A multi-regional environmental input-output model to quantify embodied material flows

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Osnabrück, Vienna, June 2007

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ABSTRACT

In this paper, we introduce a global, multi-regional, environmental input-output (MRIO) model to fill parts of the existing gaps with regard to data and empirical analysis of material flows. The basic intention is to construct a MRIO model with a monetary core for the year 2000, i.e. through linking IO tables and bilateral trade data (both mainly from official OECD data sources). This monetary core model is extended by a global data set on material inputs in physical units, which is attached to the IO tables as an additional vector. The main objective of this model is to estimate indirect material flows of traded products (measured as their raw material equivalent) and thus being able to calculate and analyse material flow-based indicators in a global perspective, considering comprehensive material balances on the national level, which take into account all up-stream material requirements of imports and exports.

Key words: material flow analysis, international trade, multi-regional input-output analysis, resource productivity

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1 INTRODUCTION[1]

This methodological concept paper is part of work package 5 of the petrE project, ("Resource productivity, environmental tax reform and sustainable growth in Europe", see http://www.psi.org.uk/petre) which deals with global dimensions of sustainable growth in Europe.[2] One of the forecast models applied in petrE is the GINFORS (Global Interindustry Forecasting System; see Lutz et al., 2005, Meyer et al., 2007a, b) model, developed by GWS in Osnabrück. In the GINFORS model, a global data base on material inputs, comprising extraction of biotic (agriculture, forestry, fishery) and abiotic (fossil fuels, metal ores, industrial and construction minerals) natural resources in all countries of the world, is fully integrated into the model system. This integration was first performed in the EU project MOSUS (see www.mosus.net) and will be further developed and improved in the petrE project. As material extraction in different countries is determined by parameters ("drivers") of economic performance and energy use, this extension allows determining all indirect economic effects on resource extraction in the simulation and evaluation of different scenarios (see Giljum et al., 2007).

However, the GINFORS model cannot allocate material extraction to specific economic variables in the country models, such as domestic final consumption or exports without taking into account dynamic economic impacts, which make comparisons to other static approaches impossible. This impedes the assessment of all direct and indirect (up-stream) materials needed for producing specific imported and exported goods. Consequently, comprehensive material flow-based indicators, such as "Total Material Consumption (TMC)" can not be calculated and the resource base of, for example, the European economy cannot be determined in a comprehensive manner, as the trade dimension cannot directly be taken into account.

Although indicators such as TMC have been estimated applying life cycle assessment (LCA) oriented approaches, these studies lack comprehensiveness, as in most cases, data on indirect material flows were only available for raw materials and basic commodities, but not for higher manufactured products. The global environmental input-output model introduced in this paper is designed to fill parts of the existing gaps with regard to data and empirical analysis of material flows. It will be based to a large extent on existing databases, which have been created in the MOSUS project and are now improved and updated in the petrE project. The main purpose of this model is to assess direct and indirect resource extraction necessary in different countries and world regions to produce internationally traded products. Only if this information is available, a comprehensive physical trade balance for each country can be calculated, which allows assessing to what extent an economy is dependent on natural resource inputs from abroad. This knowledge

[1] The paper was also presented at the 16th International Input-Output Conference, Istanbul, Turkey, 2-6 July 2007.

[2] We gratefully acknowledge financial support of the Anglo-German Foundation.

then reveals, whether or not the production and consumption system of a country is actually improving its resource productivity or just substituting resource-intensive domestic production by imports from other world regions.

This paper is structured as follows: In Section 2 we illustrate the importance of integrated physical accounting approaches for analyses of current globalisation processes and increasing international trade on world markets. In Section 3, we describe the methodological framework of the multi-regional material flow model, illustrating in particular, how the different data sets are integrated and inter-linked. Section 4 contains a description of the technical implementation and the calculation algorithms. Shortcomings of the current model and envisaged improvements in the future are outlined in Section 5. Section 6 summarises possible areas of application of the model. In Section 7 we draw the conclusions and provide an outlook on the upcoming work in this part of the petrE project.

2 International Trade and Material Flows

Increasing international trade and deeper integration of different world regions in global markets are one central characteristic of current globalisation processes. Between 1990 and 2005, world trade volumes in products augmented by 5.8% annually, while production only grew by 2.5% per year. Growth in trade was highest for manufactured products (6.4%), followed by agricultural products (3.8%) and fuels and mineral products (3.5%) (WTO, 2006).

The inclusion of natural resource requirements of traded products therefore receives growing importance, when domestic production and consumption patterns are evaluated from the perspective of global sustainable development. In order to assess world-wide environmental consequences related to production and consumption of a specific country or world region (such as Europe), it is necessary to take trade aspects fully into account. In addition to direct imports and exports, all material requirements necessary to produce the traded goods (these are also termed indirect material flows associated with or embodied in imports and exports), have to be considered in the analysis. Only thereby possible shifts of environmental burden associated with extraction and processing of materials can be illustrated, resulting from changing global patterns of production, trade and consumption.

A number of studies examined the distribution of environmental pressures between different world regions due to the economic specialisation in the international division of labour, applying methods of physical accounting and environmental-economic modelling. Several studies found empirical evidence for increasing externalisation of environmental burden by industrialised countries through trade and increasing environmental intensity of exports of non-OECD countries (see, for example, Ahmad and Wyckoff, 2003; Atkinson and Hamilton, 2002; Giljum, 2004; Giljum and Eisenmenger, 2004; Machado et al., 2001; Muradian et al., 2002; Nijdam et al., 2005; Peters et al., 2004; Schütz et al., 2004).

These findings become particularly relevant, as the externalisation of environmental burden through international trade might be an effective strategy for industrialised countries to maintain high environmental quality within their own borders, while externalising the negative environmental consequences of their consumption processes to other parts of the world (see, for example, Ahmad and Wyckoff, 2003; Giljum and Eisenmenger, 2004; Muradian and Martinez-Alier, 2001; Tisdell, 2001; Weisz, 2006).

This global environmental responsibility is increasingly addressed by environmental policy strategies of the European Union and the OECD. One of the overall objectives of the renewed EU Sustainable Development Strategy (EU SDS) is to "actively promote sustainable development worldwide and ensure that the European Union's internal and external policies are consistent with global sustainable development and its international commitments" (European Council, 2006, p. 20). High levels of resource use are regarded as one major obstacle for the realisation of an environmentally sustainable development in Europe and worldwide. The core strategy to achieve a transformation towards more sustainable production and consumption patterns is to realise de-coupling (or de-linking) between economic growth, the use of natural resources and related environmental degradation (European Commission, 2005). Also OECD environmental ministers adopted a recommendation on material flows and resource productivity that is aimed at better integrating resource flow-based indicators in environmental-economic decision making (OECD, 2004). Raising the eco-efficiency of production and consumption activities should allow the same or even more products to be produced while providing long-term quality service with significantly reduced inputs of materials (as well as energy and land) and decreasing disposals of pollutants to nature.

3 INPUT-OUTPUT BASED APPROACHES TO CALCULATE INDIRECT MATERIAL FLOWS

Within the large family of approaches for accounting and modelling material flows (for an overview see Femia and Moll, 2005), methods of environmental input-output analysis (eIOA) play a central role for performing policy-related MFA studies. In particular, eIOA enables opening up the "black box" of economy-wide MFAs and thus providing information on branch and product-specific developments of resource flows and resource productivity. Thereby, environmentally important sectors and products ("hot spots") can be identified and ranked. It further allows analysing implications for natural resource use of structural changes of the economy, as well as of changes in technology, trade, investments and consumption and lifestyles.

The integration of material accounts in physical units into economic input-output models was first explored by Leontief et al. (1982), in order to forecast trends in the use of non-fuel minerals in the US. In several studies for the case of the German economy, monetary IO models were linked with material flow accounts on the economy-wide level to estimate direct and indirect material inputs to satisfy final demand (for example, Moll et al., 2004). IO analysis of material flows within a dynamic IO model was first performed by Lange (1998) for the case of the Indonesian economy. Bailey and colleagues (2004) performed an analysis of material flows within an ecological IO framework to analyse material flow paths and cycles in the industrial system of selected production branches (such as the aluminium industry).

One major advantage of the IO approach compared with LCA-oriented approaches is that it avoids imprecise definitions of system boundaries, as the entire economic system is the scope for the analysis. Furthermore, it allows estimating total resource inputs for all types of products with less effort than the LCA-based method, as only material inputs of those economic sectors have to be assessed, which are extracting raw materials (mainly agriculture, forestry and fisheries for biotic materials, and mining and construction for abiotic materials). However, applying the IO approach also entails disadvantages. These refer in particular to the high level of aggregation of economic sectors in the IO tables, which impede analysis of specific materials (such as single metals or single agricultural products) and lead to problems of inhomogeneities within (theoretically homogeneous) sectors (see chapter 6 for details).

In most studies at the national level carried out so far, imports were either included only as direct material flows (without considering up-stream indirect requirements) or indirect material requirements were estimated applying the assumption of an identical production technology of imported products and the domestic economy (for example, Moll et al., 2004; Weisz, 2006). However, distortions of results can be considerable, if countries show significant differences in technology and economic structure, which is often the case, when trade relations between industrialised and developing countries are investigated (see Haukland, 2004). For these reasons, a multi-regional modelling approach is required (see below).

Three basic eIOA approaches for constructing material flow models can be distinguished (Schoer, 2006). IO-based material flow models can use a monetary IO table (MIOT) extended by additional vectors of natural resource inputs in physical units. eIOA models can be based on a physical IO table (PIOT), reflecting all economic transactions in mass units (Giljum and Hubacek, forthcoming). Or intermediate forms of hybrid IO tables (HIOT) can be applied including both monetary and physical information in the interindustry flow table, with the most material intensive sectors being represented in physical units (see Weisz and Duchin, 2006; Weisz, 2006).

In the model dealing with global material flows introduced in this paper, focus is put on the first approach. The main reasons are that data availability with regard to PIOTs is still very limited and PIOTs have only been compiled for a very small number of countries (see Giljum and Hubacek, forthcoming; Weisz, 2006). Furthermore, the debate on how to apply IO analysis based on PIOT models is still ongoing (Dietzenbacher, 2005).

It is also important to note that, by using a MIOT as the core matrix, one can illustrate the economic *responsibilities*, which agents hold for inducing material extraction. A MIOT approach thus follows economic causalities, whereas a PIOT approach follows physical causalities (see Rodrigues and Giljum, 2005). Allocating material inputs with a MIOT, a PIOT or a hybrid model delivers significantly different results, in particular with regard to the calculation of trade balances (for example, Hubacek and Giljum, 2003). While in a PIOT and a hybrid model, large amounts of raw materials are allocated to the most material intensive sectors of the domestic economy, in particular the construction sector, the MIOT-based model allocates a larger share to those sectors with high values of economic output; therefore, service sectors of the domestic economy receive more environmental responsibility in the MIOT than in the PIOT model. If exports of a country have a higher value per weight ratio than production for final domestic consumption, the MIOT model allocates a higher share of raw material inputs to exports than a PIOT or a hybrid model (see Weisz, 2006). We will come back to this issue in chapter 5.

Hybrid MFA-IO models have also proved a suitable approach to estimate material contents of final products, such as the content of metals in cars (see Nakamura and Nakajima, 2005).

Schoer (2006) presents a mixed approach for calculating indirect material inputs of traded products by dividing all imported goods of a very detailed list of products into either suitable for the IO- or the LCA-based calculation. The author explains that the final goal would be to obtain an IO model, which delivers information concerning material intensities of traded products on a very disaggregated product- and country-specific basis. The author further states that this information is, however, not available yet, and thus applies the assumption of identical production structures for domestic production and imports.

The model introduced in this paper is designed to deliver the missing information, however, with limitations regarding possibilities of disaggregation (see chapter 5 below).

Referring to the example of the German economy, Schoer concludes that the IO approach should be applied as the standard approach, assuming that a certain convergence of production technologies is taking place on global markets. Consequently, the IO approach would be valid for some raw materials, and most semi-finished and finished products. In this case, the average raw material content of the domestic products is assigned to the respective imports. The LCA (or coefficient) approach would need to be applied, if imported products are either not produced in the domestic economy or if products are produced under climatic, geo-physical or other conditions that are considerably different from the domestic conditions.

In order to overcome the shortcomings of a single-country model, in particular with regard to environmental consequences of increasing international trade, a number of studies were published in the past few years, which applied multi-regional IO (MRIO) modelling to assess environmental pressures embodied in international trade.

Wiedmann et al. (2006, p. 111) list several major advantages of the MRIO approach:

MRIO models allow for integration of (monetary) trade flows with environmental databases and permit environmental impacts embedded in trade to be accurately and comprehensively evaluated, as variations in production structures and technologies between different countries and world regions are taken into account

Different IO-based analyses on the international level can be undertaken with a MRIO model (e.g. structural path analysis, production layer composition, quantification of shared responsibilities between producers and consumers of goods – see footnote 1 above). With a MRIO model, direct, indirect and induced effects of international trade can be captured.

Two basic types of MRIOs can be distinguished (see Peters and Hertwich, 2006; Wiedmann et al, forthcoming):

(1) *Linked single-region models*, where national IO tables are exogenously linked with bilateral trade data for different countries or regions. In this case it is assumed that the domestic economy trades with all other regions, but the other regions do not trade amongst each other. This significantly reduces data requirements without introducing significant errors. Lenzen et al. (2004) illustrated that the effects not captured with such a model are of the magnitude of 1-4%. However, if environmental effects shall be analysed in parallel for a larger number of countries with the same MRIO including all indirect effects, a true multi-regional IO model is needed.

(2) *True multi-regional IO models* endogenously combine domestic IO tables with import matrices from a set of different countries and world regions into one large matrix of technical coefficients and are therefore able to capture international production chains among all trading partners as well as feedback loops. True multi-regional IO models can then further be specified into two types. In the most comprehensive case, trade matrices illustrate industry and region of the production country as well as industry and region of the consuming country. Another type includes trade matrices, which only illustrate the origin and industry of the production country, but do not deliver information on the receiving industries in the importing country (Wixted et al., 2006).

A number of MRIO models of the second type have been presented in the literature, differing significantly with regard to the number of countries/regions and sectors disaggregated in the model. Wiedmann et al. (2006) and Wiedmann et al. (forthcoming) provide extensive reviews of MRIO models to assess indirect environmental effects of trade. A comprehensive review of models is therefore not carried out in this paper.

It should only be mentioned that the most comprehensive true MRIO model presented so far is the model used for analysis of embodied CO_2 emissions of OECD countries (Ahmad, 2003; Ahmad and Wyckoff, 2003; see also Yamano et al., 2006, for an updated study). Calculations are carried out for 24 countries (responsible for 80% of global CO_2

emissions) with IO tables of 17 sectors, linked by bilateral trade data for 42 countries and world regions and CO_2 emissions data from the International Energy Agency. As this model uses the same core data set of IO tables and bilateral trade data as the model introduced in this paper, a number of methodological issues regarding the construction of this OECD model are of high relevance for our MFA-IO model. We will come back to these issues in the next chapter.

4 CONSTRUCTING A GLOBAL MUTLT-REGIONAL MFA-IO MODEL

In the following, we provide a detailed description of the used data sources and the methods to link the various data sets. The basic intention is to construct a MRIO model with a monetary core for the year 2000, i.e. through linking OECD IO tables and OECD bilateral trade data (BTD). This monetary core model is extended by a global data set on material inputs in physical units, which is attached to the IO tables as an additional vector.

The main objective of this model is to estimate indirect raw material inputs of traded products and thus being able to calculate comprehensive material flow-based indicators, considering comprehensive material balances on the national level, which take into account all up-stream material requirements of imports and exports. The model for assessing indirect raw material inputs embodied in international trade and for calculating comprehensive MFA indicators as presented below follows the principles of material flow accounting in an international IO framework (Rodrigues and Giljum, 2005, for an illustrative two country example see Giljum et al. 2007).

4.1 DATA SOURCES

In this section, we describe the data sources for the three main data sets required for setting up the model: input-output tables, trade data and material extraction data.

Input-output tables

Many national statistical offices publish IO-tables on a more or less regular basis. However, as these tables differ in data quality, sectoral disaggregation, currencies, price concept and base years, they are not suitable for constructing a consistent multi-regional IO model system. In contrast the construction of a global MFA-IO-model requires a harmonised dataset (same classifications) which covers as many countries as possible disaggregated in a maximum number of sectors. Preferable this dataset of IO tables is provided by one single source, to ensure that the same assumptions are used in data harmonisation procedures.

International datasets of harmonized input-output and trade data are presented by GTAP (Global Trade Analysis Project) and the OECD. GTAP is the most extensive database currently available, comprising input-output data and other relevant data for constructing a multi-regional IO model for 87 countries or regions and 57 sectors. However, the use of this large dataset is postponed here due to possibly inconsistent and non-transparent data harmonisation. Further more several of the undertaken data manipulations may have been required solely by the underlying CGE-model. Additionally, as data are submitted voluntary from GTAP users (for free access to the GTAP dataset), the dataset sometimes includes unofficial and not always the most recent data. The possible application of this dataset, which has a strong focus on agriculture, will be examined in the course of the project.

The OECD is another supplier of internationally harmonised IO tables, which – to our evaluation – presents a more reliable and more transparent dataset, as harmonization is undertaken by only one institution. The latest (2006) edition of IO tables published by the OECD includes 28 OECD countries (except Island and Luxemburg) and 9 non-OECD countries (Argentina, Brazil, China, India, Indonesia, Israel, Russia, Singapore and Taiwan) in 48 harmonised sectors. In the following the dataset and its compilation is described in more detail.

The tables of the 2006 edition are based around the year 2000 (Yamano and Ahmad 2006). The underlying data are submitted to the OECD by national statistical offices, which were asked to provide data in accordance with the ISIC Rev. 3 harmonised industry structure. Furthermore, national statistical offices could submit any relevant data (e.g. supply-use tables) at the most detailed and practicable level in order to maximise compliance and to minimise costs. Against this background most countries submitted data using national industrial classification systems. The consideration of supply-use tables basically stem from the fact that IO tables are not compiled by all national statistical offices, but in this case they produce supply-use-tables. By using standard assumptions these can easily be converted into symmetric IO tables.

As industry classification of the database is based on the ISIC Rev. 3 system, IO tables are consistent with other OECD databases such as the STAN Bilateral Trade Database (BTD). Industry data can also be linked to IEA's energy balances. This enhances the quality of the whole database as we use BTD data to capture international trade flows (see below).

In its latest edition of IO tables, the OECD extended the number of industries to 48. Against the background of analysing material flows related with international trade flows this was very desirable as some material and resource intensive sectors were separated. However, the dataset still aggregates some industries with diverging total material requirements.

Furthermore, the latest OECD IO dataset contains shortcomings due to imperfect concordance between national data and ISIC Rev. 3. In some countries a few industries are aggregated into other sectors. However, these inaccuracies are also described explicitly (see Yamano and Ahmad, 2006).

Even though the OECD dataset comprises 3 years as a maximum for a country and not all IO tables of an edition refer to the same year, these shortcoming of the database is not of relevance for this type of analysis, as it aims to capture all material requirements of final demand of a certain industry at a fixed point in time (the year 2000). Furthermore it is reasonable to assume that production technologies and relative prices (IO coefficients) remain constant for short periods of time (Ahmad and Wyckoff, 2003).

Besides the IO tables representing total interindustry requirements and total final demand in million US$, the OECD provides two sub-tables of the overall IO table for each country – one shows the interindustry requirements on domestic production and final demand produced and consumed domestically in the respective country, while the other represents interindustry and final demand requirements on foreign production (import matrix).

At the moment our model comprises 52 countries and regions, with the OECD dataset providing IO tables for 35 of these countries and regions. For the remaining countries and regions IO tables are derived under the assumption that the country or region under consideration holds the same production technology as a neighbouring country or a country with a similar economic structure. The impacts of this assumption will be analysed in sensitivity analyses in further steps of the project.

Table 1 lists the chosen assumptions. To close the model on a global scale we assume in a first step that the rest of the world has the same production structure as Argentina. In future analysis, we may follow Ahmad and Wyckoff (2003) who used the USA and China as lower and upper bounds for the (IO) production technology for the countries forming rest of the world. Another possible improvement might be the explicit calculation of material coefficients of all countries without original IO information from material extraction data.

Table 1: Estimating IO-tables for countries were no IO data are available

Country	Structure of
Chile	Brazil
Cyprus	Greece
Estonia	Poland
Hong Kong	Korea
Latvia	Poland
Lithuania	Poland
Luxemburg	Belgium
Malta	Greece
Mexico	Brazil
OPEC	Indonesia
Philipines	Korea
Singapore	Korea
Slovenia	Slovak Republic
South Africa	Brazil
Switzerland	Germany
Thailand	Korea
Rest of the world	Argentinia

In the course of the petrE project, these constructed IO tables can later be replaced by IO tables provided by national statistical offices. Against this background the generated database may serve as a starting point, in a later version the database could be extended to countries which are not yet included in the model (see also section 5 below).

Bilateral trade data

Data on international trade, which's modelling is the core element of a model calculating all direct and indirect material requirements of certain countries, should cover a maximum number of industries in a classification consistent with that of the applied IO tables. As mentioned above the bilateral trade data (BTD) of OECD are based on the ISIC Rev. 3 likewise IO tables provided by OECD. In total, BTD comprises imports and exports of goods for each OECD country broken down by 61 trading partners and 25 industries. The 2006 version covers the years 1988 to 2004. The dataset is derived from OECD's International Trade by Commodities Statistics (ITCS). For compiling the BTD dataset, ITCS data were converted from product classification to an industry classification using a standard conversion key (OECD, 2006).

However, the BTD dataset captures only OECD trade with the rest of the world, while trade between two non-OECD countries is not recorded. Thus, some of the main material consuming countries such as China and India as well as their trade flows with major material extracting countries such as Brazil, South Africa and Russia are not included in the dataset. As these trade flows are crucial for calculations of direct and indirect material flows both on a global scale and on a country level and in order to close the trade model on the global level, the database is completed by UN COMTRADE data and country by country trade data from the Direction of Trade Statistics from the IMF (2006 edition). If no other sector information on bilateral trade flows has been available, the export structure of countries to the OECD from the BTD data has applied to exports to non-OECD countries.

Import and export data normally do not match due to differing classifications and price calculations (e.g. cif versus fob). For our model, we prefer import data to reach global identity of exports and imports (which logically has to be the case, but does mostly not hold for international trade datasets), as importers normally have higher interest to report comprehensively. By consolidating these three datasets, trade matrices for 52 countries/regions are established. Trade matrices *TM* show for every good *k* all trade flows between exporting countries and importing countries. Additionally a trade matrix for a service aggregate was calculated based on OECD data which were completed by IMF's information on balances of payments. In the first version, we focus on material embodied in manufactured goods. In later versions of the model the trade dataset could be further completed, in order to disaggregate more countries and/or industries, such as service sectors.

Material input data

With regard to material input data, a large and increasing number of material flow studies are available from national and international statistical offices, environmental agencies and research institutions (see above). The first global dataset in a time series of 1980 to 2002 was recently compiled in the framework of the "MOSUS" (Modelling opportunities and limits for restructuring Europe towards sustainability) project, funded by the European Commission (see Behrens et al., forthcoming) and is presented by SERI on a separate website (www.materialflows.net).

In the MOSUS project, resource extraction data, disaggregated by more than 200 raw material categories, has been compiled for 188 countries in a time series from 1980 to 2002, taking into account changes in frontiers due to splitting up of former USSR, Czechoslovakia, Yugoslavia and PDR of Ethiopia, as well as reunification of Germany in 1990.

The compilation of material input data followed the nomenclature and categorisation of materials listed in the handbook for economy-wide material flow accounting published by the Statistical Office of the European Union (EUROSTAT, 2001) and covers the following aggregated material groups (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

In addition to used material extraction, i.e. materials that enter the economic system for further processing, the database also includes estimates on unused extraction, i.e. overburden from mining activities and unused residuals of biomass extraction. The model calculations described below can therefore be performed either only with used material extraction or with total (used plus unused) extraction, in order to calculate different MFA indicators.

The international database on natural resource extraction was developed mainly from international statistics available from the International Energy Agency (IEA), the US Energy Information Administration (US EIA), the Food and Agricultural Organisation of the United Nations (FAO), the United Nations Industrial Commodity Statistics, United States Geological Survey (USGS), the World Mining Congress, and the German Federal Institute for Geosciences and Natural Resources (BGR) (see Giljum et al., 2004 for details).

Table 2: Aggregated material categories in the MOSUS MFA database

Fossil fuels	Coal	
	Oil	
	Gas	
	Other fossil fuels	
Minerals	Ores	Iron ores
		Non-ferrous metal ores
	Industrial minerals	
	Construction minerals	
Biomass	Food	
	Feed	By-products of harvest
		Grazing
		Fodder
	Animals	
	Forestry	
	Other biomass	

In the course of the petrE project, the MOSUS MFA database is being updated and improved. For example, former estimations of construction materials, which are in general poorly covered in international statistics, have been replaced or complemented by data from EUROSTAT (for the EU-15 countries) and USGS (for the US, Mexico and New Zealand).

4.2 Allocation of imports to industries in the IO table

In contrast to an ideal model framework, BTD and IO data are less comprehensive. BTD comprises overall trade flows, country by country and sector by sector, but does not distinguish between intermediate imports and imports of finished goods. IO data distinguishes intermediate inputs in domestic requirements and imported requirements, but does not provide the country origin of trade flows.

Alongside with domestic interindustry requirements [A^{AA}] data on A^{KC} and y^{KC} are required (where c and k are countries indices with c = A, B, C and k = A, B; C and c≠k). Data on interindustry requirements from country k to country c [A^{KC}] are neither provided by OECD BTD nor by OECD IOT data. But the latter splits IO tables into two sub-tables: one shows the interindustry requirements on domestic production in country c (A^{CC}), while the other represents the domestic interindustry requirements on foreign production ${}^{m}A^{C}$ as well as the imported foreign production directed to domestic final demand ${}^{m}y^{C}$:

$$ {}^{m}A^{C} = \sum_{c \neq k} A^{KC} \tag{1} $$

and $$ {}^{m}y^{C} = \sum_{c \neq k} y^{KC} \tag{2} $$

Assuming the same trade shares for intermediate imports ${}^{m}A^{C}$ and imports of finished goods ${}^{m}y^{C}$ provided by OECD BTD, it is possible to calculate the intermediate and final demand imports for each industry on a country by country basis:

$$ A^{KC} = \hat{s}^{m} \cdot A^{C} \tag{3} $$

$$ Y^{KC} = \hat{s}^{m} \cdot y^{C} \tag{4} $$

with $$ \{\hat{s}\}_j = \{m^{KC}\}_j \Big/ \left\{\sum_k m^{KC}\right\}_j \tag{5} $$

where $\{m^{KC}\}_j$ is the total flow of imports of product j of country c from country k (Meyer et al., 2007b, Peters and Hertwich 2006). The trade share matrix ŝ represents for every product j the share of every country kin the imports of country c.

4.3 ALLOCATION OF RAW MATERIAL EXTRACTION TO INDUSTRIES IN THE IO TABLE

One key decision concerns the allocation of the material extraction data to economic sectors in the IO tables, in order to calculate the material intensity coefficients. In contrast to e.g. emissions of greenhouse gases, which origin practically in all economic sectors (see Ahmad and Wyckoff, 2003), raw materials are only extracted by a very limited number of industries. Therefore, the very detailed material input data, covering more than 200 raw materials, must be aggregated, in order to link material input data to the sectors available in the IO tables. An intuitive solution would be to allocate the extracted raw materials to the corresponding extraction sectors, for example, agricultural products to the agriculture sector, forestry products to the forestry sector and fisheries to the fishery sector. However, aggregation of industries in the OECD IO tables precludes this procedure, as e.g. only one sector for biomass extraction is considered.

Compared with previous editions, the OECD 2006 edition of IO tables separated some of the material extraction sectors, for example, mining and quarrying of fossil fuels from all other minerals. However, if material extraction would strictly be allocated to the primary extracting sectors, only three aggregated material categories could be separated: biomass, fossil fuels and minerals. This level of disaggregation is not satisfying, as it would imply that, for example, the same mix of mineral raw materials would be delivered to industries of processing of metal ores, production of non-metallic mineral products as well as construction. It is obvious that such an allocation would produce significant errors with regard to the composition of material use in different sectors. Furthermore, a more detailed breakdown of materials is required, in order to link material flows closer to environmental problems caused by certain flows and to investigate the economic driving forces inducing extraction and use of specific materials (see Schoer, 2006).

Therefore, we develop an approach, which allocates specific raw material inputs to those industries, which serve as the main recipient of raw material inputs at the first stage of further processing (see Table 3). As Schoer (2006) points out a miss-assignment in the first steps of production will lead to larger errors than a biased allocation at later production stages, as the processing of materials in the first production steps follows rather specific processes with particular input relations. Whereas in later production stages, the original raw materials are mixed into semi-finished and finished products and distributed over a much larger number of sectors.

Table 3: Allocation of MFA categories to economic sectors in the IO table

MFA category	Allocated to sector of IO table (number of sector in brackets)
Agriculture, grazing and fish	Food products (4)
Forestry	Wood and wood products (6) and Pulp and paper products (7)
Fibre crops	Textiles (5)
Coal and oil	Coke and refined petroleum products (8)
Natural gas	Manufacture of gas (27)
Iron ores	Iron and steel (13)
Other metal ores	Non-ferrous metals (14)
Industrial minerals	Non-metallic mineral products (12)
Construction minerals	Construction (30)

The respective material input coefficient thus is not calculated by dividing the amount of extracted material by total output of the extraction sector, but by fix IO relations at the first stage of processing. For example in the case of mineral products, several sectors (see Table 3) receive raw material inputs from the mining and quarrying sector. We can further disaggregate the three major material groups of biomass, fossil fuels and minerals into the categories given in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Through this initial disaggregated allocation, specific compositions of material inputs to certain industries at further stages of processing can be captured by the model. If more than one sector serves as recipient at the first stage of processing (as is the case with wood), we divide material extraction according to the shares of (monetary) deliveries from the extraction sector to the processing sector (in the example of wood: deliveries from sector 1, Agriculture, to sector 6 and 7), assuming that the weight/value ratio is equal for deliveries to different sectors.

5 Technical implementation of the model calculations

The approach shortly described in section 3 requires the construction of an IO table that comprises all upstream requirements between and within the considered countries. Besides problems of constructing such a “super-matrix”, which is very large and complex due to the number of considered countries and industries, additionally technical problems during data processing have to be solved, for example storage and inversion of such a large matrix.

Against this background direct and indirect material embodied in traded goods are calculated in an iterative procedure which is based on the approach introduced by Ahmad and Wyckoff (2003).

For identifying material inputs embodied in international trade flows we calculate total direct and indirect material embodied within domestically consumed products whether imported or produced domestically. This requires a distinction between four categories of (product) use (for a similar classification system, see Rodrigues and Giljum, 2005):

1. Manufactured goods and services produced and consumed domestically. This category is termed “Domestic Final Demand (DFD)“
2. Domestically produced manufactured goods and services exported to other countries. We denote this category as “Domestic Production of Exports (DEX)“
3. Imported manufactured goods and services consumed domestically. This category is termed “Imported Final Demand (IFD)“
4. Imported manufactured goods and services exported to other countries again. We denote this category as “Imported Production of Exports (IEX)“

This distinction allows calculating some of the standard material flow indicators described earlier in this paper. If the vector of material inputs in each of the countries / world regions comprises total (used plus unused) material extraction, we can calculate “Total Material Requirement (TMR)” by adding up all four categories:

$$TMR = M_m^{DFD} + M_m^{DEX} + M_m^{IFD} + M_m^{IEX} \quad (6)$$

By subtracting from TMR those materials (of domestic and foreign origin), which are allocated to exports of the respective country, we arrive at “Total Material Consumption (TMC)”:

$$TMC = \left(M_m^{DFD} + M_m^{IFD}\right) - \left(M_m^{DEX} + M_m^{IEX}\right) \quad (7)$$

If the vector of domestic material extraction only comprises used extraction, than the latter calculation delivers ”Raw Material Consumption (RMC)“.

We can also calculate a comprehensive physical trade balance (PTB) by subtracting the exported categories from the imported:

$$PTB = M_m^{IFD} - \left(M_m^{DEX} + M_m^{IEX}\right) \tag{8}$$

5.1 Linking IO tables with trade data

Using IO-analysis domestic demand produced domestically (*DFD*) is equal to:

$$DFD = (I - A)^{-1} \cdot FD \tag{9}$$

where A is a matrix of domestic input coefficients with components a_{ij} defined as the ratio of factor inputs from domestic industry i to the output of industry j. A comprises 48 industries whereof 25 are manufacturing industries. I is the unit matrix and FD is a vector of domestic final demand.

Additionally, domestic demand can be met by foreign production. This imported final demand (*IFD*) can on the one hand serve domestic interindustry requirements and on the other hand imports can be directly purchased as domestic final demand FDI.

$$IFD = (I - B)^{-1} \cdot FD + FDI \tag{10}$$

where B is the input coefficient matrix for imports (import matrix), with components b_{ij} that represent the ratio of imports from foreign industry i to the (domestic) output of industry j (see section 4.2). At the same time parts of foreign demand is satisfied by domestic production. Similarly to equation (9) demand for exports goods produced domestically DEX can be shown to be equal to:

$$DEX = (I - A)^{-1} \cdot EX \tag{11}$$

EX is a export vector that is defined as foreign requirements on domestic production. Adding EX and FD yields the total domestic final demand. However, parts of export demand again, are served by imports

$$IEX = (I - B)^{-1} \cdot EX + AEX \tag{12}$$

IEX in turn can be separated into goods that are produced in the exporting country and into those that already have been imported to the exporting country AEX. To capture international trade flows (and material embodied in these flows), domestically required imports IFD and IEX are divided up for every industry to the delivering countries k according to their import shares S_k:

$$IFD_k = S_k \cdot IFD \tag{13}$$

$$IEX_k = S_k \cdot IEX \tag{14}$$

Adding IEX and IFD yields total domestically required imports.

5.2 INTEGRATION OF MATERIAL INPUT DATA INTO THE MODEL SYSTEM

Multiplying material requirements to monetary equations (9) to (12) yields material embodied in the four categories of product use for every country c. ${}^{m}R_c$ is a matrix representing the ratio of material embodied per monetary value of domestic output by industry in country c for all material categories (see Table 3).

$$MDD = {}^{m}R_c \cdot DFD \tag{15}$$

$$MID = \sum_k \left({}^{m}R_k \cdot IFD \right) \tag{16}$$

$$MDE = {}^{m}R_c \cdot DEX \tag{17}$$

$$MIE = \sum_k \left({}^{m}R_k \cdot IEX \right) \tag{18}$$

Adding up MDD and MID denotes total domestic consumption of material, whereas material embodied in domestic exports can be shown to be equal to Z^C, which denotes the sum of material extracted domestically and embodied within manufactured goods and services exported from country c (category 2) and material extracted by other countries k and embodied within manufactured goods and services exported to country c and exported to other countries k again (category 4):

$$Z_C = MDE_C + MIE_C = {}^{m}R_c \cdot DEX + \sum_k \left({}^{m}R_k \cdot IEX \right) \tag{19}$$

Equations (19) for the different countries k are interdependent. The material embodied in a countries export depends on the material embodied in all other countries exports. The calculation of ${}^{m}R_k$ therefore involves an iterative process. We follow Ahmad and Wyckoff (2003) and initially assume that a country produces its exports completely domestically. Thus, formula (18) is equal to zero for all countries at the beginning of the process. Then we solve equation (17) for each country, the results are then used in equations (15), (16), and (18). This procedure is repeated for all countries as long as ${}^{m}R_k$ differs between two iterations for any of the countries k.

6 SHORTCOMINGS AND FUTURE IMPROVEMENTS OF THE MODEL

The model outlined in the previous chapters will be the most comprehensive model for the calculation of indirect material flows introduced so far. However, a number of shortcomings can be identified, which will be the focus for extensions and improvements in the future.

Constructing a hybrid MFA-IO model

Several IO-based MFA studies (for example, Weisz and Duchin, 2006) highlighted the differences in results for indirect material flows, when different types of IO models are applied (see Section 3 for details). As described above, a model of the type introduced in this paper with an economic core of monetary IO tables and monetary trade data applies *economic causalities* for allocating raw material extraction to different categories of (domestic and foreign) final demand.

If the *physical causalities* shall be investigated, for example, in order to assess the actual contents of metals in final products (see Nakamura and Nakajima, 2005), the use of additional physical information is indispensable, in order to construct hybrid IO tables (HIOTs) containing both monetary and physical units. This is in particular the case, as the underlying assumption of MIOT-based models that the aggregated monetary output structures adequately represent the physical use structures of different materials, does in general not hold true, in particular with regard to the first steps of the production chain (Schoer, 2006).

Schoer (2006) distinguishes two types of hybrid IO MFA models. (1) Simple HIOTs, where the first stages of interindustry deliveries, i.e. from the extraction sector to the sector processing raw materials, are represented in physical units. Already in this simple case, specific HIOTs should be constructed for each type of raw material, in order to reflect the specific physical supply and use structure of certain materials for the first step of the production chain. (2) In the expanded HIOT model, the particular physical use structures of certain raw materials are also integrated for the second (or even more) steps of the production chain, requiring an even more detailed disaggregation of the relevant production processes.

Physical information can in the best case be extracted directly from physical IO tables (PIOTs), following the same classification as the monetary table (see Weisz and Duchin, 2005; Weisz, 2006 for examples using the Danish MIOT and PIOT). However, as PIOTs only exist for a very limited number of countries (see Giljum and Hubacek, forthcoming), Schoer (2006) remarks that required information on the physical use structures could also be approximated by extracting detailed information from the supply and use tables underlying the monetary IO table. For example, in the German case, the use table includes information for about 1500 products.

Improvements concerning IO tables

With regard to the use of IO tables in the model, several improvements shall be undertaken in the future.

(1) The first concerns the number of sectors, which are disaggregated in the IO tables.

Currently, only a small number of sectors of high relevance for material extraction and processing is separated in the OECD tables. For example, there is only one sector for the production of biomass (agriculture, forestry, fishery) and only two sectors for mining and quarrying (of energy and non-energy raw materials). If a larger number of flows of specific raw materials shall be studied (e.g. on the level of single metals, such as copper or zinc), existing aggregated sectors must be split into sub-sectors through making use of more detailed data in the supply and use tables underlying the IO tables or of additional detailed sector statistics. A more detailed resolution of IO tables is a prerequisite to provide a detailed analysis of the environmental impacts related to sectors or products (see, for example, Huppes et al., 2006; Tukker et al., 2005).

(2) Improvement is also required with regard to the procedure of approximating the production structure of countries, where so far no IO table is available, by the structure of a neighbouring country. With this regard, we intend to replace the assumed IO tables by real tables from national sources, either already published or expected to be published in the coming years.

(3) In particular for the calculation of material flow-based indicators, a number of countries in Africa, Asia and Latin America, which have high levels of material extraction and export, are currently aggregated in the category of “Rest of the World”. These include countries such as Peru or Ukraine. In order to avoid distortions of results due to this geographical aggregation and in order to be able to calculate material flow-based indicators for a larger number of emerging and developing economies, the integration of additional country models is a necessary future step.

Integrating additional trade data

Trade relations between two countries in the model are currently represented only by a total of 25 groups of manufactured products according to the industry classification of OECD BTD and IO tables databases. Additionally we calculate trade relations for an aggregate of service products. In order to enable more detailed analysis of specific trade flows with particular relevance for material flow-based indicators, the number of categories in the trade models must be increased. This is particularly important for raw materials (of both renewable and non-renewable sources) and semi-processed products (such as basic metal products).

Possible data sources for such extensions are the UN COMTRADE database, which contains very detailed trade on goods level.

Advantages of a more detailed representation of international trade, however, can only be fully exploited, if also in the IO tables, further disaggregation is undertaken (see above).

7 AREAS OF APPLICATION

A global environmental IO model as described in the chapters above can be applied to investigate a number of issues of key relevance for the transformation towards global sustainable resource use and increased resource productivity.

1. Calculation of indirect („embodied“) material requirements: For all countries in the global IO-MFA model, indirect material requirements can be calculated for both imports and exports. The level of disaggregation is determined by the classification of sectors and product groups, which are defined in the available IO tables and trade data sets (see above). In a first step, the model will be applied to cover the category of material use. In subsequent steps, other environmental extensions (energy, land use, water consumption, emissions, etc.) shall be integrated into this model.

With regard to the material dimension, the calculated indirect material flows reflect the extraction of all raw materials (measured as „raw material equivalents“, see above) necessary along the whole (international) production chain in order to produce different products and deliver them to the border of the analysed country.

2. Analysis of indirect („embodied“) material requirements: Results obtained in step 1 can then be analysed according to (a) different product groups and industries/sectors, (b) countries of origin (imports) and destination (exports) and (c) different material categories.

Separate analyses of single material categories will be possible, considering the limitations posed by the level of aggregation in the IO tables and trade data (see chapter 4). These separated calculations are of relevance, in order to better link the quantitative information on indirect material flows to specific environmental impacts related to their use (e.g. implications for climate change due to fossil fuel use; implications for land use and land cover changes due to biomass extraction, etc.).

In the final version of the model it shall be possible to calculate material intensities of specific trade flows within the monetary trade matrices and thus provide insights into the distribution of material intensities along international production chains. As a first step, however, focus is put on solving the entire trade-environment model, including the allocation of material requirements to domestic final demand in the IO tables of all countries.

3. Calculation of comprehensive material flow-based indicators: Due to a complete balancing of material use of a country (including domestic extraction on the one hand and imports, exports and related indirect material requirements on the other hand), comprehensive material flow-based indicators on the national level can be calculated. These include Total Material Requirement (TMR) as an input indicator and Raw Material Consumption (RMC) and Total Material Consumption (TMC) as consumption indicators (see above).

Also comprehensive indicators of resource productivity can be calculated by combining e.g. TMC or RMC with GDP data. Thereby, resource productivity of a country is not only expressed related to direct material flows, but including all up-stream material requirements necessary to produce imported (and exported) products.

4. Analysis of international production chains and structural paths: The international model will allow analysing specific international production chains with particular importance for the country of interest. This type of analysis can illustrate the number of processing steps, their geographical distribution and estimations of the transport intensity. The application of the method of „structural path analysis“ (see, for example, Peters and Hertwich, 2006) allows determining those chains of interindustry deliveries, which contribute most to material consumption of a country.

5. Historical analyses of the interrelations between economic growth, structural changes, international trade and the distribution of environmental pressures in different world regions can be performed. Thereby, empirical background for debates such as the pollution haven hypothesis and the Environmental Kuznets Curve (EKC) can be provided. Furthermore, analyses of de-coupling of economic growth from resource use can be undertaken, considering indirect environmental effects related to international trade.

6. Analyzing of future scenarios: Data on future developments of international trade, structural change and material extraction generated with forecasting and simulations models (such as GINFORS, see Meyer et al., 2007b) can be fed back into this multi-regional IO model. Thereby, the simulated scenarios can be evaluated with regard to future global distribution of environmental pressures.

8 CONCLUSIONS

In this methodological concept paper we introduced a multi-regional input-output model extended by material input data. This model is designed to fill some of the existing data gaps with regard to indirect material flows associated with internationally traded products. The model will allow to calculate comprehensive material balances on the national (and European) level and to derive indicators of material consumption and resource productivity, considering direct and indirect environmental responsibilities of European imports and exports in terms of material flows.

In the next task in this work package, we will first turn to the preparation of the data sets. This includes checking the latest set of OECD IO tables with regard to missing data, for example, due to the aggregation of two sectors in only one row and column. Later in the project, the defined assumptions for those countries, for which no IO table exists so far, will be tested and, if available, "place-holder" IO tables will be replaced by published IO tables from national sources. The work also involves assessment of the coverage of bilateral trade, in particular filling of data gaps in the OECD BTD data set by UN COMTRADE and IMF trade data. Finally, material extraction data for the year 2000 will be aggregated into the categories as described above.

Following the preparation of the data sets, they will be imported into the software programme performing the calculations as described above. Calculations of the different material inputs induced by domestic demand and exports in the different countries will be undertaken following the algorithms explained in section 4.

First results with regard to the calculation of comprehensive physical trade balances as well as indicators of material consumption and resource productivity will be available by September 2007.

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