

Quantifying indirect material flows of traded products with a multi-regional environmental input-output model

A methodological concept paper

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Abstract

With annual growth rates of international trade constantly above growth of production in the world economy, the inclusion of material requirements of traded products receives growing importance, when domestic production and consumption patterns are evaluated from the perspective of global sustainable development. 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. Although material flow-based indicators including indirect material flows 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. 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, i.e. through linking IO tables and bilateral trade data. 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. We first provide a description of the concept of indirect material flows and summarise different approaches for their calculation. The methodological framework of the MRIO-MFA model is introduced, illustrating in particular the structure of the different data sets and how they are integrated. We describe how the technical implementation and the calculation algorithms of the model and outline shortcomings of the current model and envisaged improvements in the future.

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

1 Introduction

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 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).

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 decoupling (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.

Although comprehensive material flow-based indicators have been estimated for some countries 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.¹

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 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 provide a comprehensive description of the concept of indirect material flows and summarise different approaches for their calculation. 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 and which calculation algorithms will be applied to calculate different material flow-based indicators. Shortcomings of the current model and envisaged improvements in the future are outlined in Section 4. Section 5 contains the conclusions.

2 The calculation of indirect material flows

Material flow accounting and analysis (MFA) is receiving growing importance as a tool to illustrate environmental pressures induced by production and consumption activities of a country or world region. The basic concept underlying the MFA approach is a simple model of the interrelation between the economy and the environment, in which the economy is an embedded subsystem of the environment and – similar to living beings – dependent on a constant throughput of materials and energy. A full material balance on the national level reveals the composition of the physical metabolism of an economy and depicts domestic material extraction, imports and exports in physical units, the physical growth of the economy's infrastructure, and the amount of materials released back to nature (EUROSTAT, 2001). Material inputs to the economic system are either (a) accumulated within the socio-economic system (net addition to stock, such as infrastructure and durable consumer goods); (b) consumed domestically within the accounting period (in most cases one year) and thus are released back to nature as waste and emissions; or (c) exported to other

¹ The model is constructed as part of the petrE project ("Resource productivity, environmental tax reform and sustainable growth in Europe", see <http://www.psi.org.uk/petre>), funded by the Anglo German Foundation.

economies.

Attached to imports and exports are the so-called “indirect flows” (or embodied material requirements), which indicate all (up-stream) materials that were required for manufacturing and delivering the product to the border. Indirect flows comprise both used and unused components (see below for a detailed description). Indirect flows associated to imports do not actually enter the national economy – they remain in the country of origin; therefore they have also been termed ‘hidden flows’ (Moll and Bringezu, 2005).

A large number of resource-use indicators can be derived from economy-wide material flow accounts. These indicators can be grouped into input, output, consumption and trade indicators. The most commonly used indicators for describing aggregated resource use of a country comprise direct material flows and thus exclude unused domestic extraction and indirect flows of trade (see, for example, Moll and Bringezu, 2005; Weisz et al., 2006). These indicators are “Direct Material Input (DMI)”, which equals the sum of domestic extraction and imports and “Domestic Material Consumption (DMC)”, which is calculated by subtracting exports from DMI. DMC thus is the closest equivalent to aggregate income in the conventional System of National Accounts.

There are two indicators considering indirect material flows, which are most commonly referred to in theoretical and empirical MFA studies. “Total Material Requirement (TMR)” is an input indicator, which takes into account all primary materials required by a national economy in order to perform its production. In addition to DMI, TMR includes also unused material, i.e. material which is extracted but not further processed in the production system (e.g. mining waste). TMR also includes upstream material flows of imports (indirect flows associated to imports) which were necessary to produce the respective import good. “Total Material Consumption (TMC)” equals TMR minus exports (including indirect flows associated to exports). Hence, TMC considers all primary materials which are associated to the (intermediate and final) consumption of a national economy. Another proposed consumption indicator including indirect material flows is “Raw Material Consumption (RMC)”, which only comprises used materials and equals TMC minus unused domestic extraction, both within the borders of the analysed country and abroad. This concept is introduced in order to allow separate use of data on used material extraction, which is in most cases of significantly higher quality than those referring to unused extraction (for example, Weisz, 2006). Finally, an indicator suggested to account for total material inputs of production is “Total Material Production (TMP)”, which, in contrast to TMC, does not allocate environmental responsibilities to the final consumers, but to the producers of different products. It is thus a mirror indicator to TMC (Rodrigues and Giljum, 2005).² With regard to the analysis of international trade relations, the “Physical Trade Balance (PTB)” is the most commonly applied indicator. The PTB is

² In the literature on environmental indicators, there is an ongoing debate whether environmental consequences of production and consumption activities should be allocated to the consumer (consumer responsibility), to the producer (producer responsibility) or whether the responsibility should be shared by different actors (for example, Lenzen et al., 2006; Rodrigues et al., 2006).

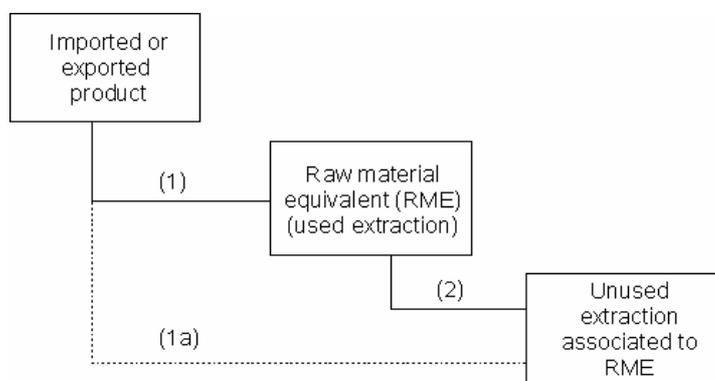
calculated by subtracting exports from imports, in contrary to the calculation of monetary trade balances. A PTB can either only include direct material flows (the actual weight of imports and exports), or also all up-stream material requirements of imported and exported products.

The concept of „raw material equivalents“

In particular for cross-country comparisons and assessments on the international level, the information value of indicators for direct material flows (i.e. DMI and DMC) is limited by the fact that none of them accounts for all required primary materials. DMI and DMC therefore measure imports and exports in a different unit than used domestic extraction. If extracted domestically, e.g. used metal extraction is accounted as crude ore (net metal content plus ancillary mass). It is thus accounted at the functional system boundary between environment and economy. If the same metal ore is imported, in DMI and DMC only the weight of the imported ore is accounted, but not all raw material extraction necessary to produce the imported ore. Hence, an imported good is 'lighter' in terms of weight than the used domestic extraction required to produce it. Therefore, in case of a country that is importing for example all required iron ores from abroad, the DMI and DMC of this country is lower than that for a country which is domestically extracting iron ore in order to further process it to steel (Moll and Bringezu, 2005).

Direct comparison of aggregated resource use of countries is therefore only possible, if traded products are accounted in terms of their raw material requirements. These so called raw material equivalents (RME) express the total amount of used raw material which was directly and indirectly required for manufacturing a product along the production chain. A quantification of RME thus allows for a standardisation of physical foreign trade flows to the same economy-environment system boundary as applied in used domestic extraction. RME are therefore indispensable for analysing the ongoing process in highly developed (industrialised) countries of shifting environment-intensive activities, such as production of steel or other metal smelting, to the rest of the world.

Figure 1: The components of indirect material flows



Source: Adapted from EUROSTAT, 2001

Indirect material flows comprise two components. Used extraction which was needed to produce the traded goods; this equals RME, calculated in step (1) (see Figure 1); and unused domestic extraction associated to this RME, assessed in step (2). In several MFA studies, the calculation of indirect flows was mainly restricted to the estimation of the unused extraction related to the import of products (in most cases, basic commodities), without quantifying RMEs (step 1a) (see, for example, Bringezu and Schütz, 2001). Figure 1 clarifies this definition of indirect material flows and the subsequent calculation steps.

In the literature, several approaches have been applied to calculate indirect material flows. These approaches shall be briefly reviewed in the following.

LCA-oriented approaches

This methodological approach to calculate indirect material flows required in the life-cycle of a product was developed at the Wuppertal Institute in Germany. The so-called Material Intensity Analysis (MAIA) (Schmidt-Bleek et al. 1998) is an analytical tool to assess the material inputs along the whole life-cycle, including direct material inputs and the so-called „ecological rucksack“, which is defined as the total sum of all materials which are not physically included in the economic output under consideration, but which were necessary for production, use, recycling and disposal. This calculation methodology is mainly suitable for the calculation of indirect flows associated to biotic and abiotic raw materials and products with a low level of processing. To calculate indirect flows for semi-manufactured and finished products by applying this methodology requires the collection of large amounts of data for every product under consideration. Therefore, indirect flows have so far been calculated for a very limited number of processed biotic and abiotic products.

However, as Weisz (2006) notes, it is not only the fact that the number of required rucksack factors is by far too large. LCA approaches also lack appropriate standards to guarantee consistency and comparability of material flow accounts, as LCA factors do not account for so-called second and third round effects of the intermediate use and supply chains within industrial production systems. These intermediate flows are, however, of increasing importance in highly industrialised economies. For these reasons, other approaches for calculating indirect material flows have been developed, applying in particular input-output analysis.

Environmental input-output analysis

Within the large family of approaches for accounting and modelling material flows, 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.

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 section 4 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.

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. 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, 2005; 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). 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).

Multi-regional environmental IO models

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 CO₂ 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 CO₂ emissions) with IO tables of 17 sectors, linked by bilateral trade data for 42 countries and world regions and CO₂ 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.

3 Constructing a global multi-regional MFA-IO model

In the following, we provide a detailed description of the conceptual foundations, 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, i.e. through linking IO tables and 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.

Conceptual foundations

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). We begin the description of the construction of such a model with a theoretical example of a two-country example, each comprising three production sectors. The flows of goods in this system look as follows (Figure 2).

Figure 2: Interindustry and inter-country flows of goods in a two-country model

		Country A			Country B		
		1	2	3	1	2	3
Country A	1	Z_{11}^{AA}	Z_{12}^{AA}	Z_{13}^{AA}	Z_{11}^{AB}	Z_{12}^{AB}	Z_{13}^{AB}
	2	Z_{21}^{AA}	Z_{22}^{AA}	Z_{23}^{AA}	Z_{21}^{AB}	Z_{22}^{AB}	Z_{23}^{AB}
	3	Z_{31}^{AA}	Z_{32}^{AA}	Z_{33}^{AA}	Z_{31}^{AB}	Z_{32}^{AB}	Z_{33}^{AB}
Country B	1	Z_{11}^{BA}	Z_{12}^{BA}	Z_{13}^{BA}	Z_{11}^{BB}	Z_{12}^{BB}	Z_{13}^{BB}
	2	Z_{21}^{BA}	Z_{22}^{BA}	Z_{23}^{BA}	Z_{21}^{BB}	Z_{22}^{BB}	Z_{23}^{BB}
	3	Z_{31}^{BA}	Z_{32}^{BA}	Z_{33}^{BA}	Z_{31}^{BB}	Z_{32}^{BB}	Z_{33}^{BB}

We see that the multi-country flow matrix in this two-country example consists of four sub-matrices, two for the domestic economies of countries A and B (denoted with AA and BB) and two for the trade relations between them (matrices AB and BA). This system of monetary flows provides a full description of intermediate inputs and outputs of each production sector from both domestic and foreign origin. In a three-country case, three flow matrices for the domestic economies and six for the trade relations would be separated. In general, a model with n countries results in a flow matrix (and therefore also a multiplier) of n^2 sub-matrices. This implies that data requirements for a global model, which disaggregates a large number of countries, grow exponentially (see below).

Figure 2 can be rewritten in condensed matrix form:

$$Z = \begin{bmatrix} Z^{AA} & Z^{AB} \\ Z^{BA} & Z^{BB} \end{bmatrix} \quad (1)$$

The input coefficients (here illustrated for country A) are calculated by dividing inputs to sector j by gross output of sector j :

$$a_{ij}^{AA} = z_{ij}^{AA} / X_j^A \quad (2)$$

In a similar way, inter-country trade coefficients can be derived, with gross output of sectors in the receiving country serving as the denomination. Again, the example of country A as the receiving country is presented:

$$a_{ij}^{BA} = z_{ij}^{BA} / X_j^A \quad (3)$$

The complete multi-country matrix of technical coefficients results in:

$$A = \begin{bmatrix} A^{AA} & A^{AB} \\ A^{BA} & A^{BB} \end{bmatrix} \quad (4)$$

By defining multi-country output vector as $X = \begin{bmatrix} X^A \\ X^B \end{bmatrix}$ and the corresponding final demand vector as $Y = \begin{bmatrix} Y^A \\ Y^B \end{bmatrix}$, we can re-write the complete two-country input-output system in matrix form:

$$Y = (I - A)X \quad \text{or} \quad X = (I - A)^{-1}Y \quad (5)$$

The term is similar to the standard representation of the static IO model for the one-country case. The matrix $(I - A)^{-1}$ represents the multi-country multiplier matrix.

Extending this input-output system by material input data is similar to the procedure for

the one-country case (see, for example, Moll et al., 2004). We first calculate a vector of material intensity (m) by dividing material extraction of each sector (M_j) by total (monetary) output of each sector (X_j). Note that M is zero for all sectors not involved in primary material extraction (for a detailed discussion on the allocation of different material categories to sectors see section 4.4):

$$m = M/X \quad \text{for all } j \quad (6)$$

The extended multi-country Leontief inverse matrix or multiplier matrix weighted by material input coefficients (M_m) is calculated by post-multiplying the diagonal vector of sectoral material input coefficients (\hat{m}) with the Leontief inverse matrix.

$$M_m = \hat{m}(I - A)^{-1} \quad (7)$$

The element ij of this weighted multiplier matrix illustrates the amount of material inputs of sector i needed to produce one additional unit of output of sector j . In order to calculate direct and indirect material input required to satisfy final demand in the different countries (disaggregated by economic sectors), the weighted multiplier is multiplied with the multi-regional vector of domestic final demand (see above).

$$r = M_m * Y_{dom} \quad (8)$$

With r : vector of direct and indirect material inputs for domestic consumption

It is important to note that in such a multi-regional IO-MFA system, which is closed on the global level, primary material input of each economic sector (M) only comprises domestic material extraction, whereas in a single country study, also physical imports from other countries must be included. This results from the fact that in a global accounting system, material intensities of all traded products are calculated directly by the model, based on numbers for domestic material extraction in each country and the economic interdependencies of (domestic and foreign) production branches.

Data sources

In this section, we describe the data sources for the three main data sets required for setting up the model: IO 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. 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 harmonisation 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. The tables of the 2006 edition are based around the year 2000 (Yamano and Ahmad 2006). 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. 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 36 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.

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. 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.

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. 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. 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 is aggregated to the following material groups (Table 1).

Table 1: 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 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).

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 only one sector for biomass extraction and two sectors for mining and quarrying (fossil fuels and minerals) are separated.

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 2). 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 2: 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 receive raw material inputs from the mining and quarrying sector. Through this initial disaggregated allocation, specific compositions of material inputs to certain industries at further stages of processing can be captured by the model.

Technical implementation of the model calculations

The approach described above 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:

$$TMR = M_m^{DFD} + M_m^{DEX} + M_m^{IFD} + M_m^{IEX} \quad (9)$$

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)“:

$$TMC = (M_m^{DFD} + M_m^{IFD}) - (M_m^{DEX} + M_m^{IEX}) \quad (10)$$

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:

$$PTB = M_m^{IFD} - (M_m^{DEX} + M_m^{IEX}) \quad (11)$$

4 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. 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).

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, 2006; 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).

(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 the structure of 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).

5 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 working steps, 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 3.

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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