capital mobility in a single actor open economy.

Springer distinguishes perfect and imperfect capital mobility. Imperfect mobility is either due to preference differentials in households investment decisions (e.g. home bias in capital allocation), which is modelled by a portfolio approach, or due to the restriction on physical capital mobility. In the latter case, capital has a vintage structure, and only the most recent vintage of capital is internationally mobile. But in addition to these reasonable imperfections, capital mobility is implicitly restricted due to the assumption of a fixed marginal propensity to save (Springer, 2003, p. 128) and a fixed current account deficit (p. 206). These assumptions are common in CGE models, but neglect important degrees of freedom in the representative households' decision-making on investments. Furthermore, within the CGE framework, spillovers are understood to represent secondary terms of trade effects induced by price changes (Böhringer and Rutherford, 2002). The CGE approach, however, is challenged when trying to integrate spillovers, representing technology transfers, and endogenous technical change in an intertemporal (dynamic) framework. CGE analyses based on the usual static approach (Kverndokk et al., 2004) cannot detect lock-in and path-dependency effects associated with spillovers. This likely has an influence on the policy instruments recommended, e.g. in dealing with climate change.

While there are some attempts of running IA studies by CGE models (e.g., Kemfert, 2002), often, the economic modules within IA models belong to the class of economic growth models, mainly characterized by the objective of maximizing global welfare (e.g., Manne et al., 1995; Nordhaus and Yang, 1996). Emissions trading is a major component of interregional linkages in those economic modules. Few of them integrate goods trade and even less consider capital mobility. A major challenge of modeling interregional linkages is to deal with distribution effects. Intertemporal trade balances are introduced in order to avoid an implausible redistribution of wealth. The Negishi approach is a well-known solution technique for multi-region modeling (Manne and Ruherford, 1994; Leimbach and Toth, 2003) based on the method of joint maximization (Dixon, 1975). By means of adjustable welfare weights, the regions' utility functions are combined in a single global welfare function. The process of iteratively finding the welfare weights, which are associated with an equilibrium and a pareto-optimal solution simultaneously, is also called tatonnement process.

The Negishi approach technically assumes to have the regions in a single model.

While also applying the economic growth model type, here we pursue another way of regional coupling by assuming decentralized regional actors. This follows from the modular modeling concept recently introduced into IA (Jaeger et al., 2002; Leimbach and Jaeger, 2004)[2]. According to this approach regions may be represented as autonomous modules linked by a numerical coupling module. Only few implementations of the modular approach to multi-region modeling exist. Meyer and Lutz (2002) presented an example that uses a trade module embedded in a simulation framework and supported by econometric analyses. Bahn et al. (1998) reported about an application based on the decomposition principle and Mathematical Programming techniques, respectively. In that example, however, the regions are just linked by a global emission reduction goal. The application of programming methods becomes numerically demanding when there are several markets and intertemporal interactions between them.

The approach, presented here, tries to tackle this challenge. It relies on Mathematical Programming and decomposition too. Similar to the Goal Coordination Approach of Singh (1980), the original joint optimization problem is split into single optimization problems of decentralized systems (i.e. regions). On a higher level, a control entity coordinates the local solutions in an iterative fashion in order to achieve the overall optimum. Singh demonstrated for the Goal Coordination Approach that the optimal solution will be achieved if there is no duality gap. Shapiro (1979) distinguished between the price-oriented and the resource-oriented decomposition method. The latter is applied here. In the resource-oriented decomposition, the coordinator has to compute an optimal allocation of the common resources. The present approach considers all traded goods as common resources. Based on the allocation of resources the agents determine their economic activities. There is an exchange of information between the coordinator and the agents until the global situation cannot be improved anymore. The equilibrium reached in this way, however, is a conditional one, based on the weights the coordinator assigns to each agent's improvement in evaluating the global situation. Bahn et al. (1998) assume economies of the same state of development which implies equal weights. Such an assumption, obviously, restricts the application of the multi-region model-

[2]The modular approach to IA aims at establishing a framework within which various configurations of model experiments can be performed with modules produced and implemented on different machines and in different software environments, and combined across different institutions.

ing approach. The present approach follows the rationale of the Negishi approach. A distinguished equilibrium can be obtained by equalizing intertemporal trade balances.

3 Balance of payment concept

In modeling regional interactions, a consistent system of accounting, that balances flows between regions, is required. At least when a model is advanced to an empirical state, this becomes important. However, with respect to capital mobility, in the modeling literature there is a lack of clearness how to treat capital flows. In this section, we present our framework of modeling capital flows which follows the balance of payment (BOP) concept (see IMF, 1993). Particular focus is on foreign direct investments which play a major role in modeling technology spillovers.

The BOP concept, which prevents the rather unrealistic simultaneous prevalence of both export surplus and capital inflow as a steady state phenomenon, relates goods trade, service and income transfers to capital transfers and foreign investments. Denoting the export of goods and services with X, the import with M, net incomes with NI, capital transfers and foreign investments with CT and reserve assets with RA, we get the following basic balance of payment equation[3] (for reasons of transparency and convenience we omit current transfers as well as the time index):

$$X - M + NI = CT - \frac{dRA}{dt}.$$

If we neglect net incomes and reserve changes for the moment, and furthermore relate the current account to the macroeconomic variables savings (S) and investments (I), we obtain:

$$X - M = S - I = CT.$$

A current account deficit results from an excess of imports. Under the reasonable assumption that these imports are based on domestic demands, either savings decrease (if consumption goods import is in excess) or investments increases (if

[3]In practice, this balance will not hold due to errors in the national accounting systems. Hence, empirical data bases include an error residual.

investment goods import is in excess). In any case, an excess of investments over savings arises (S<I). Foreign capital (CT) is needed to absorb the spare investments. Inversely, in a country with an excess of exports, savings exceed investments that are available domestically. Savings surplus can only be reduced by foreign investments. Alternatively, the exporter may build-up reserves, if no adequate investment opportunities exist. Negative reserves are possible. They can be interpreted as financial capital that is borrowed from foreign banks in order to either finance foreign investments or pay for imports when there are no deposits from exports or savings left.

The BOP concept distinguishes three types of capital transfers: foreign direct investments, portfolio investments and other investments. The role played by foreign direct investments (FDI) is ambiguous. Usually, model studies consider FDIs as related to the creation of new physical capital. The International Monetary Fund (IMF) uses the term FDI in a different way. According to IMF's definition, FDIs comprise all financial transaction that aimed to acquire dominant equity shares of foreign firms. That means, FDIs represent a change of share-holding just as other foreign investments[4]. For FDIs that are linked to new investments (e.g. construction of power plant abroad) the change of share-holding is just virtual. Such FDIs get into the BOP in two ways (IMF 1993, chapter IV, paragraph 78):

- as production (and investment) of the destination country and subsequent purchase of the foreign investor (capital exporter).
- the investment is declared as export of services.

Thus, the only consistent way of dealing with FDIs which include physical investments is to consider it simultaneously as part of the current account balance (services export) and the financial account balance (capital transfer). In this analysis, we model FDIs in exactly this way. Hence, we restrict FDIs to just a part of total FDIs in the sense of IMF's definition, but relate them to physical capital transfers like other modeling studies do.

While the BOP concept links trade flows and capital flows, nothing has so far been said about the terms of trade implications. A long lasting current account

[4]IMF draws a line at 10% of total equity shares. All foreign investments that yield a share volume above this threshold are considered as FDIs, all others as portfolio investments.

deficit may lead to a currency devaluation. Since economic growth models don't directly deal with exchange rates, we will take terms of trade effects into account by an intertemporal budget constraint combined with net foreign asset accounting. Capital transfers build up net foreign assets or liabilities. Net foreign assets are subject to a return on capital. The intertemporal budget constraint can be met alternatively by balancing the intertemporal trade balance or by requesting to level off the net foreign assets.

4 The basic model

Within this section we present the model structure of our modular approach to multi-region modeling. Figure 1 shows the modular structure for a two-region model including the main interface variables. There are two knowledge domain modules representing region I and region II, and there is a numerical coupling module - the trade module. Finding a solution of the coupled model is an iterative process which ends if the interface variables don't change anymore. Within each iteration, first the region modules will be solved and afterwards the trade module.

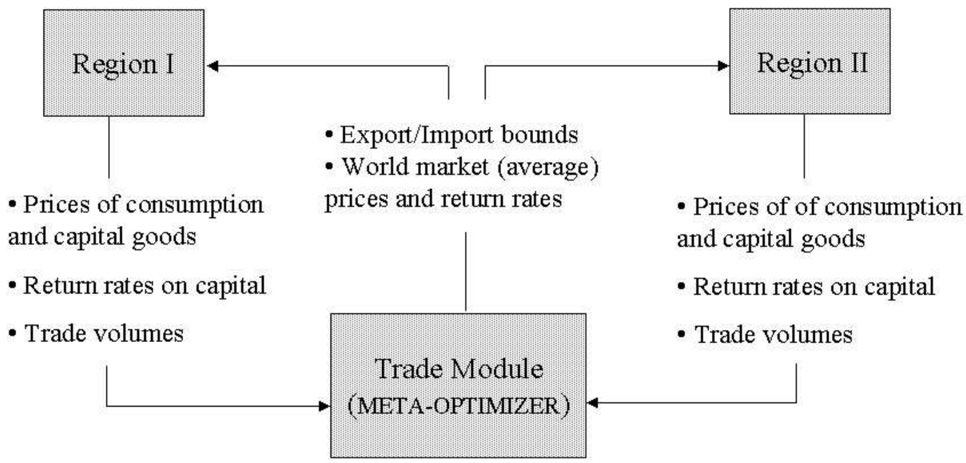

Figure 1: Modular structure

Throughout the model presentation, we use the following indices:

t time periods,

i, k regions,
j goods,
r iterations.

With j=$\{G, F, R\}$ the following types of trading goods are distinguished:
G consumption good,
F investment good,
R primary energy carriers.

Although the modules are time discrete, we use the continuous form of representing time in order to increase transparency.

4.1 Region module

We restrict the elaboration of the region modules to the structural elements which are essential for the foreign activities of an economy. Each region module is represented by an economic growth model that includes a welfare (*U*) maximizing objective function:

$$Max\ \ U_i^r = \sum_{t=1}^{T} f[C_i^r(t)] \cdot e^{-\rho t}. \tag{1}$$

This welfare function measures the utility of the region's representative household. Utility is a function *f* of the consumption path *C(t)* subject to discounting by discount rate ρ. For *f* it holds

$$f'[C] > 0; \ \ f[C]'' < 0.$$

Production functions *g* with capital *K*, labor *L* and energy *E* as production factors generate sectoral output *Y*:

$$Y_{ij}^r(t) = g_j[A_i^r(t), K_i^r(t), L_i^r(t), E_i^r(t)]. \tag{2}$$

Production factors are allocated from a common pool. Thus, perfect cross-sectoral mobility of capital and labor is implicitly assumed. Variable *A* denotes the productivity level which either may be factor-specific or represents total factor productivity. *A* can be treated either as an endogenous variable (following endogenous growth theory) or as an exogenously given variable (following the classical growth theory). Labour is assumed to be exogenously given.

The output of the consumption goods sector represents regional gross product net of investments. It is used to meet demands on consumption and exports, while being incremented by imports:

$$Y^r_{i,j=G}(t) = C^r_i(t) + \sum_k (X^r_{ik,j=G}(t) - X^r_{ki,j=G}(t)). \tag{3}$$

X_{ikj} denotes the export from region i to region k. It simultaneously denotes import of region k from region i which, however, is part of optimization of another region. Particular constraints ensure equivalence of both (see below). Note that the trade variables represent net export and net import values. The usage of separate export and import variables, which for net values actually could be omitted, is due to the subsequent modeling of technological spillovers.

The investment goods sector provides domestic investments (control variable *I*) and meets foreign demands on investments goods (in contrast to eq. 3, here only the export part is included):

$$Y^r_{i,j=F}(t) = I^r_i(t) + \sum_k X^r_{ik,j=F}(t). \tag{4}$$

Primary energy resources are produced by extraction. With *v* representing the energy content of resources, energy, resources extraction and export are linked within the following equation:

$$E^r_i(t) = v \cdot [Y^r_{i,j=R}(t) + \sum_k (X^r_{ki,j=R}(t) - X^r_{ik,j=R}(t))]. \tag{5}$$

For this model we do not distinguish between different sectoral capital stocks. Capital accumulation follows the standard capital stock equation of motion (δ represents the depreciation rate) extended by the FDI import variable:

$$\Delta K^r_i(t) = I^r_i(t) + \sum_k X^r_{ki,j=F}(t) - \delta_i(t) \cdot K^r_i(t-1). \tag{6}$$

The current account balance *CA* sums up the net exports of the different tradables multiplied by their relative prices (with the consumption good price $\tilde{p}_G$ as numeraire):

$$CA_{ik}^r(t) = \sum_j (\tilde{p}_j^{r-1}(t)/\tilde{p}_{j=G}^{r-1}(t) \cdot [X_{ikj}^r(t) - X_{kij}^r(t)]). \tag{7}$$

Prices are given in terms of averaged shadow prices obtained in the previous iteration. The balance of payment links trade flows with capital flows:

$$CA_{ik}^r(t) = \Delta RA_{ik}^r(t) + CT_{ik}^r(t). \tag{8}$$

The difference between the current account *CA* and capital transfers *CT* results from building reserves (*RA*) which for simplicity reasons are assumed to be given exogenously. This balance of payment equation does not take explicitly net incomes into account. Implicitly, however, net incomes reduce the amount of capital transfers that is requested to level off the balance of payment. Furthermore, net incomes in the form of return rates on foreign investments are considered by the net foreign assets (NFA) equation of motion:

$$\Delta NFA_{ik}^r(t) = \tilde{\mu}^{r-1}(t) \cdot NFA_{ik}^r(t) + CT_{ik}^r(t). \tag{9}$$

$\tilde{\mu}$ represents the rate of return on capital. Net foreign assets increase by the return amount, if net incomes are not transferred. The return rate is computed based on the solution of the previous iteration, in particular on the shadow prices λ of the capital stock equation (6).

$$\mu_i^r(t) = -\frac{\Delta\lambda_i^r(t)}{\lambda_i^r(t-1)}. \tag{10}$$

Within the financial account we distinguish between foreign direct investments *FDI* and other investments *OI*:

$$CT_{ik}^r(t) = FDI_{ik}^r(t) - FDI_{ki}^r(t) + OI_{ik}^r(t). \tag{11}$$

Capital flows by other investments are represented by a single variable only (which is negative for inflows). As discussed in the previous section, foreign direct investments are part of both the current account and the financial account. The respective variables are related as follows:

$$FDI_{ik}^r(t) = \tilde{p}_{j=F}^{r-1}(t)/\tilde{p}_{j=G}^{r-1}(t) \cdot X_{ik,j=F}^r(t). \tag{12}$$

This implicitly means that all investment goods export is actually accompanied by foreign direct investments.

The range of regional interactions, usually modelled, is extended by spillovers. Spillovers may be due to foreign direct investments. Empirical research, reported by Takii (2004), demonstrated for several countries that foreign firms (resulting from foreign direct investments) tend to have higher productivity than domestic ones, hence improving the host's country aggregated productivity. Within our model an additional change of the total factor productivity in a region k is a function of foreign direct investments of region i in region k and of productivity differences between region k and i:

$$\Delta A_k^r(t) = \sum_{i=1}^{n} \left(\frac{FDI_{ik}^r(t)}{K_k^r(t)} \right)^{\zeta} \cdot \beta \cdot max(0, A_i^{r-1}(t) - A_k^{r-1}(t)). \tag{13}$$

β represents a spillover coefficient, i.e. the intensity of technology spillover. ζ ($0 < \zeta < 1$) depicts the elasticity of productivity changes on FDIs. Note that the FDI variable is divided by the capital stock in order to avoid scaling effects (otherwise larger regions would get higher productivity gains).

This modular approach towards multi-region modeling is based on trade flow boundaries $\bar{X}$ which are computed by the trade module in the previous iteration. If i denotes the region under consideration, for exports it holds:

$$X_{ikj}^r(t) \geq \bar{X}_{ikj}^{r-1}(t). \tag{14}$$

Analogously the following import constraint holds:

$$X_{kij}^r(t) \leq \bar{X}_{kij}^{r-1}(t). \tag{15}$$

Both constraints are binding, since

$$\frac{\partial U_i^r(t)}{\partial \bar{X}_{ikj}^r(t)} \leq 0$$

and

$$\frac{\partial U_i^r(t)}{\partial \bar{X}_{kij}^r(t)} \geq 0.$$

This guarantees the balancing of interregional trade flows. The region module is completed by several initial conditions:

$$K_i^r(1) = k_i \tag{16}$$

$$A_i^r(1) = a_i \tag{17}$$

$$Y_{i,j=R}^r(1) = rx_i \tag{18}$$

$$NFA_{ik}^r(1) = fa_{ik} \tag{19}$$

$$\tilde{p}_j^0(t) = pa_j(t) \tag{20}$$

$$\tilde{\mu}^0(t) = b(t) \tag{21}$$

$$\bar{X}_{ikj}^0(t) = x_{ikj}(t) \tag{22}$$

and non-negativity conditions:

$$C_i^r(t), K_i^r(t), Y_{ij}^r, I_i^r(t), X_{ikj}^r(t), FDI_{ik}^r(t), E_i^r(t), \theta_i^r(t) \geq 0. \tag{23}$$

The set of control variables Q$_i$ of each region i can be denoted by:

$$Q_i = \{I_i, X_{ik,j=G}, X_{ik,j=R}, X_{ki,j=G}, X_{ik,j=R}, FDI_{ik}, FDI_{ki}\}.$$

4.2 Trade module

The purpose of the trade module is to mediate between the region modules (i.e to clear markets, ensure intertemporal balancing, and set world market prices) and to determine flow barriers that correspond to a competitive equilibrium, respectively. The objective function *O* of the trade module maximizes the total gains from a shift in the trade structure. These are obtained from the difference between the importers marginal utility (import price *pi*) of additional import units ($\bar{X}$ - *X*) and the exporters marginal utility loss (export price *pe*):

$$Max\ \ O^r = \sum_{t=1}^{T}\sum_{i=1}^{n}\sum_{k=1}^{n}\sum_{j=1}^{l}([pi_{ikj}^r(t) - pe_{ikj}^r(t)] \cdot [\bar{X}_{ikj}^r(t) - X_{ikj}^r(t)]). \tag{24}$$

The potential trade flows $\bar{X}$, which represent the flow barriers in the regional modules, serve as control variables in the trade module. Each region may either be an exporter or an importer of a particular good:

$$\sum_{t=1}^{T}\sum_{k=1}^{n}\bar{X}^r_{ikj}(t)\cdot\sum_{t=1}^{T}\sum_{k=1}^{n}\bar{X}^r_{kij}(t)=0. \tag{25}$$

One could increase flexibility by taking this constraint into account for each period separately. This, however, could lead to artificial investment goods exports in anticipation of spillover gains from reexports in next periods. Moreover, an intertemporal trade balance has to be met:

$$\sum_{t=1}^{T}\sum_{j=1}^{l}\left(\tilde{p}^r_j(t)\cdot\sum_{k=1}^{n}[\bar{X}^r_{ikj}(t)-\bar{X}^r_{kij}(t)]\right)\leq\epsilon. \tag{26}$$

In order to support feasibility and hence progress of the iteration process, the value of parameter ϵ has to be chosen close to, but significantly different from zero. This equation serves to level off the trade deficits of each region in the long run and prevents in a similar way as within the Negishi approach implausible redistribution effects. Due to the complementary relation between trade and capital transfers, which implies that capital flows are balanced in line with trade flows, this equation represents also a substitute of balancing the net foreign assets:

$$NFA^r_{ik}(T)=0.$$

Hence, equations (9) and (10) serve diagnostic purposes only. In order to stabilize the iterative algorithm, the potential change of trade flows, represented by the difference $\bar{X}$ - X, is restricted to a fraction γ of the respective output levels:

$$-\gamma\cdot Y^r_{ij}(t)\leq\bar{X}^r_{ikj}(t)-X^r_{ikj}(t)\leq\gamma\cdot Y^r_{ij}(t). \tag{27}$$

Prices are endogenous in the integrated system. However, they are exogenous for the region modules as well as for the trade module. They are computed after the region modules are solved and before the trade module starts. As mentioned, prices are determined as shadow prices which can be described in form of partial derivatives:

$$pi^r_{kij}(t)=\frac{\partial U^r_i(t)}{\partial\bar{X}^r_{kij}(t)} \tag{28}$$

$$pe^r_{ikj}(t)=\frac{\partial U^r_i(t)}{\partial\bar{X}^r_{ikj}(t).} \tag{29}$$

Note that within the objective function (24) the price differential is formed by the import price of region k and the export price of region i (with i≠k). Since the shadow prices cannot be expected to converge offhand (even in the equilibrium), world market prices (which are needed in order to compute the current account and the intertemporal trade balance) are determined based on averages (with n representing the number of regions):

$$\tilde{p_j^r}(t) = [\frac{\sum_{i=1}^n \sum_{k=1}^n pi_{ikj}^r(t)}{(n-1)\cdot n} + \frac{\sum_{i=1}^n \sum_{k=1}^n pe_{ikj}^r(t)}{(n-1)\cdot n}]/2 \qquad \forall i \neq k. \tag{30}$$

This also applies to the return rates on capital:

$$\tilde{\mu}^r(t) = \frac{\sum_{i=1}^n \mu_i^r(t)}{n}. \tag{31}$$

While the trade module determines the flow barriers, within the region modules these barriers represent lower and upper boundaries (eq. 14 and 15). They are purely algorithmic devices. The trade module does not reflect the real adjustment process of markets. Its result, however, resembles the outcome of this process. In essence, the trade module is an iterative algorithm that can be conceived as representing an auctioneer who balances interactions of decentralized agents. It differs from the Walrasian auctioneer and other excess demand algorithms that by means of price adjustments iteratively clear markets and balance trade flows, respectively (e.g., Kumar and Shubik, 2004) [5]. Above all, it is an adjustment algorithm that operates in an intertemporal model setting.

The data flow (see Figure 1) and the adjustment process are as follows. The region modules send trade volumes, shadow prices and return rates data to the trade module. The trade module uses this information in order to adjust the flow barriers, which it sends back together with average prices and return rates data to the region modules. Furthermore, the current productivity level of each region is made available for each other region's optimization within the next iteration. Capturing the interactions between the regions, i.e. balancing the trade and investment flows, is an iterative process. In each iteration the regions are confronted with new flow barriers. This iterative process ends when the return rates on capital are equalized between the regions, or when they converge and the trade structure does not

[5] See also Luenberger and Maxfield (1995) for advanced adjustment algorithms to compute competitive equilibria.

change anymore. Convergence behavior can be influenced by parameter γ which additionally can be adjusted during iterations.

The objective function of the trade module maximizes the marginal welfare gains of foreign activities. While the formal notation only relates to the prices of tradables, the profitability of capital transfers is implicitly taken into account. This is due to the close relationship between the current account and the financial account.

5 Modular approach vs. Negishi approach

In Table 1 we want to compare the tatonnement process of the classical Negishi approach and the present modular approach for a conventional model setting without spillover effects. This comparison is based on the following equilibrium conditions:

- equalized rates of returns on capital [6]
- balanced intertemporal budget constraint
- clearance of trade markets.

Table 1: Tatonnement process

Negishi approach	Modular approach
Iterative adjustment of welfare weights	Iterative adjustment of flow barriers
Equal rates of return in each iteration	Intertemporal budget constraint is balanced in each iteration
Achieve balanced intertemporal budget constraint	Achieve equalized rates of return on capital

[6] In the standard Heckscher-Ohlin model trade results in equalization of factor prices. Cunat and Maffezzoli (2004) demonstrate that significant differences in the capital-labor ratios of different countries make this equalization impossible. This is associated with specialization on either capital-intensive or labor-intensive goods.

In contrast to standard approaches based on a Walrasian tatonnement process, here, the market clearance condition will be met by means of appropriate constraints in both approaches from the outset. This applies after some initial iterations also to the intertemporal budget constraint within the modular approach and to the return rates within the Negishi approach. While the Negishi approach iterates towards an evened intertemporal budget constraint, the modular approach iterates towards equalized return rates on capital. The next section will show whether differences in the tatonnement processes will yield different results. Meeting the equilibrium condition of equalized return rates, however, depends first on a neoclassic type of production function, in particular holds

$$g'[K] \geq 0; \;\; g''[K] \leq 0,$$

and second, on the exclusion of externalities like spillover effects. In the presence of externalities induced by foreign direct investments, regional return rates on capital may differ. Convergence has to be tested as the case arises.

The Negishi approach is challenged when spillover effects has to be taken into account. This, first, is due to the request to model trade flows in a bilateral form. In its common application (cf. Leimbach and Toth, 2003) the Negishi approach is based on the shadow prices of tradables as derived from the trade balance equation (X_i represents net export of region i):

$$\sum_i X_i = 0.$$

Within the bilateral model formulation (with k as another region index), this trade balance changes to

$$\sum_i (\sum_k X_{ik} - \sum_k X_{ki}) = 0.$$

This can be transformed to

$$\sum_i \sum_k X_{ik} - \sum_i \sum_k X_{ki} = 0,$$

$$\sum_i \sum_k X_{ik} - \sum_k \sum_i X_{ik} = 0,$$

$$\sum_i \sum_k (X_{ik} - X_{ik}) = 0.$$

The last equation is met by any arbitrary value for X_{ik} and results in an infeasibility for any change of the right hand side. Hence, this trade balance has no meaningful dual variable and prevents the Negishi approach from being operable.

Using alternative shadow prices could be a way out. A reformulation of the above described model in order to make it applicable for the Negishi approach would combine all constraints from the region modules (except for eqs. 14 and 15) with a global welfare function and a trade balance. The shadow prices of the instances of the production functions (eq. 3) are usable to obtain consumption goods prices, investment goods prices and energy resources prices. However, the equivalence of these production prices with market prices can only be guaranteed if there is unrestricted flow of goods an capital. But even then, the Negishi approach based on production functions shadow prices may fail in case of existing externalities like spillover effects. Spillovers exhibit price relevant effects that are bound to interregional linkages. They cannot be grasped by production prices. In contrast, the modular approach provides a straightforward way to derive market-relevant prices by means of equations (28) and (29). Hence, in dealing with spillover effects priority shall be given to the modular approach.

6 Model experiments

Primary aim of the experiments is to validate the model presented in section 4. This is done, first, by testing the convergence behavior, second, by contrasting the results with those of the Negishi approach, and third, by means of sensitivity analyses. As instances of the functions f (see section 4.1) we apply the common logarithmic welfare function. The production function for the consumption goods sector is specified as Cobb-Douglas function:

$$Y^r_{i,j=G}(t) = (1+\kappa)^{t-1} \cdot A^r_i(t) \cdot [(1-\theta^r_i(t)) \cdot K^r_i(t)]^\alpha \cdot L^r_i(t)^\eta \cdot E^r_i(t)^{1-\alpha-\eta}. \quad (32)$$

In addition to productivity changes induced by spillover effects, A is assumed to change exogenously according to growth rate κ. Variable θ denotes the share of total capital stock which is allocated to the investment goods sector[7]. Investment goods production is assumed to be a function of capital only:

$$Y^r_{i,j=F}(t) = \psi_i \cdot \theta^r_i(t) \cdot K^r_i(t)^{\phi}. \tag{33}$$

With the elasticity parameter ϕ equal to 1, this equation becomes a Leontief-type production function and parameter ψ could be interpreted as technological coefficient (investment goods output per unit capital stock). Following the neoclassical assumption of diminishing marginal productivity, we chose a value for ϕ that is close to, but significantly lower than 1. Moreover, ϕ is assumed to be constant over time for simplicity reasons. The resource extraction function is modelled as a time trend (with ω as growth rate):

$$Y^r_{i,j=R}(t) = Y^r_{i,j=R}(1) \cdot (1+\omega)^{t-1}. \tag{34}$$

The stock of reserves is fixed to zero. The time horizon is from 1990 to 2050, including 12 five-year time steps. We omit a transversality condition. Thus terminal effects may occur in numerical results.

We started with a model including the following generic regions:

- IR - developed world region;
- DR - developing world region.

The developed region is characterized by higher productivity level and higher initial capital stock (per capita), the developing region by higher resource endowment and population growth. While data are used that are in an order of those provided by international data bases, the model is not at all calibrated. Hence, results should only be interpreted in a qualitative sense. The experiments mainly serve to provide evidence of the mechanics of the implemented cause-effect chain. All modules are programmed in GAMS (Brooke et al., 1992) and numerically solved with the nonlinear programming solver CONOPT3. The programmes are available upon request from the authors. See Annex A for the selected parameters and initial values.

[7]The assumption of an aggregated capital stock is not a request of the model type, but for simplicity reasons only.

6.1 Non-spillover case

Within a first set of model experiments we assume that technological spillovers do not exist and technical progress is completely exogenous. In analysing the results, we first take a look at the convergence behavior. The upper graphics of Figure 2 demonstrates convergence of the welfare measures. In this example around 100 iterations are needed. Convergence can be sped up by increasing parameter γ. This, however, simultaneously increase the risk of failing convergence.

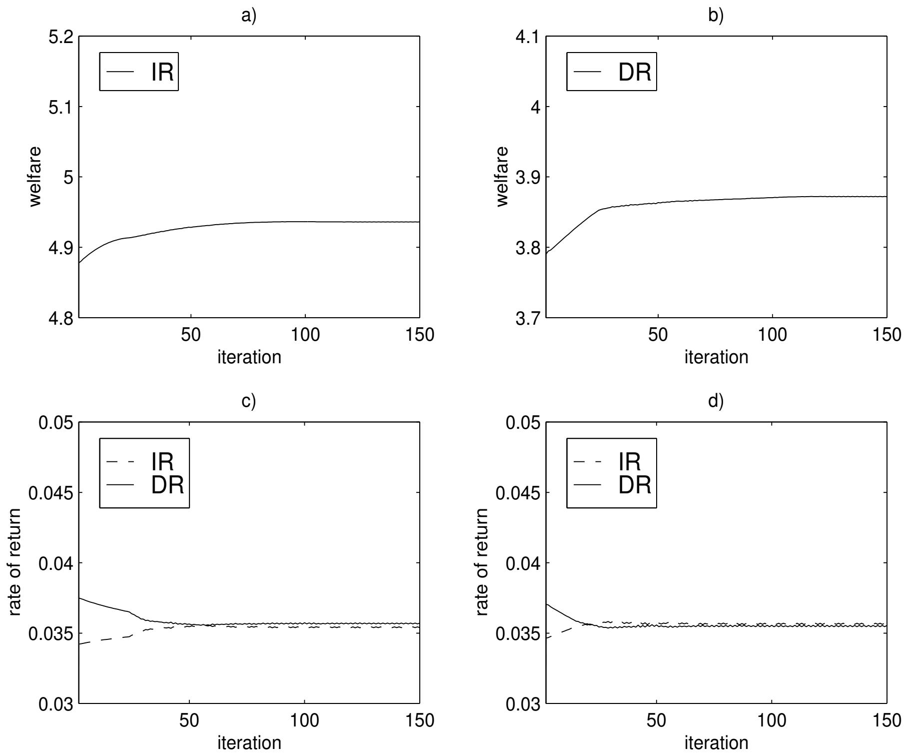

Figure 2: Convergence of welfare (a and b) and return rates on capital in 2010 (c) and 2020 (d).

The lower graphics show the convergence of the return rates on capital of the year 2010 and the year 2020. The convergence process is almost completed after 50 iterations. This, however, is not a uniform result. The return rates in other years exhibit a different speed of convergence. Moreover, the required number of iteration also depends on the initial flow barrier. Nevertheless, convergence behavior is quite robust.

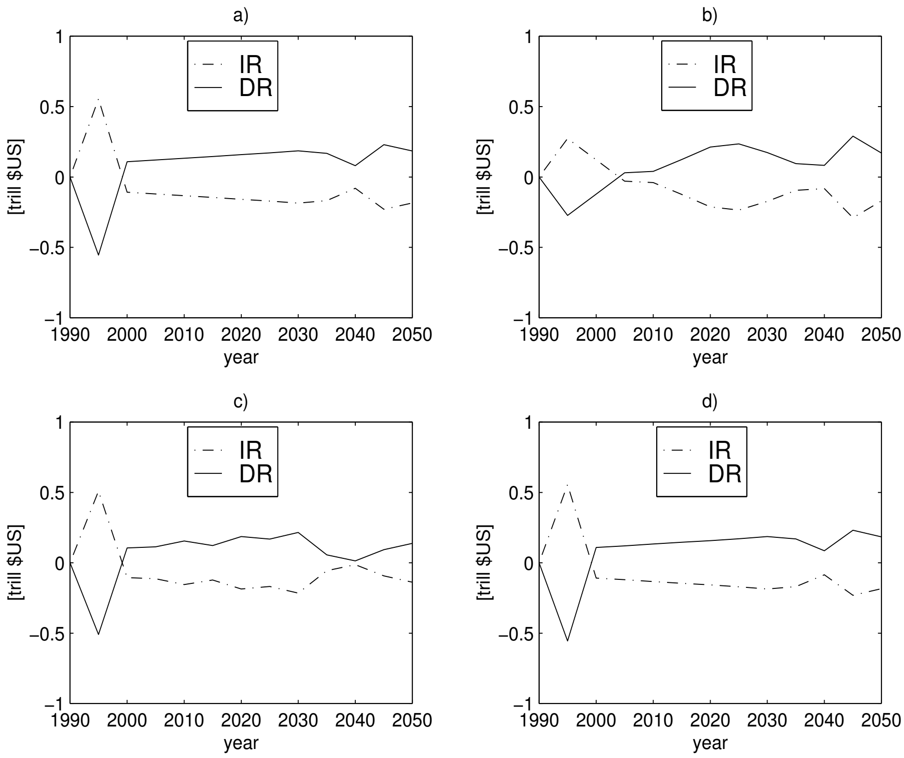

Figure 3: Current account resulting from Negishi approach (a), and from the modular approach after (b) 10 iterations, (c) 40 iterations, and (d) 300 iterations

In contrast to the return rates, the prices of tradables (computed as shadow prices) do not completely converge. This is due to the effect of the intertemporal budget constraint which for regions with a current account deficit requests to export tradables. The exporting region may have higher welfare sensitivity (shadow prices) than the importing region with respect to the trading good. Each export of such a good, however, increases its shadow price and hence the difference to the respective price within the importing region.

As a next quality check of the modular approach, its results are compared to those from the the Negishi approach. First, it turns out that the return rates presented in Figure 2 converge towards the respective values that result from the Negishi approach. Second, the Negishi solution in terms of main variables can be reproduced completely with sufficient numerical precision. Given the methodological differences, the correspondence is remarkable. Correspondence appears after around 50 iterations for per capita consumption, gross product, and welfare figures. More iterations are needed to obtain export trajectories that fit to each other. In a multi-regional setting quite different trade pattern can produce similar welfare. This indicates a problem of trade simulations in an optimal control framework. Nevertheless, even the trade pattern could be reproduced quite well. Figure 3 shows the convergence of the trade structure with the modular approach as well as the correspondence with the trade structure from the Negishi approach. In the following we will analyse the trade and foreign investment structure indicated by Figure 3.

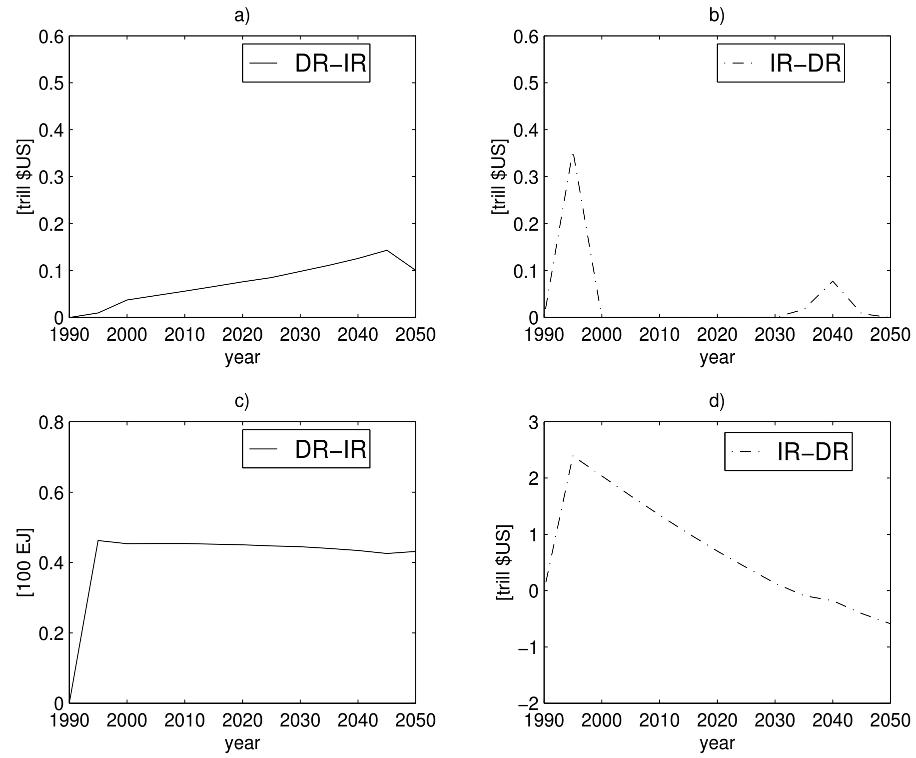

Figure 4: Net export of a) consumption goods, b) investment goods, c) primary energy (first mentioned region in the legend always denotes the exporter), and d) net foreign assets (discounted)

Due to differences in resources endowments and productivity, the regions' trade profits vary. The developing region, endowed with affluent resources, benefits most from trade and capital mobility (2.2% in relative welfare units compared

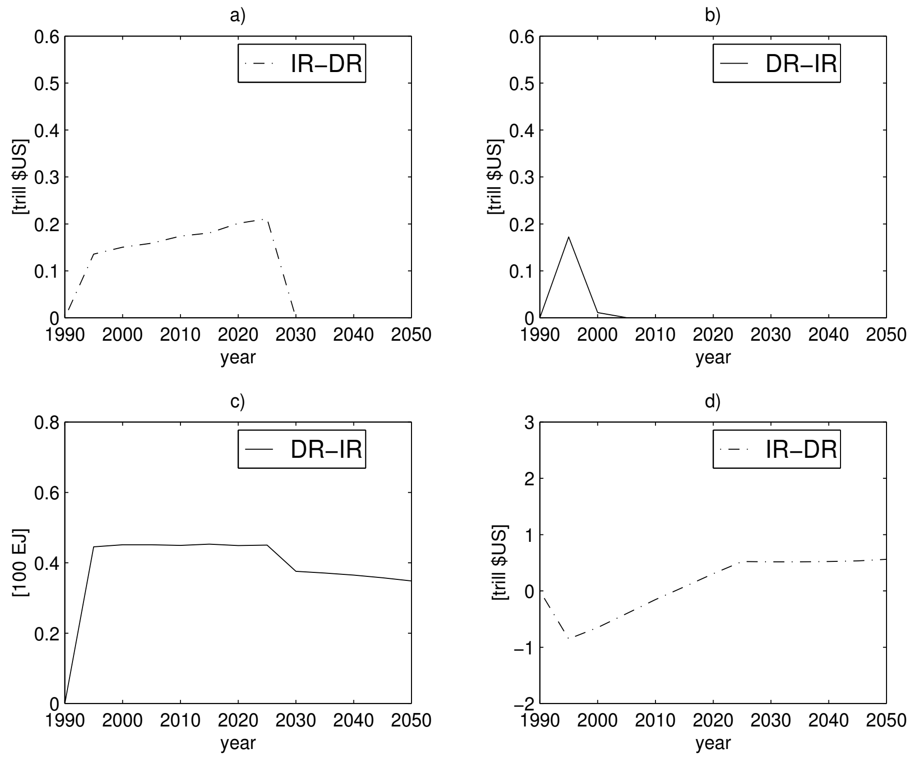

Figure 5: Net export of a) consumption goods, b) investment goods, c) primary energy (first mentioned region in the legend always denotes the exporter), and d) net foreign assets (discounted)

to 1.2% for the developed region). A major merit of the model is its capability to provide insights into the dynamics of regional interactions. Figure 4 illustrates some details of the intertemporal and bilateral trade structure. Besides the expected result that the developing region exports primary energy, we see that there is also increasing export of final goods from DR to IR. Both exports will lead to level off the current account deficit of DR and reduce the foreign assets of IR, respectively, which arise due to substantial initial foreign direct investments of IR in DR[8]. This is a typical result within an intertemporal optimizing framework. There is a bias to immediately adjust the capital stock to a level from which it is easier to approach the steady state. The level of these "induced" foreign direct investments depends on

[8]Note that in Figures 4, 5, 6 net exports are represented by its physical equivalents, partly measured in $units. No price relevant information (discounting, changes in relative prices) are included.

the initial capital stock levels. Increasing the initial capital stock (from 4 to 8 trill. $US) leads to a reversed trade pattern with respect to investment and consumption goods (see Figure 5). DR exports investment goods, IR exports consumption goods. Capital flows are more balanced from the beginning. Nearly no trade in consumption goods and only small investment goods export of the developed region in order to compensate for resource imports result with an initial capital stock of 6 trill $US.

6.2 Spillover case

Within the second set of model experiments, we take technological spillovers into account. Consequently, technological progress is partly endogenized. The question arises whether there are spillover gains for each of both involved regions and what changes in the trade and capital flow structure result. Externalities caused by the spillover effect lead to a divergence of the marginal values of exports and imports of the same good. This, in particular, applies to the host country of spillovers and will challenge the applied routine of determining average prices (eq. 31). A weighted price averaging is now introduced (with XS$_j(t)$ representing the trade sum of good j in period t):

$$XS_j^r(t) = \sum_{i=1}^{n}\sum_{k=1}^{n} X_{ikj}^r(t). \tag{35}$$

$$\tilde{p}_j^r(t) = [\sum_{i=1}^{n}\sum_{k=1}^{n} \frac{X_{ikj}^r(t)}{XS_j^r(t)} \cdot pi_{ikj}^r(t) + \sum_{i=1}^{n}\sum_{k=1}^{n} \frac{X_{ikj}^r(t)}{XS_j^r(t)} \cdot pe_{ikj}^r(t)]/2 \qquad \forall i \neq k. \tag{36}$$

With taking spillover effects into account (assuming the spillover intensity β=0.015), trade in FDI goods claims significant shares on total trade - see Figure 6. DR receives a sustained flow of foreign direct investments. Figure 6, furthermore, shows an overall intensification of trade and capital mobility in the spillover case (compare to Figure 4). Figure 7 illustrates the consumption gains from the spillover effect. The reference point is the default non-spillover solution from last section. While gains in both regions increase with time, there are yet significant differences in the patterns of gains. The developing region gains in all periods. The increase is moderate. The developed region, in contrast, lose in initial periods, but gain more

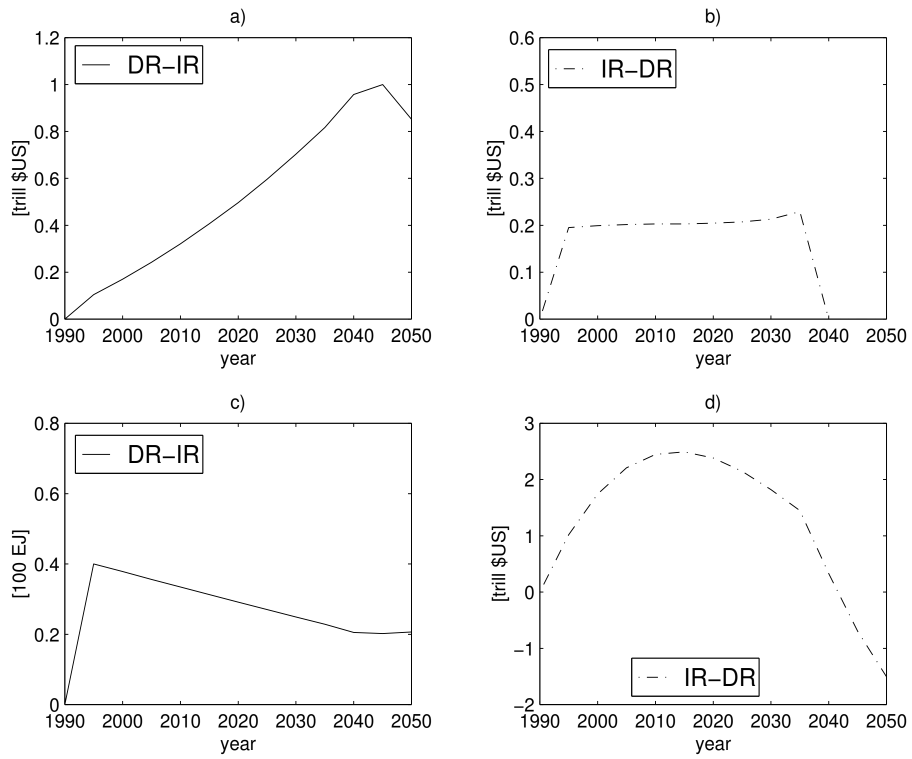

Figure 6: Trade structure in the spillover case: net export of a) consumption goods, b) investment goods, c) primary energy, and d) net foreign assets (discounted)

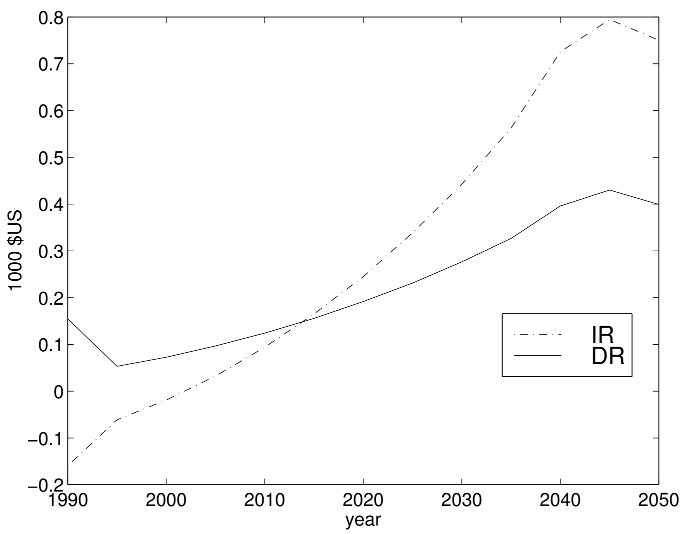

Figure 7: Per capita consumption gains from spillover effect

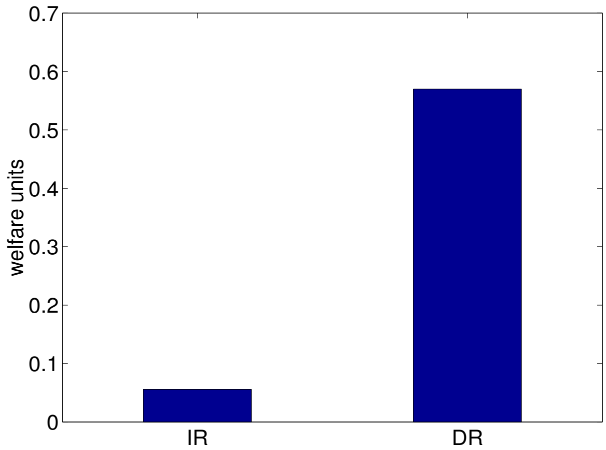

Figure 8: Welfare difference between spillover and non-spillover case

later. Due to the discounting effect the consumption gains of the developed region do not become manifest in an equal increase in welfare (see Figure 8). In relative terms, the developing region increases welfare by 14.7%, whereas the developed region increases welfare by 1.1% only.

The consumption and welfare gains of the developing region are directly linked to productivity increases caused by technological spillovers. Positive feedbacks from technology spillover to the developed region, while on a moderate level only, are mainly due to higher prices of the FDI goods in comparison to prices of the consumption goods. The developed region being the exporter of FDI goods benefits from this. The level of gains, in general, depends on the specification of parameter β. There is no empirical foundation for β so far. Hence, we shall stress again that this result can only be interpreted in a qualitative sense.

Due to the fact that by introducing spillover effects the mathematical model structure becomes non-convex, multiple optima may exist. This does not apply to the single models (region modules and trade module). Within the region modules, the representative agent has no direct control over this external effect. However, the spillover effect influences the shadow prices in the region modules and due to the exchange of shadow price information, the spillover effect gets into consideration within the trade module. The above algorithm of finding the optimal solution of the multiregional optimization problem does not guarantee to find a global optimum.

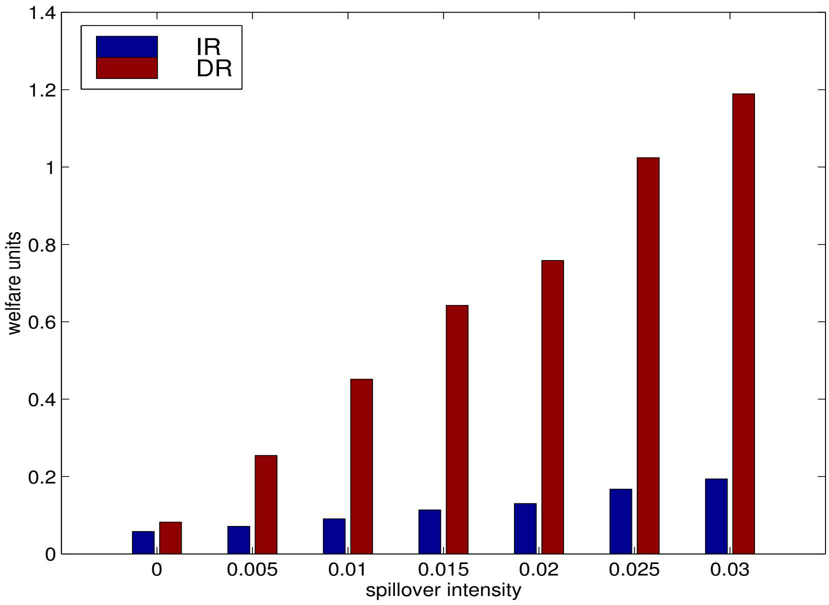

Figure 9: Sensitivity of welfare gains from trade on spillover intensity

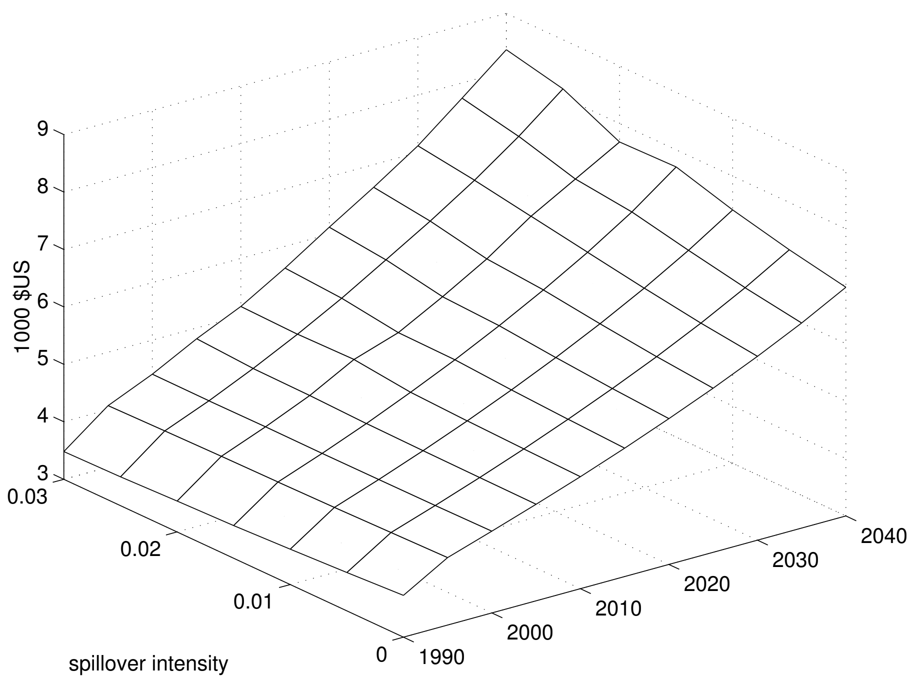

Figure 10: Per capita consumption sensitivity on spillover intensity in IR

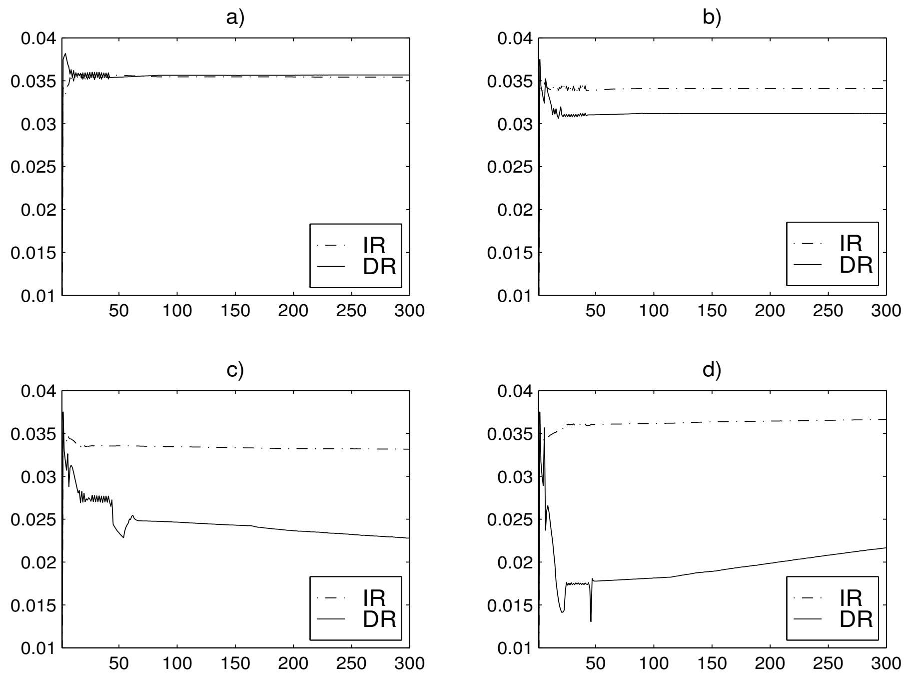

Figure 11: Convergence of return rates in 2010 with varying spillover intensity: a) β=0.0, b) β=0.02, c) β=0.04, d) β=0.05

We run sensitivity analyses in order to study the robustness of the spillover model. The spillover coefficient β is varied within the interval [0, 0.03]. Well-behaved changes occur over a wide range. Figure 9 summarizes the regional welfare gains for different spillover intensities related to the non-trade/non-spillover case. The basic pattern (where DR benefits most from trade) is as already explained above. Additionally, we see that the welfare gains of DR increase most significantly with inreasing spillover intensity. This is linked with increasing capital inflow and temporary negative net foreign assets.

As to IR, Figure 10 shows the sensitivity of the consumption per capita trajectory on the spillover intensity, again demonstrating robustness. However, even with moderate spillover intensity, one of the above mentioned equilibrium conditions cannot be kept anymore. The regional return rates do not converge to a common level. This is not a failure of the present approach, but is due to the external effect, in particular due to the deviation of the export and import prices of investment goods in DR. Whereas with moderate spillover intensity, the return rates converge at least to different levels (Figure 11 a and b), increasing the spillover coefficient further results, first, in a deviation of the return rates, and finally, in non-convergence (Figure 11 c and d). The latter brings the model into a state where robustness gets lost. Thus, one crucial point of further research is to empirically found the reasonable range of the spillover intensity.

7 Conclusions

We presented a modular approach to multi-region modeling which is applicable in an intertemporal optimization framework. We compared the results from this novel approach with those of the well-known Negishi approach. In the economic literature (Negishi, 1972) the welfare optimality of the Negishi approach is proven. This has still to be demonstrated for the modular approach. In a first step, we show the correspondence in the solution of both approaches. This is remarkable in face of the technical differences in the underlying algorithms. In a second step, we carried out some numerical model experiments to validate the mechanics of the multiregional model.

The modular approach gains distinguished importance in modeling spillover effects, since the Negishi approach has limited capabilities to model them. However, the non-convex model structure implied by integrating spillover effects challenges also the modular approach. Moreover, modeling spillovers from foreign investments on a net base can be criticized. On the other hand, despite of deficiencies in the model structure, the fact that there is only a small positive feedback from technology spillover to the technologically leading world region (which in essence loose in relative terms) might give a new argument to the Lucas Paradox (cf. Lucas, 1990, 'Why Doesn't Capital Flow from Rich to Poor Countries?'). It partially explains why real world capital transfers towards the developing regions are not as high as they would be expected from the return rate differentials .

With respect to the climate change problem, the spillover result imply limited incentives to export new energy technologies. Hence spillover effects cannot be considered to make temporary subsidies, that support the market penetration of climate-friendly technologies, dispensable. On the other hand, the aggregation level of the present analysis is not appropriate to make final conclusions about spillover feedback effects on single sectors or even single firms.

References

[1] Bahn, O., Haurie, A., Kypreos, S., Vial, J.-P., 1998. Advanced mathematical programming modeling to assess the benefits from international CO_2 abatement cooperation. Environmenmtal Modeling and Assessment 3, 107-115.

[2] Barro, R.J., Mankiw, N.G., Sala-i-Martin, X., 1995. Capital Mobility in Neoclassical Models of Growth. American Economic Review 1, 103-115.

[3] Blomström, M., Globerman, S., Kokko, A., 1999. The determinants of host country spillovers from foreign direct investments: review and synthesis of the literature. SSE/EFI Working Paper Series in Economics and Finance, No. 339, School of Economics, Stockholm.

[4] Böhringer, C., Rutherford, T.F., 2002. Carbon Abatement and International Spillovers, Environmental and Resource Economics 22, 391-417.

[5] Brooke, A., Kendrick, D., Meeraus, A., 1992. GAMS - A User's Guide, Release 2.25. The Scientific Press, San Francisco.

[6] Debreu, G. (Ed.), 1996. General Equilibrium Theory. Edward Elgar, Cheltenham.

[7] Dixon, P.B., 1975. The Theory of Joint Maximization. North-Holland, Amsterdam.

[8] Edenhofer, O., Bauer, N., Kriegler, E., 2005. The Impact of Technological Change on Climate Protection and Welfare. Ecological Economics, forthcoming.

[9] Hejazi, W., Safarian, A.E., 1999. Trade, Foreign Direct Investment, and R&D Spillovers. Journal of International Bussiness Studies 30, 491-511.

[10] IEA, 2003. World Energy Investment Outlook. International Energy Agency, Paris.

[11] IMF, 1993. Balance of Payment Manual. International Monetary Fund, Washington.

[12] Jaeger, C., Leimbach, M., Carraro, C., Hasselmann, K., Hourcade, J.C., Keeler, A., Klein, R., 2002. Community Integrated Assessment: Modules for Cooperation. Working Paper, FEEM Nota di Lavoro 53.2002, Fondazione Eni Enrico Mattei, Milan.

[13] Janssen, M.J., 1998. Modelling Clobal Change: The Art of Integrated Asessment Modelling. Edward Elgar, Celtenham.

[14] Kemfert, C., 2002. An integrated assessment model of economy-energy-climate-the model WIAGEM. Integrated Assessment 3, 281-299.

[15] Kumar, A., Shubik, M., 2004. Variations on the Theme of Scarf's Counter-Example. Computational Economics 24, 1-19.

[16] Kverndokk, S., Rosendahl, K.E., Ruherford, T.F., 2004. Climate Policies and Induced Technological Change: Which to Choose, the Carrot or the Stick? Environmental and Resource Economics 27, 21-41.

[17] Leimbach, M., Toth, F.L., 2003. Economic Development and Emission Control over the Long Term: The ICLIPS Aggregated Economic Model. Climatic Change 56, 139-165.

[18] Leimbach, M., Jaeger, C., 2004. A modular approach to Integrated Assessment modeling. Environmental Modelling and Assessment 9, 207-220.

[19] Luenberger, D.G., Maxfield, R.R., 1995. Computing Economic Equilibria Using Benefit and Surplus Functions. Computational Economics 8, 47-64.

[20] Manne, A.S., Mendelsohn, M., Richels, R., 1995. MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies. Energy Policy 23, 17-34.

[21] Manne, A.S., Rutherford, T.F., 1994. International Trade, Capital Flows and Sectoral Analysis: Formulation and Solution of Intertemporal Equilibrium Models, in: Cooper, W.W., Whinston, A.B. (Eds.), New Directions in Computational Economics. Kluwer, Dordrecht, pp. 191-205.

[22] Meyer, B., Lutz, C., 2002. Endogenized trade shares in a global model, in: Uno, K. (Ed.), Economy-Energy-Environment Simulation. Kluwer, Dordrecht, pp. 69-80.

[23] Neary, J.P. (Ed.), 1995. International Trade. Edward Elgar, Aldershot.

[24] Negishi, T. 1972. General Equilibrium Theory and International Trade. North-Holland, Amsterdam.

[25] Nordhaus, W.D., Yang, Z., 1996. A Regional Dynamic General-Equilibrium Model of Alternative Climate- Change Strategies. American Economic Review 86, 741-765.

[26] Rotmans, J., van Asselt, M.B.A., 1996. Integrated Assessment: A Growing Child on its Way to Maturity. Climatic Change 34, 327-336.

[27] Schneider, S.H., 1997. Integrated Assessment Modeling of Global Climate Change: Transparent Rational Tool for Policymaking or Opaque Screen Hiding Value-Laden Assumptions? Environmental Modeling and Assessment 2, 229-248.

[28] Shapiro, J.F., 1979. Mathematical Programming: Structures and Algorithms. Wiley, New York.

[29] Singh, M.G., 1980. Dynamical Hierarchical Control. North-Holland, Amsterdam.

[30] Springer, K., 2002. Climate Policy in a Globalizing World: A CGE Model with Capital Mobility and Trade. Springer Verlag, Berlin.

[31] Takii, S., 2004. Productivity Differentials Between Local and Foreign Plants in Indonesian Manufacturing, 1995. World Development 32, 1957-1969.

A Default parameters and initial values

ρ	:	0.03
δ	:	0.08
v	:	1.0
β	:	0.015
ζ	:	0.9
γ	:	0.002
ϵ	:	0.0000001
κ	:	0.008
α_{IR}	:	0.28
α_{DR}	:	0.3
η_{IR}	:	0.67
η_{DR}	:	0.6
ψ_{IR}	:	0.16
ψ_{DR}	:	0.16
ϕ	:	0.9
ω	:	0.01
k_{IR}	:	8 trill. \$US
k_{DR}	:	4 trill. \$US
a_{IR}	:	2.5
a_{DR}	:	1.2
$L_{IR}(1)$	:	0.5 bill. (constant)
$L_{DR}(1)$	:	0.8 bill. (grows by 1%)
rx_{IR}	:	20 EJ
rx_{DR}	:	120 EJ
$fa_{IR,DR}$	:	0.0
$x_{IR,DR,j}$	:	0.0
$pa_j(t)$	:	1.0
$b(t)$	:	0.05