Resource productivity, environmental tax reform and sustainable growth in Europe

The Global Resource Accounting Model (GRAM)
a methodological concept paper

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Summary

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). Work package 5 deals with the global dimensions of sustainable growth in Europe and investigates world-wide consequences of a European transformation towards sustainable growth based on an environmental tax reform and significantly increased resource productivity.

With annual growth rates of international trade constantly above growth of production in the world economy, the inclusion of natural resource requirements of traded products 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. 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 the Global Resource Accounting Model (GRAM), a global, multi-regional, environmental input-output (MRIO) model designed to fill parts of the existing gaps with regard to data and empirical analysis of material flows. The basic intention of GRAM is to construct a MRIO model with a monetary core (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 GRAM 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 comprehensive description of the concept of indirect material flows and summarise different approaches for their calculation. The methodological framework of the GRAM model is described in detail, illustrating, in particular, the structure of the different data sets and how they are integrated and inter-linked. 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. Finally, we summarise possible areas of application of this model in the petrE project and beyond.

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

Contents

1 Introduction

This methodological concept paper[1] 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. One of the forecast models applied in petrE is the GINFORS (Global Interindustry Forecasting System; see Lutz et al., 2005, Meyer et al., 2007, 2008) 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 is 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., 2008).

However, the GINFORS model cannot allocate material extraction to specific variables of final demand 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 indicators on material consumption (for details see chapter 3.2) cannot be calculated and the resource base of, for example, the European economy cannot be determined in a comprehensive manner, as the materials directly and indirectly delivered to Europe through international trade cannot be taken into account.

Although material consumption indicators 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 Resource Accounting Model (GRAM) 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 EU project MOSUS ("Modelling opportunities and limits for restructuring Europe towards sustainability", see www.mosus.net) and are now improved and updated in the petrE project. The main purpose of the GRAM 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

[1] We greatly appreciate the valuable comments by Hector Pollitt (Cambridge Econometrics) on an earlier version of this paper.

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. Section 3 provides a comprehensive description of the concept of indirect material flows and summarises different approaches for their calculation. In Section 4, we describe the methodological framework of the GRAM model, illustrating in particular, how the different data sets are integrated and inter-linked. Section 5 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 6. Section 7 summarises possible areas of application of the model. In Section 8 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 2006, world export volumes augmented by 5.5% annually while production only grew by 2.5% per year. Growth in trade was highest for manufactured products (6.0%), followed by agricultural products (4.0%) and fuels and mineral products (3.0%) (WTO, 2007).

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; Peters and Hertwich, 2006, 2008; 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 The calculation of indirect material flows

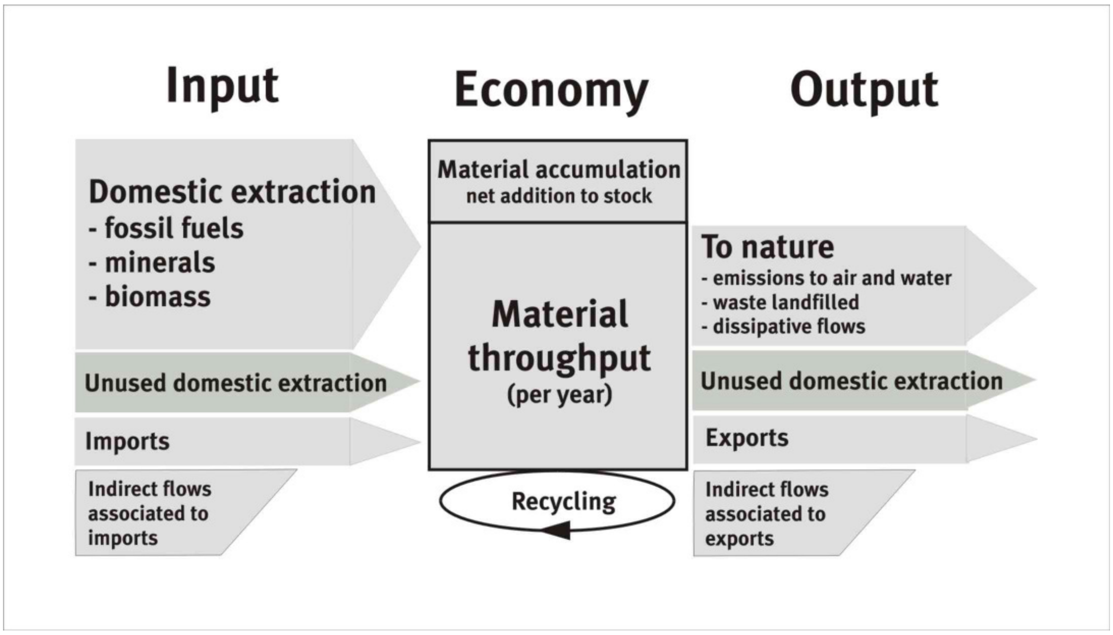
3.1 The basics of material flow accounting and analysis

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. Raw materials, water, and air are extracted from the natural system as inputs, transformed into products and finally re-transferred to the natural system as outputs (waste and emissions). To highlight the similarity to natural metabolic processes, the terms "industrial" (Ayres, 1989) or "societal" (Fischer-Kowalski, 1998) metabolism have been introduced. Since the beginning of the 1990s, MFA has been a rapidly growing field of scientific interest and major efforts have been undertaken to harmonise the different methodological approaches developed by different research teams (Bringezu et al., 1997; Kleijn et al., 1999), resulting in the publication of a standardised methodological guidebook for economy-wide material flow accounting by the

Statistical Office of the European Community (EUROSTAT, 2001).

A general material balancing scheme on the national level, including all relevant input and output flows, is presented in Figure 1. The material balance 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. 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 economies. It is important to note that this standard material balancing scheme regards the domestic economy as a black box, i.e. does neither disaggregate economic sectors nor intermediate from final demand.

Figure 1: General scheme for economy-wide MFA, excluding water and air flows



Source: adapted from EUROSTAT, 2001

Unused domestic extraction refers to materials that never enter the economic system and thus can be described as physical market externalities (Hinterberger et al., 1999). This category comprises overburden and parting materials from mining, by-catch from fishing, wood and agricultural harvesting losses, as well as soil excavation and dredged materials from construction activities.

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).

It shall be emphasised that the concept of indirect or embodied material flows must be extended, when an input-output-based approach is applied, which is the case for the model introduced in this paper. In this case, also for domestically produced goods, indirect flows can be illustrated, i.e. requirements of domestic materials, which are used along the production chain to produce a good delivered to final demand. Thus, in reality, all products generate indirect material flows and the fact that the domestic economy is regarded as a black box in economy-wide material flow accounting is just a special definition of the more general case (see Rodrigues and Giljum, 2005 for a conceptual framework of accounting of indirect material flows).

A large number of national MFA studies have been presented for developed countries (for example, Adriaanse et al., 1997; EUROSTAT, 2002, 2005; Matthews et al., 2000; Poldy and Foran, 1999; Schütz and Bringezu, 2008; Weisz et al., 2006) and transition economies (Hammer and Hubacek, 2002; Mündl et al., 1999; Scasny et al., 2003). Concerning countries in the global South, economy-wide MFAs have been compiled for Brazil and Venezuela (Amann et al., 2002), for Chile (Giljum, 2004), for Mexico (Gonzales, 2007), for Ecuador (Vallejo, 2006) and for China (Xu and Zhang, 2007).

A first estimation of the material basis of the global economy was presented by Schandl and Eisenmenger (2006) for the year 1999. A time series for resource extraction of all countries of the world from 1980-2002 was compiled in the course of the EU project “MOSUS” (Behrens et al., 2007). The availability of detailed material input accounts is necessary for building global economic-environmental models, as described below.

3.2 Material flow-based indicators

Within the internationally harmonised classification systems for environmental indicators, such as the pressure-state-response (PSR) framework of the OECD or the extended Driving Forces-Pressures-State-Impact-Response (DPSIR) system used in the EU, material flow-based indicators are part of the pressure indicator group. These indicators identify and describe socio-economic activities, which exert pressures on the environment, such as agricultural or industrial production, transport, and energy use.

A large number of resource-use indicators can be derived from economy-wide material flow accounts (OECD, 2007). These indicators can be grouped into input, output, consumption and trade indicators. All indicators are aggregated by weight and expressed in the unit of tons.

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.

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 product.

"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 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.

3.3 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.

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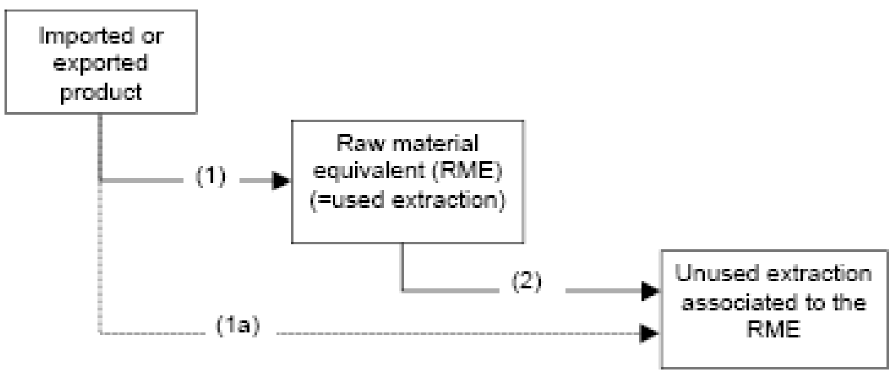
[2] In the literature on environmental indicators, there is an ongoing debate whether environmental consequences of production and consumption activities should be allocated to the consumer (consumer responsibility), to the producer (producer responsibility) or whether the responsibility should be shared by different actors (Gallego and Lenzen, 2005; Lenzen et al., 2006; Rodrigues et al., 2006).

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.

Indirect material flows as illustrated in Figure 1 above comprise two components. Used extraction which was needed to produce the traded goods; this equals RME, calculated in step (1) (see Figure 2); 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 2 clarifies this definition of indirect material flows and the subsequent calculation steps.

Figure 2: The components of indirect material flows



Source: EUROSTAT, 2001

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

3.4 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“ (Ritthoff et al., 2002; Schmidt-Bleek 1992, 1994). The ecological rucksack can be 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. Thus, by definition, the ecological rucksack results from the life-cycle-wide material input (MI) minus the mass of the product itself“ (Spangenberg et al. 1998, p. 15). To use the terms proposed by EUROSTAT, the ecological rucksacks of imported products equal their indirect flows and consist of both used and unused materials. The so-called „rucksack-factor“ is the ratio of the materials included in the ecological rucksack and the produced good (ton per ton).

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 (see Ayres et al., 2004 for a US example).

For these reasons, other approaches for calculating indirect material flows have been developed, applying in particular input-output analysis.

3.5 Input-output based approaches

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, Acosta, 2007; 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, 2008). 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, 2008; 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 6.

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).

3.6 Combining LCA and IO approaches

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 GRAM model introduced in this paper is designed to deliver the missing information, however, with limitations regarding possibilities of disaggregation (see chapter 6 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.

3.7 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, 2007):

(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, 2007) provide extensive reviews of MRIO models to assess indirect environmental effects of trade. A comprehensive review of existing models is therefore not carried out in this paper.

It should only be mentioned that a MRIO model to calculate embodied CO_2 emissions of OECD countries has been constructed (Ahmad, 2003; Ahmad and Wyckoff, 2003; see also Yamano et al., 2006, for an updated study), which uses the same core data set of IO tables and bilateral trade data as the model introduced in this paper. Therefore, a number of methodological issues regarding the construction of this OECD model are of high relevance for the GRAM model. We will come back to these issues in the next chapter.

4 Constructing the Global Resource Accounting Model (GRAM)

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 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 the Global Resource Accounting Model (GRAM) is to estimate indirect raw material inputs of traded products and thus be 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.

4.1 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 3).

Figure 3: 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 3 can be rewritten in condensed matrix form:

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

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

$$a_{ij}^{AA} = z_{ij}^{AA} / X_j^A \tag{2}$$

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:

$$a_{ij}^{BA} = z_{ij}^{BA} / X_j^A \tag{3}$$

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

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

By defining the 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:

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

The term is similar to the standard representation of the static IO model for the one-country case. The matrix $(I\text{-}A)^{-1}$ 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 *(Mj)* by total (monetary) output of each sector (*Xj*). 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):

$$m = M/X \qquad \text{for all } j \tag{6}$$

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.

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

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).

$$r = Mm * Ydom \tag{8}$$

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.

4.2 Data sources

In this section, we describe the data sources for the three main data sets required for setting up the GRAM 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. Furthermore 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, third revised (2006) edition of IO tables published by the OECD includes 27 OECD countries (except Iceland, Luxemburg and Mexico) and 9 non-OECD countries (Argentina, Brazil, China, India, Indonesia, Israel, Russia, Singapore and Taiwan) in 48 harmonised sectors (see Tables 1, 2 and 3). 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 be converted into symmetric IO tables, either in purchaser prices, which is more easily done than into basic prices, where e.g. taxes have to be distributed across sectors.

As Table 1 and Table 2 illustrate most of the received data as well as those submitted in earlier years need to be converted to the predefined and originally requested structure, in a way that they are consistent with the industry classification used in OECD systems and that they are using the same price basis. In contrast to the GTAP database the assumptions made in connexion with data harmonisation as well as the harmonisation process itself are explicitly described (see Ahmad and Wyckoff, 2003).

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. Table 3 provides an overview of the considered industries and discloses future potentials of disaggregation.

Table 1: Data sources for the OECD I-O industry-by-industry database

	OECD-Country	Source	Year	Tables				
				Supply	Use total	Use import	I-O total	I-O import
1	Australia	Australian Bureau of Statistics	1998/99				x	x
2	Austria	Eurostat	2000	x	x		x c	x c
3	Belgium	National Bank of Belgium	2000	x	x		x c	x c
4	Canada	Statistics Canada	2000				x	x
5	Czech Republic	Czech Statistical Office	2000	x	x	x		
6	Denmark	Danmarks Statistik	2000				x	x
7	Finland	Eurostat	2000				x	x
8	France	National Institute of Statistics and Economomic Studies	2000	x	x		x c	
9	Germany	Eurostat	2000	x	x		x c	x c
10	Greece	Eurostat	2000	x	x			
11	Hungary	Eurostat	2000	x	x		x c	x c
12	Ireland	Eurostat	1998	x	x		x c	x c
13	Italy	Eurostat	2000	x	x		x c	x c
14	Japan	Ministry of Economy, Trade and Industry	2000	x			x c	x c
15	Korea	Bank of Korea	2000				x c	x c
16	Netherlands	Statistics Netherlands	2000				x	x
17	New Zealand	Statistics New Zealand	1995/96				x	x
18	Norway	Eurostat	2001				x	x
19	Poland	Eurostat	2000	x	x		x c	x c
20	Portugal	Eurostat	1999	x	xPU		x c	x c
21	Slovak Republic	Eurostat	2000	x	XPR		x c	
22	Spain	Eurostat	2000	x	x	x		
23	Sweden	Eurostat	2000	x	xPU		x c	x c
24	Switzerland	Federal Institute of Technology	2001	x	x		x c	
25	Turkey	Turkish Statistical Institute	1998	x	x		x c	x c
26	United Kingdom	The Office for Naitonal Statistics	2000	x	xPU			
27	United States	Bureau of Labor Statistics	2000	x	xPR			

c: Commodity-by- commodity tables; **PU**: Purchasers' Prices; **PR**: Producers' Prices

Table 2: Data sources for the OECD I-O industry-by-industry database

	Non - OECD - Country	Source	Year	Tables				
				Supply	Use total	Use import	I-O total	I-O import
1	Argentina	National Institute of Statistics and Censuses	1997				x	x
2	Brazil	Brazilian Institute of Geography and Statistics	2000				x	x
3	China	National Bureau of Statistics	2000				x c PR	x c PR
4	Chinese Taipei	Directorate General of Budget, Accounting and Statistics	2001				x	x
5	India	Ministry of Statistics and Programme Implementation	1998/99	x	x	x		
6	Indonesia	Badan Pusat Statistk	2000				x c	x c
7	Israel	Central Bureau of Statistics	1995	x	x	x		
8	Russia	Federal State Statistics Service	2000	x	x			
9	Singapore	Statistics Singapore	2000				x	x

c: Commodity-by-commodity tables; **PU**: Purchasers' Prices; **PR**: Producers' Prices.

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 shortcomings of the database are 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). However, given the steep rise in energy and material prices in the past few years, more recent IO tables would need to be applied, when studies for the very recent years are performed.

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).

Table 3: OECD I-O Database – Industry classification and concordance with ISIC Rev. 3

ISIC Rev. 3 code	IO industry	BTD industry	Description
1+2+5	1	1	Agriculture, hunting, forestry and fishing
10+11+12	2	2	Mining and quarrying (energy)
13+14	3	2	Mining and quarrying (non-energy)
15+16	4	3	Food products, beverages and tobacco
17+18+19	5	4	Textiles, textile products, leather and footwear
20	6	5	Wood and products of wood and cork
21+22	7	6	Pulp, paper, paper products, printing and publishing
23	8	7	Coke, refined petroleum products and nuclear fuel
24ex2423	9	8	Chemicals excluding pharmaceuticals
2423	10	9	Pharmaceuticals
25	11	10	Rubber and plastics products
26	12	11	Other non-metallic mineral products
271+2731	13	12	Iron & steel
272+2732	14	13	Non-ferrous metals
28	15	14	Fabricated metal products, except machinery and equipment
29	16	15	Machinery and equipment, nec
30	17	16	Office, accounting and computing machinery
31	18	17	Electrical machinery and apparatus, nec
32	19	18	Radio, television and communication equipment
33	20	19	Medical, precision and optical instruments
34	21	20	Motor vehicles, trailers and semi-trailers
351	22	21	Building & repairing of ships and boats
353	23	22	Aircraft and spacecraft
352+359	24	23	Railroad equipment and transport equipment n.e.c.
36+37	25	24	Manufacturing nec; recycling (include Furniture)
401	26	25	Production, collection and distribution of electricity
402	27	25	Manufacture of gas; distribution of gaseous fuels through mains
403	28	25	Steam and hot water supply
41	29	Services	Collection, purification and distribution of water
45	30		Construction
50+51+52	31		Wholesale and retail trade; repairs
55	32		Hotels and restaurants
60	33		Land transport; transport via pipelines
61	34		Water transport
62	35		Air transport
63	36		Supporting & auxiliary transport activities; activities of travel agencies
64	37		Post and telecommunications
65+66+67	38		Finance and insurance
70	39		Real estate activities
71	40		Renting of machinery and equipment
72	41		Computer and related activities
73	42		Research and development
74	43		Other Business Activities
75	44		Public administration and defence; compulsory social security
80	45		Education
85	46		Health and social work
90-93	47		Other community, social and personal services
95+99	48		Private households with employed persons & extra-territorial organisations & bodies

At the moment the GRAM 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. 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. Table 4 lists the chosen assumptions.

Table 4: 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

It is intended that these constructed IO tables will 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 6 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 as are the 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 (see Table 3). The 2006 version covers the years 1988 to 2004 and for the first version of GRAM, the data for the year 2000 are used. 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. OECD has announced a new version of the BTD including full trade information for important non-OECD countries as China and India for spring 2008, which will further improve the consistency of the approach.

Import and export data normally do not match due to differing classifications and price calculations (e.g. cif versus fob). For the GRAM 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 GRAM 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 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., 2007) 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).

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).

In the course of the petrE project, the MOSUS MFA database is being updated to the year 2005 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). Furthermore, global production data on minerals is calculated based on a new data set on world mineral production published by the British Geological Survey (BGS). These updated datasets can be also be downloaded from the website www.materialflows.net.

4.3 Allocation of imports to industries in the IO table

Section 4.1 described the construction of an ideal model framework with full data availability. Unfortunately, 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.

As shown in section 4.1 , 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 – as described in section 4.2 – 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 ${}^{m}y^{C}$. The latter can be expressed as:

$$ {}^{m}A^{C} = \sum_{c\neq k} A^{KC} \tag{9} $$

and $$ {}^{m}y^{C} = \sum_{c\neq k} y^{KC} \tag{10} $$

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:

$$ A^{KC} = \hat{s}\,{}^{m}A^{C} \tag{11} $$

$$ Y^{KC} = \hat{s}\,{}^{m}y^{C} \tag{12} $$

with $$ \{\hat{s}\}_j = \{m^{KC}\}_j / \{\sum_k m^{KC}\}_j \tag{13} $$

where $\{m^{KC}\}_j$ is the total flow of imports of product j of country c from country k (Meyer et al., 2008, Peters and Hertwich 2006). The trade share matrix ŝ represents for every product j the share of every country k in the imports of country c.

4.4 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 (see Table 3 above) precludes this procedure, as only one sector for biomass extraction is considered. The same holds true for mining of different fossil fuels, metal ores and other minerals.

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).

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. Schoer (2006) therefore suggests 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.

We tested this approach of allocating material extraction to the first step of processing with the GRAM model and found that also this approach produces errors, as some countries export significant shares of their raw material extraction without previous processing. Material extraction would therefore not be treated as embodied materials of raw material exports, but as input to the domestic processing industry, which, particularly for primary sector dominated economies, is not significant.

Based on these experiences, a mixed approach was developed, where we first separate material extraction, which is directly exported as raw materials. This part of extraction is thus directly linked to the exports of the three extracting sectors (1, 2 and 3). As these three sub-groups aggregate a number of materials, no distinction could be made e.g. between agriculture and forestry, or between metal ores and industrial minerals. In a second step, the remaining material extraction is then allocated to the domestic processing industries. For example, if sector 3 (mining, non-energy) delivers exports totalling 30% of its overall production, we allocate 30% of all ore and mineral extractions to exports and 70% to the respective domestic sector of processing as indicated in Table 6 (in the example of minerals, these sectors are 12, 13, 14 and 30). Table 6 summarises the allocation scheme.

Table 5: Allocation of MFA categories to economic sectors in the IO table

Category of material extraction	**Allocated to sector of IO table (number of sector in brackets)**
Agriculture, grazing, fish and fibre crops	Unprocessed exports: Agriculture, hunting, forestry, fish (1) Further processing: Food products (4)
Forestry	Unprocessed exports: Agriculture, hunting, forestry, fish (1) Further processing: Wood and wood products (6) and Pulp and paper products (7)
Coal and oil	Unprocessed exports: Mining and quarrying (energy) (2) Further processing: Coke and refined petroleum products (8)
Natural gas	Unprocessed exports: Mining and quarrying (energy) (2) Further processing: Manufacture of gas (27)
Iron ores	Unprocessed exports: Mining and quarrying (non-energy) (3) Further processing: Iron and steel (13)
Other metal ores	Unprocessed exports: Mining and quarrying (non-energy) (3) Further processing: Non-ferrous metals (14)
Industrial minerals	Unprocessed exports: Mining and quarrying (non-energy) (3) Further processing: Non-metallic mineral products (12)
Construction minerals	Construction (30)

Through this initial disaggregated allocation, both exports of raw materials and specific compositions of material inputs to certain industries at further stages of processing can (at least to some extent) 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. For the case of construction minerals, we assumed that exports are zero and all materials are allocated to sector 30 (construction) for domestic use.

5 Technical implementation of the model calculations

The approach described in section 4.1 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, “Total Material Requirement (TMR)” can be calculated by adding up all four categories:

$$TMR = M^{DFD} + M^{DEX} + M^{IFD} + M^{IEX} \tag{14}$$

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

$$TMC = TMR - (M^{DEX} + M^{IEX}) = M^{DFD} + M^{IFD} \tag{15}$$

If the vector of domestic material extraction only comprises used extraction, then 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:

$$PTB = (M^{IFD} + M^{IEX}) - (M^{DEX} + M^{IEX}) = M^{IFD} - M^{DEX} \tag{16}$$

5.1 Linking IO tables with trade data

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

$$DFD = (I\text{-}A)^{-1}\ FD \tag{17}$$

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.

$$IFD = B\ (I\text{-}A)^{-1}\ FD + FDI \tag{18}$$

where B is the input coefficient matrix for imports (import matrix), with components b_{ij} representing the ratio of imports from foreign industry i to the (domestic) output of industry j (see section 4.3). Equation (18) assures that material embodied in imports is assigned to the domestic industries via the monetary import matrix B and domestic interindustry relations $(I\text{-}A)^{-1}$ in equation (24) below. At the same time parts of foreign demand is satisfied by domestic production. Similarly to equation (17) demand for exports goods produced domestically DEX can be shown to be equal to:

$$DEX = (I\text{-}A)^{-1}\ EX \tag{19}$$

EX is an 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

$$IEX = B\ (I\text{-}A)^{-1}\ EX + AEX \tag{20}$$

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:

$$IFD_k = S_k\ IFD \tag{21}$$

$$IEX_k = S_k\ IEX \tag{22}$$

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 (17) to (20) 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.

$$M^{DFD} = {}^{m}R_{c}\ DFD \tag{23}$$

$$M^{IFD} = \sum_{k}({}^{m}R_{k}\ S_{k}\ IFD) \tag{24}$$

$$M^{DEX} = {}^{m}R_{c}\ DEX \tag{25}$$

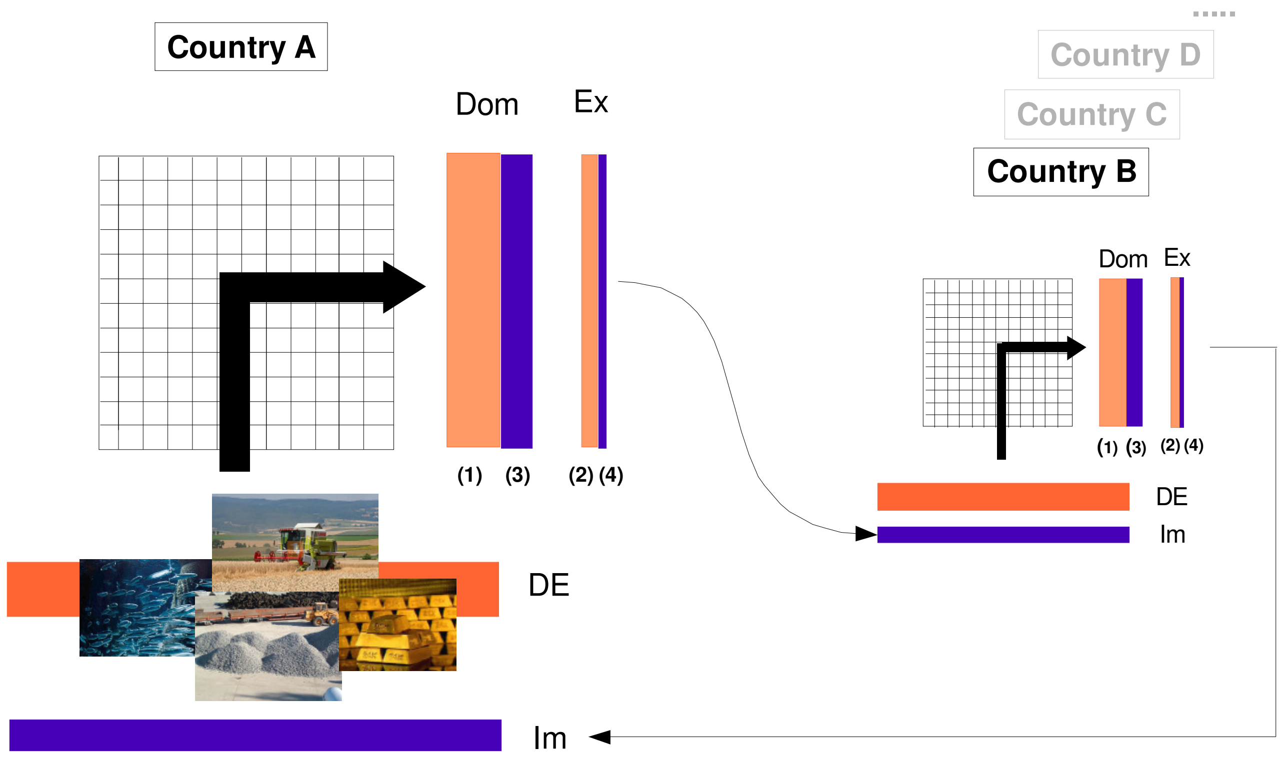
$$M^{IEX} = \sum_{k}({}^{m}R_{k}\ S_{k}\ IEX) \tag{26}$$

Adding up M^{DFD} and M^{IFD} 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):

$$Z_{C} = M^{DEX}{}_{C} + M^{IEX}{}_{C} = {}^{m}R_{c}\ DEX + \sum_{k}({}^{m}R_{k}\ S_{k}\ IEX) \tag{27}$$

Equations (27) for the different countries k are interdependent. The material embodied in a country's export depends on the material embodied in all other countries' exports. The monetary exports DEX and IEX and bilateral trade shares S are kept constant and serve as weights. Material embodied in exported imports is assigned to the domestic industries via the monetary import matrix B and domestic interindustry relations $(I-A)^{-1}$(20) and (26). 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 (26) is equal to zero for all countries at the beginning of the process. Then we solve equation (25) for each country, the results are then used in equations (24), and (26). This procedure is repeated for all countries as long as ${}^{m}R_{k}$ differs between two iterations for any of the countries k. Figure 4 provides a graphical illustration of this iterative calculation procedure.

Figure 4: Graphical illustration of the calculation procedure



Notes: DE ... Domestic Extraction; Dom ... Domestic Consumption; Im ... Imports; Ex ... Exports
Categories (1) to (4): four categories of product use (see main text above)

In the first step, domestic material extraction (DE) of country A is allocated to its domestic consumption (Dom) and exports (Ex) to countries B, C, D, etc., assuming that exports are solely produced with domestic material resources. This is done for every country parallel. The result of this process is a model of international material flows that describes all exports from any country in the world to any recipient, on the supposition that all goods are produced only with the country's domestic extraction. Thus, all steps of international division of labour are completely modelled after that step of procedure, but, as the material intensities of one country's exports depend on that of its imports, the results have to be revised, considering the imports of materials additional to domestic extraction. This has to be carried out several times for every country, as changes in the import structure of one country always entail changes in its export structure and therefore in the composition of imports of other countries. For example, changes in the material intensity of the German imports affect the material intensity of the German exports and therefore that of the British imports and vice versa. We thus face a problem of interdependencies, which we solve through an iteration process. The divergences decrease with each of the iterations and finally, material intensities of imports and exports no longer change between two iteration steps.

6 Shortcomings and future improvements of the GRAM model

The GRAM 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 3.5 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). The EU project "EXIOPOL" (see http://www.feem-project.net/exiopol) is currently establishing a detailed input-output database including environmental extensions at a very detailed sectoral level.

(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 GRAM, 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 GRAM 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, waste, emissions, etc.) shall be integrated into GRAM.

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 GRAM 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. Modelling 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 the GRAM 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 GRAM, a multi-regional input-output model extended by material input data, which is constructed in work package 5 of the petrE project. 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. A new version of OECD BTD is announced for spring 2008 and may improve the country coverage. Finally, material extraction data for the year 2000 will be aggregated into the categories as described above and integrated into GRAM, in order to produce the different material flow-based indicators.

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