Franz Stephan Lutter and Stefan Giljum and Martin Bruckner

A review and comparative assessment of existing approaches to calculate material footprints

Article published as:

Lutter, Stephan and Giljum, Stefan and Bruckner, Martin. 2016. A review and comparative assessment of existing approaches to calculate material footprints. Ecological Economics 127, p. 1-10.

A review and comparative assessment of existing approaches to calculate material footprints

Stephan Lutter [1] *, Stefan Giljum [1], Martin Bruckner [1]

[1] Institute for Ecological Economics, Vienna University of Economics and Business (WU), Welthandelsplatz 1, A-1020 Vienna, Austria

* Corresponding author: stephan.lutter@wu.ac.at; 0043 1 31336 5754

Abstract:

Effective implementation of resource policies requires consistent and robust indicators. An increasing number of national and international strategies focussing on resource efficiency as a means for reaching a "green economy" call for such indicators. As supply chains of goods and services are increasingly organised on the global level, comprehensive indicators taking into account upstream material flows associated with internationally traded products need to be compiled. Particularly in the last few years, the development of consumption-based indicators of material use – also termed "material footprints" – has made considerable progress. This paper presents a comprehensive review of existing methodologies to calculate material footprint-type indicators. The three prevailing approaches, i.e. environmentally extended input-output analysis (EE-IOA), coefficient approaches based on process analysis data, and hybrid approaches combing elements of EE-IOA and process analysis are presented, existing models using the different approaches discussed, and advantages and disadvantages of each approach identified. We argue that there is still a strong need for improvement of the specific approaches as well as comparability of results, in order to reduce uncertainties. The paper concludes with recommendations for further development covering methodological, data and institutional aspects.

Key words:

Coefficient approach; input-output analysis; material flow analysis; material footprint; resource policy; resource use indicators

1. Introduction

Economic development in the past decades was characterized by steadily increasing levels of global resource use and rising human pressures on the environment (UNEP 2011a; Giljum et al. 2014b; Krausmann et al. 2009). Issues related to material consumption and resource productivity have rapidly increased in importance in European and international policy debates in the past few years (European Commission, 2011; OECD, 2011a; UNEP, 2011). Given the increased demand for robust indicators from the policy sphere, discussions on the most suitable indicators to measure material use and material productivity are intensively ongoing. In recent years, awareness generally increased regarding the significance not only of materials and products directly used by a national economy, but also of indirect resource use required along supply chains and embodied in internationally traded products. Consideration of all indirect effects leads to a consumption – or footprint – perspective, allowing illustrating the global impacts related to final demand of a country or region.

The concept of Material Flow Accounting and Analysis (MFA) is the most important methodological framework that allows deriving indicators of material extraction, trade and consumption. MFA as standardised and applied by the European Statistical Office (EUROSTAT, 2013a) and the OECD (2007) constitutes a description of the economy in physical units (Fischer Kowalski et al., 2011). On the basis of the MFA data system a large number of indicators can be calculated (EUROSTAT, 2001; Femia and Moll, 2005; OECD, 2007). Some of them take a fully territorial perspective and account all domestically extracted raw materials. Other indicators consider the mass of internationally-traded products, such as the indicator Domestic Material Consumption (DMC), which is calculated as domestic material extraction plus direct imports minus direct exports.

DMC is currently the most widely used material flow indicator and is at the core of national reporting by EUROSTAT. Also the European Commission's "Roadmap to a Resource Efficient Europe" (European Commission, 2011) identifies GDP/DMC as the headline indicator for measuring resource productivity. The DMC indicator is also part of OECD's Green Growth Indicators (OECD, 2014). It is widely available for countries across all continents, including all OECD countries (OECD, 2011b, 2015a), the Asian and Pacific region (e.g. Schandl and West, 2010; UNEP, 2013a), Latin America (e.g. UNEP, 2013b; West and Schandl, 2013) and Africa (UNCTAD, 2012). Several studies provide comparative assessments of DMC across all countries worldwide (Dittrich et al., 2012b; Giljum et al., 2014a; Steinberger et al., 2010; Steinberger et al., 2013).

However, in recent years, the necessity to develop and apply indicators that account upstream material flows associated with internationally traded products, i.e. the material footprint, has been articulated by a large number of stakeholders, including policy makers, civil society and academia. The material footprint illustrates the amount of materials required for specific products along their entire supply chains from resource extraction to final demand. The main point of critique on the DMC indicator is that countries can apparently reduce their national material consumption and improve material productivity by dislocating material-intensive industries to other countries and substituting domestic material extraction by imports. Material footprint indicators are therefore of growing relevance, as supply chains of goods and services are increasingly organised on the global level. Hence, indicators taking into account indirect flows accommodate these new circumstances and allow understanding to what extent global value chains influence a country's economy, the environment, and the resource efficiency performance of goods and services.

As a response, various methodological concepts have been developed which aim at calculating economy-wide indicators embracing direct as well as indirect material flows related to international trade. Examples for such indicators are Raw Material Input (RMI) and Raw Material Consumption (RMC); the latter indicator has also been termed material footprint (Giljum et al., 2014b; Wiedmann et al., 2013). The Raw Material Input indicator is calculated as used domestic extraction plus imports accounted for in Raw Material Equivalents (RME), i.e. the gross weight of imports including all upstream (indirect) material flows. For the calculation of Raw Material Consumption exports in terms of RME are deducted from (i.e. OECD, 2008).

In recent years, the RMC indicator has received considerable attention in publications by academic and statistical institutions (see Table 1 below). However, also in policy debates, the indicator is being suggested to monitor material use and productivity of a country in a global context. Examples are discussions on setting targets for resource productivity in the context of the EU "Roadmap for a resource-efficient Europe" (European Commission, 2014) or providing demand-based indicators of material flows in the context of the OECD Green Growth Indicators (OECD, 2014). Especially in the latter case, efforts have intensified in the past year to further develop the RMC-type indicators in order to improve its applicability in policymaking. Main areas for improvement are identified as (1) temporal range (time series), (2) geographical (country) detail, (3) sector detail, and (4) capability for detailed analyses of supply chains.

This paper provides a comprehensive review and comparative assessment of the currently existing methodologies to calculate the RMC or material footprint indicator on the economy-wide level. The objective of the paper is to assess the strengths and weaknesses of the various approaches and evaluate them with regard to their state of development and readiness for implementation. Based on this review, we describe key areas for further development and harmonisation regarding methodology and data. Note that we focus our review on indicators of used material extraction and thus exclude those indicators, which also consider unused material extraction, such as overburden from mining or by-catch from fishery.

The paper is structured as follows: In section 2 we describe the methodology set up for the review and evaluation of existing approaches. We explain which main groups of approaches to calculate material productivity indicators have been identified and which criteria were used to analyse and comparatively evaluate the different approaches. The following sections 3 to 5 describe the three main methodologies currently in use, i.e. input-output analysis, coefficient approaches and hybrid approaches. Section 6 provides a comparative assessment of the evaluation results. In the final section 7 recommendations for further development of the material footprint methodology are provided.

2. Scope of review and evaluation methodology

Three methodologies for the calculation of material footprint indicators are generally distinguished to calculate footprint-type indicators (see, for instance, Chen and Chen, 2013) (Giljum et al., 2013): (1) top-down approaches starting from the macro-economic level in terms of economic structures and material extraction, (2) bottom-up approaches using coefficients on material input per product unit, and (3) hybrid approaches combining the two previous approaches. In this paper, we focus on representatives of these three approaches with regard to methodological development and data availability.

In the case of top-down approaches the prevailing approach is environmentally-extended input-output analysis, which integrates physical data on material use with structural information on the supply and use flows within economies; for bottom-up approaches the prevailing method is to apply coefficient approaches based on process analysis; hybrid approaches combine elements from both input-output analysis and coefficient approaches. Note that with the term "hybrid" we refer to the integration of IO and process-based methods and not to the use of mixed units (i.e. monetary and physical units) in input-output approaches. However, the latter form of hybridisation is also applied within some of the hybrid approaches.

From an overall conceptual point of view, coefficient approaches and IO analysis could be regarded as variations of the same approach (Suh and Nakamura, 2007). Both are applied to assess all required direct and indirect inputs to a specific product, are based on comprehensive input inventories, and compile them drawing on a wealth of often different but generalizable forms of allocation (Majeau-Bettez et al., 2014). Therefore, a full-fletched IO-model with a very high product detail would provide similar results compared to a LCA-based approach, given the availability of country- and time-specific data for all products. What theoretically could be tackled as a pure practical issue, however, in reality is a question of approximation of two schools of thought, as the two communities that developed the approaches have evolved independently. As the large number of recent studies on hybrid IO-LCA approaches illustrates (for example, Lindner and Guan, 2014; Onat et al., 2014; Rodríguez-Alloza et al., 2015; Watanabe et al., 2015), these schools recognise the need for convergence and with improved availability and quality of data, the differences between the methodologies may disappear altogether in the medium- to long-term. At this moment in time, however, when applying available data and methods for the calculation of material footprints, these practical issues are relevant and deserve closer attention, as they significantly influence results. The present paper shall thus act as identifier of the main areas of necessary joint efforts for the specific case of calculating material footprints.

For each methodology, the available models or applications have been identified and were considered in the review. Table 1 lists all models and related publications considered in the review including information on the used material flow data sources. A detailed description of each of the reviewed methodologies can be found in the supplementary information.

It is important to emphasise that this paper focuses on material footprint indicators on the economy-wide level, i.e. indicators that integrate all types of biotic and abiotic materials and cover a country's economy. Apart from this macro level, a large body of literature exists on approaches to calculate materials embodied in international trade or required for certain technologies on the level of single substances, using various methodologies including material flow models, input-output analysis and life cycle assessment (for example, Elshkaki and Graedel, 2013; Moran et al., 2014; Nakajima et al., 2013; Nakamura et al., 2009; Nansai et al., 2014; Wiedmann et al., 2014). In order to keep a clear focus for this paper, these publications oriented at single substances were not considered in our review. However, in future research, it would be important to better connect these two lines of research, in order to identify similarities and use mutual synergies in the further development of the underlying methodologies.

The different approaches in use were evaluated according to criteria focusing on methodological aspects (criteria group A) as well as on data-related aspects (criteria group B). The following Table 2 summarises the criteria. Note that the criteria in group B were applied to five different data types (input-output, monetary trade, physical trade, material extraction, and material coefficients). For a more detailed description of the evaluation methodology, see Lutter and Giljum (2014).

Table 1: Methodologies and publications considered in the review

Methodology	Organisation (model name)	Material flow database	Publications
Input-output approaches	WU (GTAP)	SERI/WU database (materialflows.net)	(Giljum et al., 2014b)
	JRC et al. (WIOD)	SERI/WU database (materialflows.net)	(Arto et al., 2012; Dietzenbacher et al., 2013)
	GWS et al. (GRAM)	SERI/WU database (materialflows.net)	(Bruckner et al., 2012; Wiebe et al., 2012)
	TNO et al. (EXIOBASE)	SERI/WU database (materialflows.net)	(Tukker et al., 2013)
	University of Sydney (EORA)	CSIRO database	(Wiedmann et al., 2013)
	Eurostat	Eurostat MFA data	(Watson et al., 2013)
Coefficient approach	Wuppertal Institute	Wuppertal database	(Dittrich et al., 2012a; Dittrich et al., 2013; Schütz and Bringezu, 2008)
Hybrid approaches	Eurostat[1]	Eurostat MFA data	(Schoer et al., 2012a; Schoer et al., 2012b; Schoer et al., 2013)
	ISTAT	ISTAT MFA data	(Marra Campanale and Femia, 2013)
	CUEC	Czech Statistical Office MFA data	(Kovanda, 2013; Kovanda and Weinzettel, 2013; Weinzettel and Kovanda, 2009)
	SEC	Austrian Statistical Office MFA data	(Schaffartzik et al., 2013, 2014)
	DESTATIS / UBA	German Statistical Office MFA data	(Destatis, 2009; Lansche et al., 2007)

[1] Since the publication of a handbook for material footprint calculations for the national level by Eurostat (EUROSTAT, 2015. Handbook for estimating Raw Material Equivalents of imports and exports and RME-based indicators on country level – based on Eurostat's EU RME model. Statistical Office of the European Communities, Luxembourg.) increasingly country studies are published, such as by the Swiss Statistical Agency (BFS, 2015. Der Material-Fussabdruck der Schweiz. Bundesamt für Statisitk BFS, Neuchâtel.)

Table 2: Criteria groups with specific criteria and related descriptions

Criteria group	Specific criteria	Questions
A: Methodology	Supply chain coverage	How complete are supply chains – especially of higher manufactured products – considered?
	Avoidance of double counting	Is the methodology designed in a way that double counting is avoided?
	System boundary / cut-off level	Where are system boundaries drawn – especially with regard to the truncation of upstream inputs and supply chains?
	Specification of consumption	Are the results available on a detailed level for different categories of final demand, industries or product groups, and for different material groups?
B: Data	Regional/country detail	For which countries and regions are data available?
	Sector detail	Which and how many different products (or industries) are covered in the calculation methodology?
	Source, credibility and transparency of data	Does the data stem form official sources with known credibility and transparency with regard to compilation and quality?
	Data availability	Are there data gaps?

3. Input-output approaches

As mentioned above, the prevailing top-down approaches of material footprint accounting apply economy-wide input-output (IO) analysis. IO economics was founded by the Russian-American economist Wassily Leontief, who investigated how changes in one economic sector affect other sectors (Leontief, 1936; Leontief, 1986). IO tables take an economy-wide, top-down perspective and represent the interlinkages between different branches of a national economy or different regional economies. They show in monetary or physical units the transactions between the different sectors of an economy. Thereby, IO models are flexible tools, which allow integrating data on production inputs (e.g. resources, labour or capital) and calculating indicators on input intensities (Miller and Blair, 2009). The so-called Leontief inverse shows, for each commodity or industry represented in the model, all direct and indirect inputs required along the supply chain for one unit of output delivered to final demand. When this model is extended with environmental data, e.g. on material extraction, the total upstream requirements to satisfy final demand of a country can be determined. Hence, the key assumption in IO accounting is that all material use is driven by final demand and that all material use can be attributed to elements of final demand, following a consistent accounting logic. In the past 15 years, along with the development of multi-regional input-output models covering the whole world economy, input-output analysis became an increasingly popular tool for trade-related environmental assessments as well as for the calculation of consumption-based indicators.

Advantages and disadvantages of input-output approaches

IO analysis, in particular in its multi-regional form, brings along a number of key advantages over other methodological approaches (Wiedmann et al., 2011). The main advantage of input-output analysis is that it allows calculating material footprints for all products or industries, also those with very complex global supply chains, as the whole economic system is included in the calculation system (Bruckner et al., 2012; Chen and Chen, 2013). IO analysis thus avoids truncation errors often occurring in coefficient-based approaches, i.e. errors resulting from the fact that the whole complexity of production chains cannot be fully analysed based on Life Cycle Assessment approaches, so certain upstream chains have to be cut off (see below). Another general feature of IO-based approaches is that they enable disaggregating the RMC indicator by various categories of final demand (such as private consumption, government consumption, capital investment), as well as by the product groups disaggregated in the input-output table.

Multi-regional input-output (MRIO) models also have the advantage to take into account the different resource intensities in different countries (Feng et al., 2011; Tukker et al., 2013; Wiedmann et al., 2011). By following a top-down approach, input-output analysis also avoids double counting. A specific material input can only be allocated once to final consumption, as the supply and use chains are completely represented (Daniels et al., 2011). Input-output approaches thus avoid imprecise definition of system boundaries, which is one key advantage over coefficient approaches as described in the next subsection. Another advantage of the input-output approach is that the accounting framework is closely linked to standard economic and environmental accounting (United Nations, 2012), which ensures that, at least at the national level, a continuous process of data compilation and quality check takes place.

The major disadvantage of IO analysis is the fact that most input-output models work on the level of aggregated economic sectors and product groups, assuming that each sector produces a homogenous product output. This implies that in one sector, a number of different products with potentially very different material intensities are mixed together and averaged. This homogeneity assumption leads to distortions of results, for example, when very different materials such as industrial minerals and metal ores are aggregated into one sector (Schoer et al., 2012a). However, a number of recent research projects have been devoted to the refinement of IO tables and multi-regional input-output systems to calculate footprint-type indicators (Dietzenbacher et al., 2013; Lenzen et al., 2012; Tukker and Dietzenbacher, 2013)[2]. The intentions are to create global harmonised systems, possibly with a higher level of sector detail, in particular in environmentally-sensitive primary sectors (e.g. the mining sectors).

---

[2] Examples include: EXIOPOL (http://www.feem-project.net/exiopol/), FORWAST (http://forwast.brgm.fr/), OPEN-EU (http://www.oneplaneteconomynetwork.org/), CREEA (http://creea.eu/), DESIRE (http://fp7desire.eu/), WIOD (http://www.wiod.org/), Eora (http://worldmrio.org).

A second major disadvantage is that most MRIO-based approaches use the monetary use structures of industries and products to allocate environmental satellite data, such as material extraction, to final demand, assuming proportionality between monetary and physical flows. Monetary structures, however, in many cases do not correspond well to physical use structures, as indeed price differences between different industries can occur (Schoer et al., 2012b), especially in cases where different types of materials are aggregated. The use of physical or mixed-unit input-output tables could avoid or reduce this error. Therefore, efforts are currently put into the replacement of monetary supply and use information by physical data (e.g. in weight or energy units), in order to describe the physical flows independently from prices. Due to data limitations only few examples of comprehensive national IO tables in purely physical units exist (Destatis, 2001; Mäenpää and Muukkonen, 2001; Pedersen, 1999). More recently, Weinzettel et al. (2011) presented a mixed-unit MRIO model covering the global economy. In contrast to physical IO tables, however, they do not attempt to describe all interindustry flows in physical units, but rather extend a monetary MRIO table by detailed physical satellite accounts, which capture physical flows of agricultural products from harvest to processing industries. In a next step, these satellite accounts could be extended based on available data from UN agricultural statistics in order to fully cover all flows of food products from harvest to consumption as proposed by Weinzettel et al. (2014) and Bruckner et al. (2015). Besides overcoming the proportionality assumption, physical or mixed-unit IO models are also used because, in cases where statistics in physical units are available on a much higher level of product detail than economic statistics, as is the case for the agricultural sector, mixed-unit models also help relaxing the homogeneity assumption.

Finally, there is still a lack of harmonisation of IO data across different developers and providers of MRIO data sets, which can cause differences in the material footprint indicator. This is the case as the economic information in input-output tables, e.g. regarding the relative size of certain sectors in the domestic economy, the domestic versus exported shares of final demand or the international trade flows, are not consistent across various MRIO databases.

Available models and data

The following Table 3 provides an overview of existing MRIO-based models to calculate material footprint indicators. It presents six currently existing models comparing them with regard to their main characteristics and underlying data sources. The models have different levels of detail with regard to countries/regions coverage, detailing of material extraction sectors, sector/product detail as well as with regard to available time series.

The models with the broadest country and region coverage are Eora, followed by GTAP and EXIOBASE. Especially with regard to the first two models this large coverage comes at the cost of consistency (e.g. mixing product and industry classification) as well as sector and product detail. When aiming at precisely quantifying the material flows through the economic system, a high level of detail for the primary sectors is crucial. With 26 raw materials and a total number of 200 products, EXIOBASE provides the highest level of consistent product detail among MRIO datasets. Eora's sector detail goes up to 500 for some countries, while for most of the 183 countries included in the database only 26 sectors are distinguished. Finally, all of the presented models aim at complementing their coverage towards complete time series up to the most recent year, with EXIOBASE in its upcoming version 3 even including nowcasts to the year 2016.

IO models are extended with data on material extraction per product or industry. Therefor, two databases with annual time series for global material extraction data have been applied so far: the SERI/WU Global Material Flow database available at www.materialflows.net (SERI and WU Vienna, 2014) and the global material database developed at CSIRO (Schandl and West, 2010; West and Schandl, 2013). Both databases build on databases from international organisations such as the International Energy Agency (IEA), the UN Food and Agriculture Organisation (FAO) and national geological surveys (USGS and BGS).

Table 3: MRIO-based material footprint databases and models and their main characteristics

Databases / models	GTAP 8	WIOD	GRAM	EXIOBASE 3	Eora
Regions	66, 87, 113, 134 (number increasing for later versions)	27 EU countries, 13 other major economies + RoW	48 countries (all OECD countries and other major economies)	44 + 5 RoW	187
Material extractive sectors	15	4	4	26	5
Total number of sectors: industries i / products p	57p	35i / 59p	48i	200p, 163i	20-500p/i
Time series	1997, 2001, 2004, 2007, 2010	1995-2011	1995, 2000, 2005	1995-2011 (2016)	1990-2011
Update frequency	3 years, time lag 5 years	unknown	5 years, time lag 5 years	unknown	regularly
Monetary trade data	UN COMTRADE with high credibility and transparency standards	UN COMTRADE with high credibility and transparency standards	OECD trade data; with high credibility and transparency standards	UN COMTRADE with high credibility and transparency standards	UN COMTRADE / Service Trade data.
Material extraction data	SERI/WU database; complete coverage; builds on official data sources as IEA, USGS, BGS and FAO. Estimation techniques follow official hand books and academic literature.	SERI/WU database. See GTAP entry.	SERI/WU database. See GTAP entry.	SERI/WU database. See GTAP entry.	CSIRO database; complete coverage; builds on official data sources as IEA, USGS and FAO. Estimation techniques follow official hand books and academic literature.

4. Coefficient approaches

In contrast to top-down methods, bottom-up approaches use data on trade in products (in physical units) and multiply these with coefficients on material input per unit of traded product. While IO approaches are oriented towards the final demand, the coefficient approach derives material footprints of apparent consumption, i.e. domestic extraction plus imports minus exports.

The methodology developed and applied by the Wuppertal Institute (Dittrich et al., 2012a; Dittrich et al., 2013; Schütz and Bringezu, 2008) calculates indirect material flows related to international trade by multiplying the physical quantity of each traded product with a coefficient of material inputs required along the production chain. The physical quantities of all traded commodities were taken from the UN Comtrade database. The material coefficients stem from the Wuppertal Institute's material input coefficient (MI) database (Saurat and Ritthoff, 2013) and were derived from process analyses (Schmidt-Bleek, 1992). They encompass upstream flows of both used and unused material extraction including soil erosion. However, the final coefficients do not distinguish between used and unused material flows but provide a total value.

Advantages and disadvantages of coefficient approaches

The most important advantage of coefficient-based bottom-up methods in comparison to economy-based top-down approaches is the high level of detail and transparency, which can be applied. The coefficient approach does not face restrictions regarding the definition of sectors or product groups and thus allows performing very specific comparisons of footprints down to the level of single products or materials (Dittrich et al., 2012a). This approach therefore allows for illustrating the composition of material footprints by commodity or product category in a very straightforward and transparent manner, as the overall numbers are summed up from the bottom (Mekonnen and Hoekstra, 2011).

One key disadvantage of coefficient approaches is the high level of effort to construct solid coefficients for a large number of especially highly processed products. These approaches are therefore often applied to assess the resource requirements of raw materials and basic products. The availability of coefficients for finished products with highly complex supply chains, however, is limited and double-counting is possible especially in cases where products are passing more than one border in one or different processing stages, as these products are accounted for each time they pass the border (Dittrich et al., 2012a). For instance, car components traded at the border between Austria and Germany will be accounted for as imports into Germany and multiplied with a respective coefficient. The car containing the components, assembled in Germany but then exported to Sweden will be treated as imports to Sweden and multiplied with another coefficient which does not subtract the indirect flows contained in the Austrian-German factor. Coefficient approaches also produce truncation errors, as indirect material requirements are only traced along a few processing steps. Inter-sectoral deliveries have to be cut-off at some point due to data availability (Feng et al., 2011). Existing coefficient life-cycle data bases (such as Ecoinvent) also underestimate the total environmental consequences of a national economy, as life-cycle data for services are largely missing (Schmidt and Weidema, 2009). Furthermore, issues such as infrastructure inputs are often neglected in the construction of conversion factors, thus causing an underestimation of the total footprint related to final consumption (Dittrich et al., 2013). Moreover, in contrast to IO or hybrid approaches, coefficient approaches cannot separate imports, which are directly and indirectly serving domestic final demand from those imports, which are required by the domestic economy to produce exports.

The fact that coefficients are only available for one point in time results in the fact that technological improvements are not reflected and resulting environmental pressures can be overestimated. The same holds true for limited coverage of geographical specifications, where in many cases national data have to be estimated by global averages. Coefficients are mostly based on selected studies and not on a systematic statistical census, which means that coefficients depict a specific state of technology in a certain geographical area and at a certain time which is then often assumed to be the same elsewhere (Schaffartzik et al., 2009).

Available approaches and data

Table 4 provides an overview of Wuppertal Institute's coefficient-based approach to calculate comprehensive material flow indicators with its main characteristics. This approach uses the UN COMTRADE database on physical trade, with its advantage of high credibility and transparency standards, but at the same time a number of data gaps. Trade data are available for a large number of countries (173) and products (more than 3,500 products on the 5-digit level) and for a long time series. With regard to the material coefficients, data are based on numerous industry and scientific studies. However, due to data limitations, coefficients are currently only available for around 200 products and product groups. For more detail on the coefficient approach, see the Supplementary Information.

Table 4: Main characteristics of the Wuppertal Institute's coefficient-based material footprint approach

Trade data source	UN COMTRADE with high credibility and transparency standards, but coverage gaps; Missing data are estimated via average prices.
Regions	173 country reporters, 215 trading partners
Total number of products	Data available for the 5-digt level (more than 3,500 products) and more aggregated
Time series	Physical trade data available in annual time series Material input coefficients only available for one or several years, depending on the raw material / product
Update frequency	Continuously
Material coefficients	Main source: Wuppertal Institute's MI database; majority of coefficients for one specific (mainly European) country - e.g. Germany; in some cases world averages; Database covers more than 200 products (status 2010), with differing level of detail among product groups (e.g. 6 for fertilizers, 37 for metals); timeliness differs significantly among material groups (t-10 to t-2), no time series available. Coefficients contain used and unused extraction; Disaggregation is not possible.

5. Hybrid approaches

In the past few years, hybrid approaches became increasingly popular for calculations of comprehensive material flow indicators. These approaches combine input-output analysis with process-based material intensity coefficients and aim at exploiting the advantages of both approaches. Again, note that with the term "hybrid" we refer to a combination of methodological approaches and not to the use of monetary and physical data within an input-output table. The latter might play a role in hybrid approaches though.

Hybrid approaches apply a differentiated perspective to the calculation particularly of the indirect material requirements of imports. For semi-manufactured and highly manufactured products, hybrid approaches apply the domestic technology assumption, i.e. they approximate the Raw Material Equivalents (RME) of imports by using the domestic input-output structure, assuming that the imported goods have been produced using the same technology as prevailing in the importing country. However, for some products, which are either not produced at all in the country or produced with a different set of technologies, this assumption can lead to significant errors. Therefore, for these specific imports, the Raw Material Equivalents are calculated applying process-based material intensity coefficients, which are derived from process analyses (LCA). This LCA component is particularly applied for raw materials, such as metal ores, fossil fuels or certain agricultural products with a low levels of processing.

Applying process-based coefficients to selected products allows reflecting specific aspects with regard to different materials, applied technologies and countries of origin. At the same time, processed commodities and finished goods with more complex production chains are treated with the input-output methodology, which allows considering the full upstream resource requirements and thus illustrating all indirect effects.

Advantages and disadvantages of hybrid approaches

Hybrid approaches have the key advantage of exploiting the complementary strengths of the two underlying methods, i.e. the coverage of all indirect effects and all supply chains through input-output analysis with the high resolution for key products, in particular imports of raw materials, through the application of physical trade data and process-based material intensity coefficients. This type of approach can thus ensure comprehensiveness and accuracy at the same time.

Hybrid approaches have so far been applied only for specific European countries or the aggregate EU, using an input-output table for a single region as the core of the model. On the one hand, this constitutes a certain limitation, as global aspects such as differences in applied technologies are not fully taken into account. On the other hand, the level of acceptance and quality of the underlying data is generally high, as all data, including input-output tables, physical and monetary trade data, and material extraction data, were taken from official statistical sources. The process-based material intensity coefficients stem from a variety of LCA databases (including Ecoinvent and GEMIS) and many other sources, and it is therefore more difficult to evaluate the quality of the data.

All reviewed approaches used different data sources for input-output and trade data as well as for material intensity coefficients. Hence, while the results of the different approaches regarding the RMC indicator can be compared, the reasons for the differences in the results are very difficult to trace. They can be rooted for example in the different sector disaggregation of the IO table, the use of different data on material extraction or the use of different LCA studies as source of material coefficients.

As an additional feature, the German Statistical Office (Destatis, 2009) and EUROSTAT (Schoer et al., 2012b) have developed a hybrid approach by replacing monetary transaction data in the input-output tables by detailed physical supply and use data in weight units from the German Statistical Office. However, this detailed supply and use table is not publicly available, which impedes easy replication of this particular approach by other countries.

A common feature of all hybrid approaches is also that available results are not up-to-date, i.e. the EUROSTAT approach delivers the most recent calculations for 2012. Other hybrid approaches have 2003 to 2010 as their latest year. However, all approaches could potentially be updated on a regular basis, as the required base data are available for more recent years. As for the IO approach, the input-output tables with a release delay of at least two years represent the main constraint. Moreover, in all available studies, material intensity coefficients are not available in time series, thus one factor is applied across the whole time period.

So far, all hybrid approaches apply the domestic technology assumption for calculating the material footprints of a large number of imported products assuming that imports are produced with the same technologies as in the economy under observation, which can lead to distorted results. Hybrid approaches have so far not been applied using multi-regional input-output models, which would help avoiding the domestic technology assumption.

Overview of existing approaches and data

Table 5 provides an overview of existing hybrid approaches to calculate material footprint indicators with their main characteristics. The overview encompasses five approaches, one designed for the aggregate European Union (EUROSTAT approach) and four applied for specific European countries. Product details are similar (at around 60 products) – with the exception of the very detailed Eurostat approach, which distinguishes 166 products. Also, the level of detail of the available documentation is high for all these approaches. Interestingly, the five approaches apply material coefficients from a number of different data sources ranging from the LCA databases Ecoinvent and GEMIS to product studies from academic and industry sources.

Table 5: Hybrid material footprint approaches and their main characteristics

	EUROSTAT	DESTATIS / UBA	ISTAT	CUEC	SEC
Regions	1 (EU-27)	1 (Germany)	1 (Italy)	1 (Czech Republic)	1 (Austria)
Number of material categories separately calculated	48	55	30	unknown	16
Total number of products in input-output table	166	72	59	60	57
Time series	2000-2012	2000-2010	1995-2008	1995-2010	1995-2012
Update frequency	annual	annual	unknown	unknown	annual
Monetary trade data	Official EUROSTAT statistics	German Statistical Office	Italian Statistical Office and COMEXT	Czech Statistical Office	Austrian Statistical Office
Physical trade data	Official EUROSTAT statistics	German Statistical Office	Unknown	Czech Statistical Office	Austrian Statistical Office
Material extraction data	Official EUROSTAT statistics	German Statistical Office	Italian Statistical Office	Czech Statistical Office	Austrian Statistical Office
Material coefficients / RME factors	Main source for RME factors: Ecoinvent 2.0 for the "LCA products". Additional data, e.g. from USGS and mining reports, for metal ores.	Coefficients from the German Federal Environment Agency; Detailed documentation of material coefficients available	See Eurostat approach	Main source for RME factors: Ecoinvent 2.0	Coefficients from GEMIS database. Documentation underlying the various coefficients is available

6. Summary of advantages and disadvantages

The comparative evaluation revealed that each of the three main approaches to calculate material footprint indicators has its advantages, but also drawbacks; hence, no ideal approach can be identified.

In the following we provide a summary of the comparative evaluation of the different methodologies with regard to the specific criteria as identified at the beginning of this paper. A more detailed descriptive assessment can be found in Lutter and Giljum (2014).

Table 6: Key advantages and disadvantages of the different approaches to calculate material footprint indicators

Topic	Input-output approaches	Coefficient approaches	Hybrid approaches
Supply chain coverage	+ Full coverage of supply chains of all products / product groups, as the whole (global) economy sets the boundary for the assessment - Use of monetary use structures of industries and product groups to allocate material extraction to final demand via supply chains, which differ from physical use structures, in particular for raw materials, leading to distortions in the results	- High level of effort to construct solid coefficients for higher processed products, thus availability of coefficients for finished products with complex supply chains very restricted	+ In some hybrid approaches: Better reflection of flows of materials through the economy by creation of mixed-unit tables, which integrate physical data + Exploiting the complementary strengths of input-output analysis (coverage of supply chains) and coefficient approaches (high resolution for key products), thus producing very accurate results in terms of comprehensiveness and preciseness
Avoidance of double counting	+ Avoidance of double counting as supply chains clearly distinguished from each other	- Double-counting possible in case products are passing more than one border in one or different processing stages	- Double-counting possible due to the application of coefficients
System boundary / cut-off level	+ Calculating material footprints for all products and all sectors, also those with very complex supply chains – avoidance of "truncation errors", as all indirect effects are covered + Precise definition of system boundaries	- Truncation errors, as indirect material requirements not traced along entire industrial supply chains - Underestimation of total environmental consequences of national economy, as life-cycle data for services are largely missing	- Possible truncation errors regarding the indirect material flows of imports due to the use of coefficients
Specification of consumption	+ Disaggregation of material consumption by final demand categories (e.g. private consumption, government consumption, investment, etc.) + Disaggregation of indicators by industries or product groups contributing to overall RMC + Disaggregation by material group	- Only disaggregation by material group, as concept of "apparent consumption" (i.e. intermediate plus final consumption) is applied	+ Disaggregation of comprehensive material consumption indicators by different categories of final demand (e.g. private consumption, government consumption, investment, etc.) + Disaggregation of indicators by industries or product groups contributing to overall RMC + Disaggregation by material group
Regional/country detail	+ In the case of multi-regional models: full consideration of different material intensities for a large number of countries	- Limited differentiation for coefficients regarding countries of origin	- Approaches only applied for a small number of countries and aggregated EU with very limited comparability; even pilot data are missing for many countries. - All hybrid approaches so far apply the "Domestic Technology Assumption" for

			a large number of imports, thus creating mistakes. No hybrid multi-region approach tested so far.
Product detail	- Assumption of a homogenous product output for aggregated economic sectors and product groups, leading to distortions of results, in particular when price to weight ratios are very different for products in one group	+ Very high level of product detail, as coefficients can be calculated for a large number of single products + No restrictions of sector or product group definition, as products can be aggregated according to any selected classification	+ High product detail in the basic calculations of indirect flows of imports - When linking the data to the IO model, these flows need to be aggregated to fit to the sector detail of the IO table, possibly leading to distorted results due to the violation of the homogeneity assumption
Source, credibility and transparency of data	+ Accounting framework closely linked to standard economic and environmental accounting - Procedures for manipulating input-output tables, e.g. for disaggregating existing tables or harmonizing input-output tables from different national sources, often not well documented and subject to assumptions	+ Simple and transparent method - Varying quality and limited transparency regarding coefficients	+ Large control over input data, as material flow data as well as trade and input-output data can be taken from official national statistics + High acceptance especially among European statistical institutions - Varying quality and limited transparency regarding coefficients
Data availability	+ Harmonised input-output tables are available for OECD countries - Availability of input-output tables of particularly non-OECD countries often limited + Global material extraction databases available, with uncertainties regarding some material categories (e.g. construction minerals, biomass uptake by animals/grazing)	- Coefficients mostly available only for one point in time and for a specific producer, hence do not reflect variations in technology over time and between producers or regions	+ Harmonised input-output tables are available for OECD countries - Some studies used detailed and unpublished data from the German statistical office and Eurostat, limiting replicability.

7. Conclusions and recommendations

The aim of this paper was to provide a comprehensive review and comparative assessment of the currently existing methodologies to calculate material footprint indicators on the economy-wide level. We found that three methodological approaches have been developed and applied so far: environmental input-output analysis (top-down), coefficient-based approaches (bottom-up) building on process analysis, and hybrid approaches combining elements from both input-output analysis and coefficient approaches. We assessed strengths and weaknesses of the three methodological approaches and evaluated them with regard to their state of development and readiness for implementation. The assessment revealed that – given the current data situation – none of the three approaches can be addressed as the optimal method, as each of them has specific advantages and disadvantages.

In the following, we therefore specify the main areas for future improvements and developments towards a robust accounting method for material footprint indicators across the various methods. Thereby we cluster them into actions to be set regarding (1) physical flow data, (2) extended data coverage, and (3) process and institutional aspects.

Physical flow data

Global material extraction data

For the calculation of material-related indicators it is a prerequisite to have a detailed dataset on global material extraction. Statistical offices such as EUROSTAT only recently made material accounting obligatory, resulting in more comprehensive datasets provided by EU Member States. However, these recent developments are reflected in the fact that official time series exist for recent years only (currently 2000-2013, in the case of Eurostat's material accounts) and are missing for many countries, in particular beyond the group of OECD countries.

Hence developers of MRIO-models often resort to academic sources providing more extensive global databases compiled from various statistical datasets. Examples are the above mentioned SERI/WU Global Material Flow Database (www.materialflows.net) (SERI and WU Vienna, 2014) as well as the global material flow database developed by CSRIO (Schandl and West, 2010; West and Schandl, 2013). There are ongoing efforts of these providers to further harmonize data and come up with one consistent worldwide dataset in the context of an ongoing project of the UNEP International Resource Panel (Schandl et al., forthcoming).

Physical trade data

Physical trade data are of high relevance especially when used for hybrid approaches where physical trade flows are multiplied with RME coefficients; but also in the context of linking national input-output tables to set up a multi-regional framework. The data situation seems to be satisfying for the national level in EU countries; however, on the international level, data are less reliable. Dittrich et al. (2012a) use the UN COMTRADE database providing data from 1962 up to the most recent year, applying high credibility and transparency standards. However, in UN COMTRADE data in physical units are incomplete and have to be estimated e.g. via average prices.

Hence, for a global application of hybrid approaches improving the data situation as well as further research on the completion of patchy physical trade data is required.

Extended data coverage

Product and region coverage and detail

Input-output tables generally provide high detail for manufacturing and service sectors, which contribute the highest shares to GDP; but material extraction and processing sectors, which are more relevant for material flows, are often highly aggregated. Providing a more detailed disaggregation of material intensive sectors allows considering the different use structures of various raw materials and avoiding errors due to aggregation of inhomogeneous products.

Such a disaggregation should go hand in hand with an integration of physical data into the MRIO system. On the one hand, physical data are often available in more detail than the monetary flow data and hence can be used for the disaggregation purpose. On the other hand, using physical data in specific cases instead of monetary data (a so-called "mix-unit MRIO") allows for better reproducing physical flows through the economic system.

A disaggregation is also needed to improve the suitability of the approach for the assessment of materials embodied in trade and final demand. Disaggregation would also be beneficial for linking the material flow indicators to assessments of environmental impacts using approaches of life cycle assessments (for example, Finnveden et al., 2009; Klinglmair et al., 2014).

Hand in hand with the need for a higher product detail goes the requirement for the compilation of input-output tables for a larger number of countries – especially non-OCED countries, where a significant share of global material extraction takes place. This would help avoiding the application of estimation procedures for countries lacking official data. Setup and harmonisation could be monitored by international organisations, such as the OECD, which already pursues a regular process of publishing harmonised input-output tables (OECD, 2015b). This would reduce the variance of results and thus contribute to the acceptance of the material footprint indicator in policymaking.

Timeliness and time series of input-output tables and coefficients

To evaluate developments in material use of countries or sectors over time as well as to assess the effectiveness of resource policies, the availability of time series of input-output tables and/or material coefficients is essential.

Efforts should be increased in the area of so-called "now-casting", i.e. extending time series to the current year, or even "forecasting" data and indicators into the future. Current activities in the European research project "DESIRE"[3] aim at providing

[3] See fp7desire.eu for more details about the „DESIRE" project.

fully now-casted time series of the global MRIO system as well as all environmental extensions, including material extraction, until the year 2016.

The time component is also crucial with regard to material coefficients, which are applied in coefficient and hybrid approaches. Existing datasets such as the above mentioned material input coefficients database (Wuppertal Institute, 2013), as well as coefficients produced with hybrid approaches, for example, from the Eurostat model (EUROSTAT, 2013b), so far only partly consider a time dimension in their material coefficients. Full time series would be required in order to consider changes in material inputs, e.g. regarding changes in metal ore concentrations over time (see e.g. Mudd, 2010) or changes in production technologies.

Process and institutional aspects

Credibility and transparency of data sources

As mentioned above, the usefulness of the analysed methods depends significantly on the data in use. In order to set up a global, hybrid MRIO model and to ensure its reproducibility as well as its application, it is of highest importance that the data in use are readily available and were produced following harmonised standards and by credible data providers, to reach higher consistency and reduce uncertainty in the material footprint results. In this regard, especially procedures of data manipulation and the assumptions applied in the construction of IO data sets are often not sufficiently documented, hampering a quality evaluation by users. There is hence a strong need for comprehensive and clear documentation. Additionally, accounting frameworks and data used for the preparation of input-output tables need to be closely linked to standard economic and environmental accounting, as this also increases acceptance by statisticians and policy makers.

Improvement in official data collection and indicator calculation

Improvements of data collection and of the material flow accounting methodologies applied by statistical offices are resource intensive and costly. Adding this burden to the current workload of statistical officers will not allow for a satisfying result, i.e. regular, up-to-date and high-quality data collection. Hence, political support is needed to ensure that statistical offices have the required staff to competently and effectively implement the program for calculating, monitoring and reporting material flow indicators including material footprints.

In addition to attempts by official institutions, there are various initiatives which aim at improving accounting methodologies and data collection – often with a lack of coordination which leads to parallel processes and lack of funds due to fragmentation. Entrusting one organization or agency with the leadership role in the process of data creation and methodological development could help optimizing cost and time effectiveness of current development efforts. Such a leadership role should also include identifying (pro)active countries working on such issues and facilitating exchange between their statistical offices in order to build a critical mass of experienced experts able to inform and encourage other countries to follow.

Benefits for other applications

A comprehensive MRIO system would significantly improve the calculation of other footprint-type indicators (e.g. water, land, CO_2, etc.). Thereby, the beauty lies in the fact that all the different footprints can be calculated with the same methodological basis making the results directly comparable.

Further, such a detailed data system can also be applied in other environmental-economic modelling contexts, for example when constructing and evaluating scenarios. Technological improvements in specific sectors could be incorporated in the model to predict changes in the overall footprint(s).

8. Acknowledgements

This work was funded by the German Federal Environment Agency under the Environmental Research Plan (UFOPLAN, project number 3713 93 150).

9. References

Arto, I., Genty, A., Rueda-Cantuche, J.M., Villanueva, A., Andreoni, V., 2012. Global Resources Use and Pollution:Vol. I, Production, Consumption and Trade (1995-2008), JRC scientific and policy reports European Commission Joint Research Centre (Institute for prospective technological studies), Luxembourg.

BFS, 2015. Der Material-Fussabdruck der Schweiz. Bundesamt für Statisitk BFS, Neuchâtel.

Bruckner, M., Fischer, G., Tramberend, S., Giljum, S., 2015. Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods. Ecological Economics 114, 11-21.

Bruckner, M., Giljum, S., Lutz, C., Wiebe, K., 2012. Materials embodied in international trade - Global material extraction and consumption between 1995 and 2005. Global Environmental Change 22, 568–576.

Chen, Z.-M., Chen, G.Q., 2013. Virtual water accounting for the globalized world economy: National water footprint and international virtual water trade. Ecological Indicators 28, 142-149.

Daniels, P.L., Lenzen, M., Kenway, S.J., 2011. The ins and outs of water use–a review of multi-region input–output analysis and water footprints for regional sustainability analysis and policy. Economic Systems Research 23, 353-370.

Destatis, 2001. A Physical Input-Output Table for Germany 1995. German Federal Statistical Office, Wiesbaden.

Destatis, 2009. Verbesserung von Rohstoffproduktivität und Ressourcenschonung. Weiterentwicklung des direkten Materialinputindikators. Statistisches Bundesamt, Wiesbaden.

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., de Vries, G., 2013. The Construction of World Input–Output Tables in the WIOD Project. Economic Systems Research 25, 71-98.

Dittrich, M., Bringezu, S., Schütz, H., 2012a. The physical dimension of international trade, part 2: Indirect global resource flows between 1962 and 2005. Ecological Economics 79, 32–43.

Dittrich, M., Giljum, S., Lutter, S., Polzin, C., 2012b. Green economies around the world? The role of resource use for development and the environment, Vienna & Heidelberg.

Dittrich, M., Giljum, S., Lutter, S., Polzin, C., 2013. Aktualisierung von nationalen und internationalen Ressourcenkennzahlen. Umweltbundesamt, Dessau.

Elshkaki, A., Graedel, T., 2013. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. Journal of Cleaner Production 59, 260-273.

European Commission, 2011. Roadmap to a Resource Efficient Europe. European Commission, Brussels.

European Commission, 2014. Analysis of an EU target for Resource Productivity. European Commission, Brussels.

EUROSTAT, 2001. Economy-wide material flow accounts and derived indicators. A methodological guide. Statistical Office of the European Union, Luxembourg.

EUROSTAT, 2013a. Economy-wide Material Flow Accounts (EW-MFA). Compilation Guide 2013. Statistical Office of the European Communities, Luxembourg.

EUROSTAT, 2013b. Estimates for Raw Material Consumption (RMC) and Raw Material Equivalents (RME) conversion factors. Statistical Office of the European Communities, Luxembourg.

EUROSTAT, 2015. Handbook for estimating Raw Material Equivalents of imports and exports and RME-based indicators on country level – based on Eurostat's EU RME model. Statistical Office of the European Communities, Luxembourg.

Femia, A., Moll, S., 2005. Use of MFA-related family of tools in environmental policy-making. Overview of possibilities, limitations and existing examples of application in practice. European Environment Agency, Copenhagen.
Feng, K., Chapagain, A., Suh, S., Pfister, S., Hubacek, K., 2011. Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. Economic Systems Research 23, 371-385.
Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. Journal of environmental management 91, 1-21.
Fischer Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and Indicators of Economy wide Material Flow Accounting State of the Art and Reliability Across Sources. Journal of Industrial Ecology 15, 855–876.
Giljum, S., Dittrich, M., Lieber, M., Lutter, S., 2014a. Global patterns of material flows and their socio-economic and environmental implications: a MFA study on all countries world-wide from 1980 to 2009. Resources 3, 319-339.
Giljum, S., Lutter, S., Bruckner, M., Aparcana, S., 2013. State of play of national consumption-based indicators. A review and evaluation of available methods and data to calculate footprint-type (consumption-based) indicators for materials, water, land and carbon. Report for DG Environment of the European Commission. Sustainable Europe Research Institute (SERI), Vienna.
Giljum, S., Martinez, A., Bruckner, M., 2014b. Material Footprint Assessment in a Global Input-Output Framework. Journal of Industrial Ecology. Forthcoming.
Klinglmair, M., Sala, S., Brandão, M., 2014. Assessing resource depletion in LCA: a review of methods and methodological issues. The International Journal of Life Cycle Assessment 19, 580-592.
Kovanda, J., 2013. Material Consumption in the Czech Republic: Focus on Foreign Trade and Raw Material Equivalents of Imports and Exports. Statistica 93, 32-46.
Kovanda, J., Weinzettel, J., 2013. The importance of raw material equivalents in economy-wide material flow accounting and its policy dimension. Environmental Science & Policy 29, 71-80.
Lansche, J., Lübs, H., Giegrich, J., Liebich, A., Heidelberg, U., 2007. Ermittlung und Bereitstellung von Koeffizienten zum Rohstoffeinsatz bei Importgütern. ifeu, Heidelberg.
Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2012. Building Eora: A global multi-region input-output database at high country and sector resolution. Econ. Syst. Res.
Leontief, W., 1936. Quantitative input-output relations in the economic system. Review of Economic Statistics 18, 105-125.
Leontief, W., 1986. Input-Output Economics. Oxford University Press, Oxford.
Lindner, S., Guan, D., 2014. A Hybrid - Unit Energy Input - Output Model to Evaluate Embodied Energy and Life Cycle Emissions for China's Economy. Journal of Industrial Ecology 18, 201-211.
Lutter, S., Giljum, S., 2014. Further Development of Material and Raw Material Input Indicators – Methodological Discussion and Approaches for Consistent Data Sets. A review of existing approaches. Ecologic Institute, Berlin.
Mäenpää, I., Muukkonen, J., 2001. Physical Input-Output in Finland: Methods, Preliminary Results and Tasks Ahead, Economic growth, material flows and environmental pressure, Stockholm, Sweden.
Majeau-Bettez, G., Wood, R., Strømman, A.H., 2014. Unified Theory of Allocations and Constructs in Life Cycle Assessment and Input-Output Analysis. Journal of Industrial Ecology, n/a-n/a.

Marra Campanale, R., Femia, A., 2013. An Environmentally Ineffective Way to Increase Resource Productivity: Evidence from the Italian Case on Transferring the Burden Abroad. Resources 2, 608-627.
Mekonnen, M.M., Hoekstra, A.Y., 2011. National water footprint accounts: the green, blue and grey water footprint of production and consumption. UNESCO-IHE, Delft, the Netherlands.
Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions. Second edition. Cambrige University Press.
Moran, D., McBain, D., Kanemoto, K., Lenzen, M., Geschke, A., 2014. Global Supply Chains of Coltan. Journal of Industrial Ecology.
Mudd, G.M., 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resources Policy 35, 98-115.
Nakajima, K., Ohno, H., Kondo, Y., Matsubae, K., Takeda, O., Miki, T., Nakamura, S., Nagasaka, T., 2013. Simultaneous material flow analysis of nickel, chromium, and molybdenum used in alloy steel by means of input–output analysis. Environmental Science & Technology 47, 4653-4660.
Nakamura, S., Nakajima, K., Yoshizawa, Y., Matsubae - Yokoyama, K., Nagasaka, T., 2009. Analyzing Polyvinyl Chloride in Japan With the Waste Input– Output Material Flow Analysis Model. Journal of Industrial Ecology 13, 706-717.
Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Suh, S., Shigetomi, Y., Oshita, Y., 2014. Global Flows of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum. Environmental Science & Technology 48, 1391-1400.
OECD, 2007. Measuring material flows and resource productivity. The accounting framework Environment Directorate. Organisation for Economic Co-operation and Development, Paris.
OECD, 2008. Measuring Material Flows and Resource Productivity. The OECD guide Environment Directorate. Organisation for Economic Co-operation and Development, Paris.
OECD, 2011a. Monitoring progress towards green growth. OECD indicators. Organisation for Economic Cooperation and Development, Paris.
OECD, 2011b. Resource Productivity in the G8 and the OECD. Organisation for Economic Cooperation and Development, Paris.
OECD, 2014. Green Growth Indicators 2014. Organization for Economic Cooperation and Development, Paris.
OECD, 2015a. Material Resources, Productivity and the Environment. OECD Green Growth Studies. OECD Publishing, Paris.
OECD, 2015b. OECD Inter-Country Input-Output (ICIO) Tables, edition 2015. Organisation for Economic Co-operation and Development, Paris.
Onat, N.C., Kucukvar, M., Tatari, O., 2014. Scope-based carbon footprint analysis of US residential and commercial buildings: An input–output hybrid life cycle assessment approach. Building and Environment 72, 53-62.
Pedersen, O.G., 1999. Physical Input-Output Tables for Denmark. Products and materials 1990. Air emissions 1990-92. Statistics Denmark, Copenhagen.
Rodríguez-Alloza, A.M., Malik, A., Lenzen, M., Gallego, J., 2015. Hybrid input–output life cycle assessment of warm mix asphalt mixtures. Journal of Cleaner Production 90, 171-182.
Saurat, M., Ritthoff, M., 2013. Calculating MIPS 2.0. Resources 2, 581-607.
Schaffartzik, A., Eisenmenger, N., Krausmann, F., Weisz, H., 2013. Raw Material Equivalents (RME) of Austria’s Trade. Institute of Social Ecology, Vienna.
Schaffartzik, A., Eisenmenger, N., Krausmann, F., Weisz, H., 2014. Consumption-based Material Flow Accounting. Austrian Trade and Consumption in Raw Material Equivalents 1995–2007. Journal of Industrial Ecology 18, 102-112.

Schaffartzik, A., Krausmann, F., Eisenmenger, N., 2009. Der Rohmaterialbedarf des österreichischen Außenhandels – Weiterentwicklung und Analyse. Institute for Social Ecology, Vienna.
Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., Fishman, T., forthcoming. Global Material Flows and Resource Productivity. Assessment Report for the UNEP International Resource Panel. UNEP IRP, Paris.
Schandl, H., West, J., 2010. Resource use and resource efficiency in the Asia–Pacific region. Global Environmental Change 20, 636-647.
Schmidt-Bleek, F., 1992. MIPS - A Universal Ecological Measure. Fresenius Environmental Bulletin 2, 407-412.
Schmidt, J., Weidema, B.P., 2009. Carbon footprint labeling – how to have high data quality and to maximize utilization. 2.0 LCA Consultants, Aarhus.
Schoer, K., Giegrich, J., Kovanda, J., Lauwigi, C., Liebich, A., Buyny, S., Matthias, J., Germany–Consultants, S.S., 2012a. Conversion of European Product Flows into raw material equivalents. ifeu, Heidelberg.
Schoer, K., Weinzettel, J., Kovanda, J., Giegrich, J.r., Lauwigi, C., 2012b. Raw Material Consumption of the European Union–Concept, Calculation Method, and Results. Environmental Science & Technology 46, 8903-8909.
Schoer, K., Wood, R., Arto, I., Weinzettel, J., 2013. Estimating Raw Material Equivalents on a macro-level: Comparison of multi-regional input output analysis and hybrid LCA-IOA. Environmental Science & Technology 47, 14282−14289.
Schütz, H., Bringezu, S., 2008. Resource consumption of Germany - indicators and definitions. Federal Environment Agency Dessau/Germany.
SERI, WU Vienna, 2014. Global Material Flow Database. 2014 Version. Available at www.materialflows.net. Sustainable Europe Research Institute, Vienna.
Steinberger, J.K., Krausmann, F., Eisenmenger, N., 2010. Global patterns of material use: a socioeconomic and geophysical analysis. Ecological Economics 69, 1148-1158.
Steinberger, J.K., Krausmann, F., Getzner, M., Schandl, H., West, J., 2013. Development and Dematerialization: An International Study. PloS one 8, e70385.
Suh, S., Nakamura, S., 2007. Five years in the area of input-output and hybrid LCA. The International Journal of Life Cycle Assessment 12, 351-352.
Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda Cantuche, J.M., Bouwmeester, M., Oosterhaven, J., Drosdowski, T., 2013. EXIOPOL–Development and illustratvie analyses of detailed global MR EE SUT/IOT. Economic Systems Research 25, 50-70.
Tukker, A., Dietzenbacher, E., 2013. Global Multiregional Input–Output Frameworks: An Introduction and Outlook. Economic Systems Research 25, 1-19.
UNCTAD, 2012. Economic development in Africa. 2012 report. Structural transformation and sustainable development, New York and Geneva.
UNEP, 2011. Towards a green economy. Pathways to sustainable development and poverty eradication. UNEP.
UNEP, 2013a. Recent Trends in Material Flows and Resource Productivity in Asia and the Pacific. UNEP Division of Early Warning and Assessment, Bangkok.
UNEP, 2013b. Recent trends in material flows and resource productivity in Latin America, Nairobi.
United Nations, 2012. System of Environmental-Economic Accounting. Central Framework New York.
Watanabe, M.D., Chagas, M.F., Cavalett, O., Guilhoto, J.J., Griffin, W.M., Cunha, M.P., Bonomi, A., 2015. Hybrid Input - Output Life Cycle Assessment of First -

and Second - Generation Ethanol Production Technologies in Brazil. Journal of Industrial Ecology. DOI: 10.1111/jiec.12325.

Watson, D., Fernández, J.A., Wittmer, D., Pedersen, O.G., 2013. Environmental pressures from European consumption and production. A study in integrated environmental and economic analysis. European Environment Agency, Copenhagen.

Weinzettel, J., Kovanda, J., 2009. Assessing socioeconomic metabolism through hybrid life cycle assessment. Journal of Industrial Ecology 13, 607-621.

Weinzettel, J., Steen-Olsen, K., Hertwich, E.G., Borucke, M., Galli, A., 2014. Ecological footprint of nations: Comparison of process analysis, and standard and hybrid multiregional input–output analysis. Ecological Economics 101, 115-126.

Weinzettel, J., Steen-Olson, K., Galli, A., Cranston, G., Ercin, E., Hawkins, T., Wiedmann, T., Hertwich, E.G., 2011. Footprint Family Technical Report: Integration into MRIO model. OPEN-EU project report. NTNU, Trondheim.

West, J., Schandl, H., 2013. Material use and material efficiency in Latin America and the Caribbean. Ecological Economics 94, 19-27.

Wiebe, C., Bruckner, M., Giljum, S., Lutz, C., Polzin, C., 2012. Carbon and materials embodied in the international trade of emerging economies: A multi-regional input-output assessment of trends between 1995 and 2005. Journal of Industrial Ecology 16, 636–646.

Wiedmann, T., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2013. The material footprint of nations. Proceedings of the National Academy of Sciences (PNAS).

Wiedmann, T., Wilting, H.C., Lenzen, M., Lutter, S., Palm, V., 2011. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. Ecological Economics 70, 1937-1945.

Wiedmann, T.O., Schandl, H., Moran, D., 2014. The footprint of using metals: new metrics of consumption and productivity. Environmental Economics and Policy Studies, 1-20.

Wuppertal Institute, 2013. Material intensity of materials, fuels, transport services, food. Wuppertal Institute for Climate, Environment and Energy