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Draft guidance on measuring demand-based material flows

Consultant report

This document presents the revised draft guidance for measuring demand-based material flows (material footprints) building on earlier empirical studies.

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The draft guidance is submitted to WPEI Delegates for a second reading, considering their country's experience and needs. Detailed written comments should be sent to the OECD Secretariat via the WPEI community site by Friday 20 January 2023 cob.

The draft guidance will subsequently be finalised by the Secretariat in consultation with international partners.

Action required: for discussion

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Guidance document on measuring demand-based material flows (material footprints)

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1. Introduction

1. Natural resources are fundamental for societal and human wellbeing and economic production and consumption. They provide the material basis for production-consumption systems, are an important source of income and jobs, and supply food, energy and other commodities to households. At the same time, the extensive use of natural resources in our economy drives the destruction of ecosystems and climate change, which calls for a transition towards a resource efficient and sustainable economy.

2. Policies that promote the transition towards a low-carbon, resource efficient and circular economy need to be based on sound scientific knowledge. Comprehensive datasets and indicators are a prerequisite for the policy and business community, as they assist in monitoring progress and evaluating the effectiveness of policy programmes and business decisions that aim to achieve sustainable levels of natural resource use. To fulfil this role, data and indicators need to be of high quality and internationally comparable. The OECD has supported the process of developing datasets and indicators that are conceptually sound, policy relevant and easy to establish. Indicators need to be selected according to well-specified criteria, as they need to be able to clearly address the information needs of policy makers and the public (OECD, 2011).

3. The UN System of Environmental-Economic Accounts (SEEA) provides the overarching framework for organising environmental data in a way that is compatible with the guidelines of standard economic accounting (UNDESA, 2013). Based on the SEEA framework, a wide range of environmental indicators can be derived. Material flow accounts provide one core pillar of the SEEA and promoting the use of material flow-based indicators was also in the core of the two "Recommendations of the OECD Council on Resource Productivity" (OECD, 2004, 2008). They aimed at improving the extent and quality of data on material flows within and among countries.

4. So far, in the domain of material flow accounts, the territorial indicator "Domestic Material Consumption (DMC)" has been the most widely applied indicator, because it can be derived directly from reported statistical data and it directly relates to the national political sphere of action (Krausmann et al., 2017). However, DMC needs to be complemented by demand- or consumption-based indicators of material use, as DMC does not account for 'upstream' material requirements. Countries can apparently decrease their material use through outsourcing the material basis to other countries.

5. The territorial DMC indicator needs to be complemented with a demand-based indicator (also called consumption-based indicator or footprint indicator), in order to provide an effective compass for policy design and monitoring. The demand-based material flow indicator is the "material footprint (MF)", which is also termed "Raw Material Consumption (RMC)". The material footprint quantifies domestic and foreign material extraction that is required along all supply chains to satisfy domestic final demand of goods and services (UNEP, 2021).

6. In response to the above-mentioned limitation of territorial material use indicators, the OECD has included a demand-based measure of material use in its core set of environmental indicators. It also integrated demand-based measures into the set of Green Growth Indicators, where the focus is on demand-based non-energy material productivity in association with production-based non-energy material productivity. Material productivity (demand-based and production-based) has also been identified as one of the OECD's Green Growth Headline Indicators, and features in the proposed set of indicators to monitor progress towards a resource efficient and circular economy.

7. This guidance document on calculating demand-based material flow indicators builds upon a series of studies that were performed for the OECD Environment Directorate between 2014 and 2019 to support a process towards a consensus on a harmonised international calculation approach. These studies:

(1) analysed different available methodologies to calculate demand-based material flow indicators (Lutter and Giljum, 2014);

(2) compared material footprints calculated with the OECD-ICIO database to those from other existing MRIO databases and national-specific hybrid models (Giljum et al., 2015b);

(3) applied the ICIO to specific countries to check for the robustness and reliability of results (Giljum et al., 2017); and

(4) updated the ICIO-based calculations and compared the results for specific countries to those calculated with country-specific models developed by local NSOs (Lutter et al., 2019).

8. This sequence of studies provided an assessment of the state of scientific knowledge about the robustness and reliability of demand-based indicators of material flows. It also showcased the applicability of the OECD-ICIO for material footprint analyses and identified areas where further development is needed to improve the accuracy of results.

9. The main target audience of this guidance document are National Statistical Offices (NSOs) that aim at calculating demand-based indicators of material flows using a multi-regional input-output (MRIO) approach.[1] The **objectives of this guidance document** are four-fold:

1. Provide an overview of general methodological options to calculate material footprints (Section 2);
2. Deliver an in-depth description of how material footprints are calculated based on a multi-regional input-output (MRIO) approach, including available data sources and a step-by-step description of the calculation procedure (Section 3);
3. Showcase example results and analyses that can be performed based on the comparative assessment of material footprints across OECD countries and beyond (Section 4); and
4. Summarise the available application options for users with different technical capacities and different data priorities (Section 5).

2. Overview of available methodologies

10. Three different methodological approaches can be distinguished to calculate demand-based indicators of material flows, or material footprints (Lutter et al., 2016): (1) national and multi-regional input-output analysis, (2) process-based life-cycle assessments using material intensity coefficients, and (3) hybrid approaches combing elements of the first two methodologies.

2.1. Input-output analysis

11. The first approach is based on economic input-output analysis, which integrates physical data on material flows. Input-output analysis is a top-down methodology, which starts from the macro-

[1] Note that results from MRIO-based calculations can deviate from results generated with national calculation models, such as hybrid models described in Section 2.3, due to the use of different source data and different approaches to represent supply chains.

economic level and differentiates the national to global economy into economic sectors (product groups or industries) in so-called monetary input-output tables. Physical data on material extraction is then allocated to the corresponding extraction sector(s). By means of the monetary interlinkages between sectors within a country and between countries via international trade, material extraction is attributed to the countries where final demand occurs. Hence, this approach allows for identifying the final consumer that induces specific amounts of material extraction, either in the country itself or in other countries. Input-output models can refer to a single region (i.e. one country), or to various countries, regions or even the global economy. The latter is called multi-regional input-output (MRIO) analysis (Chapter 3 provides details on the MRIO methodology).

12. The main advantages of input-output analysis are that this method fully cover supply chains of all products and product groups, also those with very complex supply chains, as the whole economy sets the boundary for the assessment. This avoids so-called "truncation errors", i.e. the practice to cut-off supply chains due to data gaps and methodological conventions, such as in life cycle assessments. Therefore, all direct and indirect inter-sectoral and final demand relations, which induce material extraction are covered.[2] Also, system boundaries are precisely defined along the SEEA conventions and double counting is avoided, as there is a unique allocation of material extraction to supply chains. When using a multi-regional framework, one key advantage is that material footprints can be calculated within one consistent calculation model for a large number of countries at the same time, thus avoiding the need to construct country-specific models. This feature is particularly important for comparative assessments on the OECD and international levels. When applying a global MRIO model, the sum of material footprints of all countries and regions in the MRIO models equals global material extraction, a level of consistency that no other method can ensure.

13. The main limitation of the input-output approach is the assumption of a homogenous product output mix for each economic sector and product group. This can lead to distortions of results, in particular when the IO database has a low sectoral/product group resolution and where value-to-weight ratios (i.e. prices) are different for various products aggregated into one sector. A typical example that will also be discussed in more detail below, is the aggregation of the extraction of gold and sand in one single "mining" sector. The use of aggregated monetary use structures of industries and product groups to allocate material extraction to final demand via supply chains can therefore lead to over- or underestimations of material footprints. To avoid such distortions, several options are available. First, to use a more detailed input-output model that differentiates a larger number in particular of material-intensive sectors. Second, to trace the flows of raw materials in higher detail outside the IO model and integrate material flows not at the level of primary extraction, but at a later stage in the supply chain, where price differences are smaller and have less impact on the overall material footprint result. A third option is to replace monetary data by physical data in the inter-industry part of the matrix (i.e. creating a mixed-unit matrix), which is particularly relevant for sectors with significant differences in prices of products sold to different receiving sectors (energy carriers and electricity are a typical example). Another limitation of the MRIO approach refers to the issue of quality and consistency of trade data, which are a core data element in the construction of MRIO databases and which will be further discussed below.

2.2. Coefficient approaches

14. The second approach are coefficient methods based on process and life-cycle analysis. This type of approach accounts for the indirect material flows associated with traded products by means of

[2] However, note that this does not hold for capital inputs into production, as capital investments are treated as a final demand category, i.e. exogenous to the inter-industry system. To fully consider capital inputs by sector, capital investments need to be endogenised, see e.g. Södersten and Lenzen (2020).

supply-chain wide material intensity coefficients, which are derived from process analyses such as Life Cycle Assessment (LCA) or similar methods. This is a bottom-up approach, starting the calculation from the level of single products or product groups and aggregating them up to the economy-wide level.

15. The key advantage of the coefficient approach is the potential very high level of product detail, as coefficients can be calculated for a large number of single products, given the availability of data. Thereby, a theoretical product detail can be achieved, which is far beyond the most disaggregated available input-output models. For example, material intensity coefficients could be calculated separately for different technologies to mine and refine a specific metal ore, such as copper or gold.

16. However, this advantage comes at the expense of high efforts to construct comprehensive material intensity coefficients in particular for processed and finished products with complex supply chains. These coefficients also have to be specifically adapted and developed for each application/country at a certain point in time. Data on material intensities of primary commodities exists in LCA databases such as ecoinvent (ecoinvent.org) as well as in the academic literature (for example, Wuppertal Institute, 2013), but often not available as a time series. However, the number of higher processed products, for which LCA coefficients are available, is still limited. Furthermore, a pure coefficient approach cannot rule out double-counting, for example in complex supply chains when products are passing several borders and different process stages and in varying combinations with other products along the supply-chain or across time. This results in widespread “truncation errors”, as indirect material requirements might not be traceable along entire industrial supply chains based on process data. Global consistency between material footprints and material extraction can therefore not be achieved.

2.3. Hybrid methodologies

17. The third approach to calculate material footprints is to combine elements from input-output analysis and coefficient approaches into so-called hybrid methods. These usually use domestic input-output tables to calculate materials embodied in imports and exports for the majority of products, and apply specific material intensity coefficients for those products that are not or differently produced in the analysed countries (which is the case in particular for material-intensive primary goods). The most prominent example for a hybrid approach is Eurostat’s model to calculate indirect material requirements of traded products and material footprints for the EU (Eurostat, 2021).

18. The main advantage of a hybrid approach is that it allows exploiting the complementary strengths of input-output analysis (comprehensive coverage of national or global supply chains) and coefficient approaches (high resolution for key products), thus producing potentially very accurate results in terms of comprehensiveness and preciseness. Hybrid approaches thus overcome data quality issues of data reporters with potential low data quality, for example regarding bilateral trade data. The hybrid approach also enables single countries to calculate the material footprints of their country even if they do not have the expertise in using or access to global MRIO models.

19. Note that a hybrid approach also allows calculating material intensity coefficients (see previous section), in case bottom-up LCA data is missing. For example, as part of its material footprint calculation method, Eurostat presents a set of material intensity coefficients, which is partly generated with a hybrid input-output model (Eurostat, 2021).

20. While hybrid approaches have a number of advantages, the main downside is that they cannot guarantee global consistency, i.e. the sum of all material footprints equalling material extraction, that is ensured with a global MRIO approach. Hybrid approaches combine two methods which have different conventions that are not complementary, i.e. a system-based IO approach with a process-based LCA approach. This might obscure the results in terms of methodological choices and assumptions. Further, setting up a hybrid model is resource-intensive and requires significant technical knowledge in both

fields of IO analysis and LCA. Hybrid approaches have therefore only been applied for a small number of countries and the aggregated EU and comparability between the existing models is limited, as the approaches are not harmonised regarding sector classifications, data sources for the material intensity coefficients, etc. These efforts are a barrier for countries with lower technical capacities and hinders the presentation of comparable indicators across a large number of countries, as required in the context of the SDG monitoring process (see the separate "Roadmap" document for more details; ENV/EPOC/WPEI(2022)8/REV1).

21. Due to these reasons, the OECD in its material footprint reports from 2017 and 2019 (Giljum et al., 2017; Lutter et al., 2019) focused on the evaluation of ICIO as a pure MRIO-based methodology. The reports acknowledged the technical suitability of ICIO to calculate material footprints, but also clearly emphasised the limitations stemming from the high sector aggregation level. In order to achieve a robust methodology for calculating demand-based material flow indicators, there is clear need to further develop ICIO and related data products. The following chapters focus on potentials and limitations of the MRIO methodology for calculating material footprints, with a particular focus on the role of OECD's ICIO.

3. Implementing the MRIO methodology

3.1. Introduction to the input-output approach and MRIO

22. Input-output analysis was once widely used in economics to investigate interdependencies between economic sectors and final demand, and to model how changes in one sector or final demand affect all other sectors. For the key methodological contributions to this field, Wassily Leontief received the Nobel Memorial Prize in Economic Sciences in 1973. The models underlying input-output economics are comprehensive, as they cover all sectors and final demand for an entire economic system. Input-output models thus apply a top-down approach, which starts from the macro-economic aggregate level and differentiates a number of economic sectors via the product and industry groups in so-called input-output tables.

23. The input-output tables represent monetary transactions between different branches of a national economy or different regional economies. The tables represent an accounting framework which is part of the System of National Accounts (SNA), where all socio-economic reporting and data gathering is conducted in a harmonised manner. Input-output tables are widely used by statistical agencies to balance reported and gathered economic data and derive indicators such as GDP. This ensures a continuous process of source data provision and quality checking.

24. Input-output tables are also flexible tools enabling the integration of environmental data, such as material inputs to production, equally to economic factor inputs such as labour or capital (Miller and Blair, 2022). This allows for addressing a wide range of economic and sustainability questions. For example, one can assess international economic linkages, such as the extent to which foreign material inputs are required for domestic production and consumption, as well as the amount of domestic materials used for production and consumption in other countries. Also, the structure and length of global commodity supply chains can be investigated.

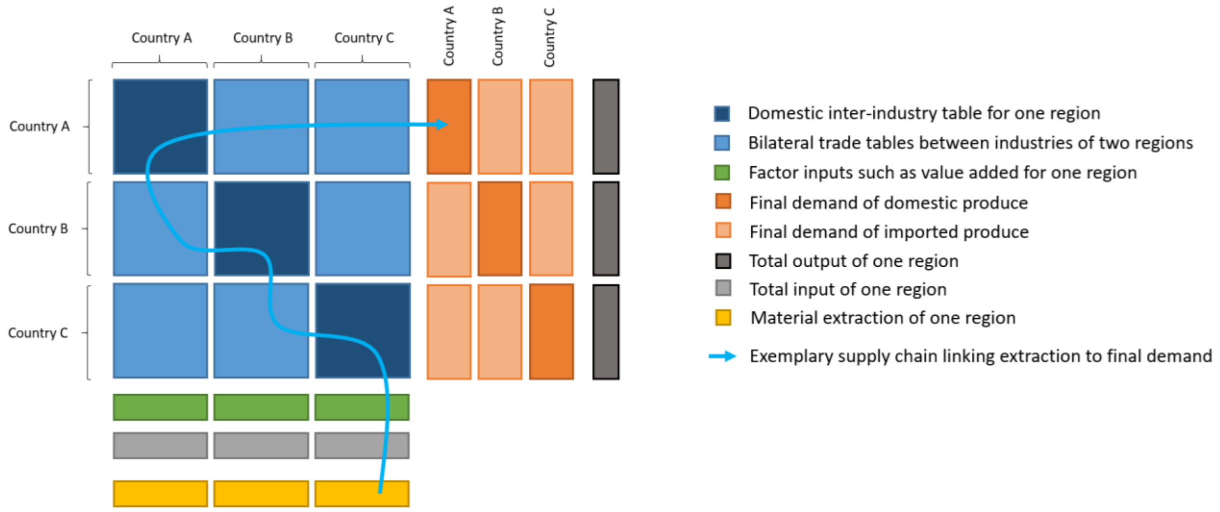
25. The flexibility to integrate environmental data made input-output analysis an increasingly popular tool for assessments of material flows (as well as of a large number of other environmental and social categories, Wiedmann and Lenzen, 2018), in particular during the past 15 years. The input-output method is frequently used for tracing monetary flows and embodied materials to the final consumption

of the respective products. This allows determining the total upstream material requirements to satisfy final demand of a given country ('material footprints'). To calculate material footprints, the mass of raw material extraction is allocated to the corresponding extraction sector(s) in the input-output tables and by means of the monetary transactions in the input-output tables and in international trade attributed to the final consuming country. Hence, this approach allows for identifying the final consumers driving the amounts of raw material extraction, both domestically and abroad.

26. Input-output models can refer to a single region (e.g. one country), or to various regions, creating a 'multi-regional input-output' (MRIO) model. MRIO models link together input-output tables of different countries or regions via bilateral trade flows. These models have a major advantage compared to single region models by considering not only domestic but all global supply chains connected to domestic economic activities. MRIOs thus allow for taking into account the varying resource intensities of material extraction and processing in different countries (Tukker and Dietzenbacher, 2013). The disadvantage is that MRIO tables are very data and labour intensive to compile and require specific technical skills to build a balanced model. However, as soon as the model is set up, the actual calculation of the material footprint indicator is less labour intensive.

27. One important issue when constructing a MRIO data base refers to the quality and consistency of international trade data, which differs substantially between countries. Adding up total exports and imports for all countries conflicts with trade balances on the global level. It is therefore impossible to produce a balanced global MRIO table while leaving national export and import data unchanged (Lenzen et al., 2013). Further, global trade databases, such as UN Comtrade, show the largest deviations from other public data sets, such as the national accounts aggregates. Therefore, the adherence of MRIO tables with UN Comtrade is in general lower compared to other data sets used as constraints in the construction procedure of the MRIO table. Another source of uncertainty stems from the application of the so-called proportionality assumption, i.e. the fact that – due to data limitations – imported commodities are proportionally allocated to the receiving sectors. This assumption creates distortions, when calculating footprint-type indicators, in particular on the sector level (Schulte et al., 2021). Quality assurance procedures, such as visual inspections of the relationship between original data and manipulated data in the developed MRIO database and comparative analyses of resulting footprint indicators and check for irregularities across time series are therefore particularly important. Several MRIO models were developed in recent years, some of them with the explicit aim to enable environmentally-extended input-output analysis for assessing sustainability-related indicators such as material footprints with a high sector and product detail. Figure 1 illustrates the basic structure of a stylised 3-country MRIO table.

Figure 1: General structure of 3-country MRIO system with material extensions



Adapted from Tukker et al., 2016

28. The blue blocks in Figure 1 describe the inter-industry block (Z) of the MRIO table; the orange ones show final demand (Y). Both blue and orange blocks have domestic parts (dark shading) and parts covering international trade (light shading). For example, the light blue blocks illustrate import flows (in columns) and export flows (in rows) between industries in different countries. The orange light-shaded part shows which goods that are produced in, for example, Country A are directly delivered to meet final demand in Countries B and C. The environmental extension (in yellow), in this case raw material extraction, is allocated to each of the material extracting sectors.

29. The light blue arrow provides an indicative example how raw materials are traced from the country of material extraction via processing and international trade to the consuming country. Consider Country C being Australia, mining iron ores that are the shipped to China (Country B), where they are used to produce steel plates. These plates are then exported to Germany (Country A), where they serve as an input to produce cars that are sold to German consumers, i.e. the arrow ends in the orange final demand block of Country A.

3.2. Comparison of available MRIO databases

30. Several MRIO databases and models have been developed to date. They differ regarding their characteristics and underlying assumptions and procedures applied in developing them, which gives rise to specific strengths and weaknesses for assessing material flow-based indicators. This section describes the main characteristics of the currently available global MRIOs with regard to geographical resolution, time coverage, sectoral resolution, underlying data, and main developing institution. This information aims to provide guidance on the selection of a specific database for the application to material flow-based indicators. Table 1 provides an overview of the main characteristics of existing MRIO databases with global coverage.

31. **Country resolution**: When selecting a MRIO database, it is of primary concern that the country or region of interest is contained in the database. From the established MRIO databases, Eora currently offers the broadest country range (189 countries plus one Rest-of-the-World (RoW) region), followed by the GLORIA database (160 countries plus RoW). Five out of eight MRIO frameworks presented in this report cover all OECD countries, including the latest version of OECD's ICIO (66 countries plus RoW).

Exceptions are EXIOBASE, WIOD and FIGARO, which were developed with a focus on the EU and its major trading partners, while many other trading partners are only represented in aggregated RoW regions. This orientation towards high-income and European economies appears problematic in a global economy, where supply chains of materials increasingly originate in the Global South. For these databases, footprint results would strongly benefit from more geographical detail in Africa, Latin American and Asian countries, instead of aggregating those into RoW regions. For EXIOBASE, a recent new version (3rx) advances country resolution by disaggregating the 5 RoW regions of EXIOBASE 3.8 into 170 countries, yielding 214 countries in total. Crucially, however, is the fact that for many of these countries there is no input-output table available. This means that Eora, GLORIA and EXIOBASE 3rx need to approximate the economic structures many of the non-OECD countries.

32. **Sector resolution**: Existing global MRIO databases differ considerably with regard to both the overall number of economic sectors as well as to the number of sectors representing material extraction activities (i.e. biomass extraction sectors, such as agriculture and forestry; and sectors of metal and mineral mining and fossil energy extraction). For some countries, the Eora database has the highest number of economic sectors (up to more than 500), however, the sector resolution is not unified across countries, with many countries only represented by 26 aggregated sectors. The EXIOBASE and GLORIA models have an identical sector resolution across all countries and regions and discern 163 industries/200 products (EXIOBASE) and 97 industries/products (GLORIA), respectively. GLORIA was particularly developed for the application to calculate material footprints and disaggregates 36 material extraction sectors.

33. Also EXIOBASE has 33 sectors referring to extraction of biotic and abiotic materials. All other MRIO databases are characterised by a significantly lower number of economic sectors. The 2021 version of ICIO contains 45 sectors, of which 4 refer to material extraction. Such a high level of sector aggregation creates problems for the calculation of material footprint indicators (see next section).

34. **Time series**: Eora and GLORIA cover the longest time period with 1990-2021 for Eora and 1990-2019 for GLORIA. Continuous and rather long time series are also available for the 2021 edition of the OECD ICIO (1995-2018), EXIOBASE (3.8: 1995-2015 with estimates up to 2022; 3rx: 1995-2015), WIOD (1995-2011 and 2000-2014) and FIGARO (2010-2019). The GTAP database only offers selected years.

35. **Underlying data, as well as required manipulations and assumptions**: Any input-output table needs to be fully balanced and internally consistent, however, international economic and trade data is always conflicting. Therefore, some data manipulations and assumptions are required when compiling a balanced MRIO database. The OECD ICIO, FIGARO and WIOD databases are closest to national level statistics, i.e. national input-output or supply-use tables, national accounts based on SNA 2008, as well as international data from OECD and UN Statistics. OECD ICIO is well linked to other OECD work streams and indicators, such as the OECD-WTO trade in value-added (TiVA). However, closeness to official statistics comes at the expense of sectoral and geographical resolution, because more detailed data available for some countries or aspects are aggregated into a common resolution. EXIOBASE, Eora, GLORIA and GTAP also rely on national statistics as starting points, but conduct more extensive data manipulation and inference to arrive at balanced global MRIO tables with very high sectoral and geographical resolution. Eora and GLORIA, which emerged from the former, do provide standard deviations for all data points which allows for basic quantification of uncertainty related to manipulation of original data.

36. Note that there is also the option to integrate an input-output table and trade data from national statistical sources in a global MRIO framework. The resulting model is called a ‘SNAC’ model, i.e. a ‘Single-country National Accounts Consistent’ model variation of a MRIO database, where the data of one specific country are fixed (Tukker et al., 2018).

Table 1: Available multi-regional input-output (MRIO) databases and their main characteristics

Item/MRIO	OECD ICIO 2021	Eora	GLORIA	EXIOBASE 3.8	EXIOBASE 3rx*	GTAP	WIOD 2013/2016***	FIGARO
Regions	66 + 1 RoW	189 + 1 RoW	160 + 4 RoW	44 + 5 RoW	214	15 to 121 + 20 RoW (varies for years)	EU 28 + 13/15 other major countries	EU27+UK+US (a) + 16 countries (b) + 1 RoW
Material extraction sectors	4	3 to many (varies for countries)	36	33		14	4	4 (a) / 2 (b)
Total sectors: industries i / products p	45 i	26-511p/i (varies for countries)	97 i/p	163 i / 200 p		37-65 p (varies for years)	35/56 i (also i/p as SUTs)	64 i/p (a) / 30 i/p (b)
Time	1995-2018	1990-2021	1990-2019	1995-2015 (2022)**	1995-2015	1993/94/96/98, 2001/5/8/12/15/19	1995-2011/ 2000-2014	2010-2019
Main developer	OECD, France	University of Sydney, Australia	University of Sydney, Australia	Norwegian University of Science and Technology, Norway		Purdue University, USA	University of Groningen, Netherlands	Eurostat & Joint Research Center, EU
References	OECD, 2021	Lenzen et al., 2013; KGM & Associates, 2022	Industrial Ecology Virtual Laboratory, 2021; Lenzen et al., 2021	Stadler et al., 2018; Stadler, 2021	Bjelle et al., 2020	Aguiar et al., 2019	Timmer et al., 2016; University of Groningen, 2021	Eurostat, 2019

*3rx is so far an experimental version (many of the economic structural data are estimated, Bjelle et al., 2020), **EXIOBASE v3.8 till 2022 is estimated based on auxiliary data (see documentation in 'References' row), ***also long-run WIOD 1965-2000 available (see documentation in 'References' row) with 25 countries + 1 RoW and 23 industries

3.3. Sector resolution and its impacts on material footprints

37. The most important characteristic for calculating robust material footprints is the sectoral resolution of an MRIO (Piñero et al., 2015; Giljum et al., 2019; Weinzettel, 2021). Input-output tables provide an abstract representation of the real-world economy as the very detailed data is not available or as the most detailed data would be too extensive to be usable. Thus, input-output tables in most cases contain aggregated sectors or product groups, rather than individual products. In input-output analysis, the product mix of each sectors' output is assumed to be homogenous no matter where they deliver to, i.e. each sector's output has a single price applied to all transactions with downstream sectors. For material flows one homogenous material intensity is assumed, i.e. a fixed relation between physical volumes and monetary values. This can lead to biased material footprints when for example the sectors 'extraction of construction minerals' and 'extraction of metal ores' with very different material intensities are aggregated into one 'mining and quarrying' sector (Giljum et al., 2017).

38. Additionally to varying material intensities, also the sectoral downstream output structure (use structure) for above sectors is likely to differ for materials such as 'sand and quarrel' versus 'iron ores'. High sector aggregation can thus cause misallocations in case only one single 'mining and quarrying' sector is represented in the input-output tables. The construction minerals are in reality only destined to construction sectors, while metal ores pass through metal refining sectors on to the manufacturing of e.g. machinery and vehicles. When aggregated in only one mining sector, the same sector output mix of minerals plus ores is attributed to all of the mentioned sectors, with construction minerals falsely ending up in machinery and transport sectors. Above mechanisms point towards the superiority of MRIOs that show higher sectoral resolution, in particular for the application of demand-based indicators on material flows (Weinzettel, 2021).

39. However, bias does not solely depend on total sector resolution but also which sectors are (dis)aggregated. The sector aggregation bias particularly applies to extractive sectors, as their resolution determines the possibilities of matching environmental extensions at the beginning of the supply chain, and they exhibit comparatively high material intensity differences which can have particularly strong influence on results. The different use structures of raw materials are thus better covered by more detailed MRIOs, such as EXIOBASE or GLORIA with 33/36 extractive sectors, and allow separation of, for example, the flows of various metal ores, minerals and fossil fuels to various industries for further processing. For these detailed MRIOs, the environmental extension could incorporate the raw material extraction data from the UNEP IRP database in its original detail in almost all material categories (see below). To some extent this is also true for Eora, which for some countries shows even higher sectoral resolution than EXIOBASE, while only discerning 26 sectors for many other countries (Eora avoids a common sector structure and integrates all information in the detail available).

40. In addition to aggregated footprints, results can in principle also inform on how much specific material categories (e.g. metal ores) or sectors (e.g. construction) contribute to the overall material footprint. However, particular caution is required when representing material footprint results disaggregated per material or sector categories: for the aggregate footprint, misallocations due to sector aggregation biases can neutralise each other, while on the more detailed material or sectoral level biases can be visible and large. In one of the OECD studies (Lutter et al., 2019) it was concluded that the resolution of an internal pilot version of OECD ICIO (75 sector resolution with 7 extraction sectors) is still insufficient to calculate disaggregated material footprint indicators robustly at sectoral detail. Therefore, if interested in material or sectoral disaggregation of material footprints, high resolution of the MRIO extractive sectors such as in EXIOBASE or GLORIA becomes even more important.

41. A recent report by EUROSTAT further investigated the question, which minimum level of disaggregation should be targeted for achieving robust material footprint results (Schör et al., 2021). Taking

the very detailed, 182-sector model to calculate EU's material footprint as a reference, the authors concluded that a small deviation of 2-3% in the aggregated footprint still requires a model with 117 sectors, most of which being material extraction or processing sectors. In order to generate footprint results with low uncertainty on the level of single product groups, even 155 sectors are recommended. These findings clearly suggest that future efforts should be focused on increasing the sector resolution of the monetary databases as well as further exploring options to improve the material footprint calculations by using additional physical data (see Section 3.5 below). Such a high sector detail in material-intensive sectors is currently not available in any of the monetary MRIO data bases. However, work is ongoing to expand the EUROSTAT material footprint model towards a multi-regional setting and a first version of a three-region model (Germany, Rest of Europe, Rest of the World) has been developed (Schör et al., 2022 (forthcoming)).

3.4. Material satellite account / material extension

42. So-called environmental satellite accounts contain the environmental data such as CO_2 emissions, energy use, land use, or raw material extraction, with which the monetary input-output tables are extended to model footprints (see Figure 1 above). The choice of satellite accounts for MRIOs from the multitude of published data has large influence on footprint results (Owen et al., 2014). Regarding raw material extraction satellites, the UNEP IRP database contains the most authoritative global material extraction dataset available to date and serves as a standard data source to extend MRIOs such as EXIOBASE and GLORIA (Stadler et al., 2018; Lenzen et al., 2021). The following sub-sections describe the UNEP IRP database in more detail and discuss two options to modify the underlying data to create material extensions for MRIOs.

3.4.1. Domestic extraction from UNEP IRP

43. The Global Material Flow Database 2021 of the UNEP IRP was developed by four institutions: the Commonwealth Scientific and Industrial Research Organisation (CSIRO, Canberra, Australia), the Institute for Ecological Economics, Vienna University of Economics and Business (Vienna, Austria), the Institute of Social Ecology, University of Natural Resources and Life Sciences (Vienna, Austria) and the Northeastern University (Shenyang, China) (CSIRO, 2021). The database was compiled by applying state-of-the-art guidelines for material flow accounting and analysis, summarized in the methodological handbooks published by the European Statistical Office and UNEP (Eurostat, 2018; UNEP, 2021).

44. The UNEP IRP 2021 dataset reports annual time series from 1970 to 2019 and covers the extraction of 80 material categories for countries world-wide. These are presented in aggregated form in four broad material categories: biomass, non-metallic minerals, metals and ores, as well as fossil energy carriers. Data is available for 13 sub-categories of those four main categories. The compilation of material extraction data utilises various international statistics and selected estimation procedures to arrive at a harmonised and consistent data set.

45. Biomass covers the harvest of agricultural, forestry and fishery products. Data was derived from the production database of the UN Food and Agricultural Organization of the United Nations (FAOSTAT, 2021). Several estimation procedures were applied to calculate amounts of used crop residues and biomass grazed by livestock.

46. For fossil energy carriers, data on extraction were primarily taken from the United Nations Energy Statistics Database (UNSD, 2020), and supplemented with the World Energy Statistics and Balances of the International Energy Agency (IEA, 2020) and the US Energy Information Administration (EIA, 2021). Primary data which had been reported in units other than tons were converted using factors published by the same data sources.

47. For metal ores, data on extraction were obtained from the British Geological Survey (BGS, 2021), the United States Geological Survey (USGS, 2021), and the World Mining Data (WMD) database (Reichl et al., 2021). In cases where only data on net metal content were reported in the statistical sources, estimations were applied to transform all reported net metal content values into gross ore equivalents. For this step, factors on metal ore concentrations were extracted from a range of sources, including recent data from the SNL Metals & Mining Database (SNL, 2021). Additionally, metal prices were used to allocate compound ores to individual metals.

48. For non-metallic minerals, data sources on extraction were identical to the ones used for metal ores. However, only a few countries and world regions report comprehensive and high-quality data on the extraction of bulk mass minerals such as sand and gravel. Therefore, these amounts were cross-checked and complemented with estimates using physical data for cement, bitumen and brick use (Miatto et al., 2017; CSIRO, 2021).

49. After compilation from international statistics, the remaining data gaps were modelled or inferred via proxy data, the details of which can be found in the database's technical annex (CSIRO, 2021).

50. Two relatively simple options exist to adapt the raw material extraction data and thereof constructed material extensions. The first option refers to replacing UNEP IRP extraction data with official national statistics, if these are deemed more reliable or useful. The second option refers to situations where raw material extension data is linked to a MRIOs with very low resolution of extractive sectors, which can severely bias resulting footprint estimates (see Section 3.3 above).

3.4.2. Option 1: replacing UNEP's IRP data on domestic extraction with official national data

51. In an earlier report to the OECD, material footprint results calculated with the ICIO database were compared with national footprint models (Lutter et al., 2019). The authors found substantial deviations in some country cases. To understand reasons for such differences, it is essential to reduce possible sources for diverging results. One key source of divergence identified were the inconsistencies between the quantities of domestic extraction reported by the national statistical institutions, and those reported in the UNEP IRP Global Material Flow Database. Currently, the UNEP IRP database only integrates officially reported statistics by individual nations to a certain extent. Deviations can occur, in particular, for non-metallic minerals, which were estimated using data on construction products and technical coefficients converting these to primary inputs in the UNEP IRP dataset. But sometimes this data is reported at higher quality in national statistics (see previous sub-section). Consistency between UNEP IRP and national accounts is aspired for in the future, e.g. aligning Eurostat data with UNEP IRP data is currently ongoing.

52. While it is generally recommended that countries continue using the UNEP IRP on domestic extraction as default, a simple first step to improve consistency with national statistics is to replace the environmental satellite data for domestic extraction from the UNEP IRP database by officially reported national data for the respective country only, keeping data for all other countries unchanged. This will alter the material footprint results of countries for the part of final demand that is satisfied with materials extracted within a countries' territory.

3.4.3. Option 2: developing 'use extensions' for aggregated MRIOs

53. The raw material extraction data for environmentally-extended input-output modelling are typically attributed to the sector responsible for the extraction – and hence to the supply of specific resources. The resource supply is then allocated to downstream sectors according to the supply sectors' monetary output structure (see above). In most cases, this approach allows for plausible assignment of resource extraction to appropriate sectors. However, when the MRIO sectors to which resource extraction is assigned are

highly aggregated and thus receive a large number of different materials, and those extractive sectors are in relationships with a large number of sectors of other countries, the so-called aggregation bias can produce substantial inaccuracies (Owen et al., 2017; Wieland et al., 2020) (see also Section 3.3).

54. An approach to address this problem is the construction of so-called 'use-extensions' (Giljum et al., 2017; Weinzettel, 2021). These imply modelling the first steps of the supply chain on a high product detail in physical units outside the monetary MRIO framework. When using a physical supply-use system, trade interrelationships between different sectors can be identified in physical terms, which allows for flows of a large number of different raw materials to be traced in physical units from the point of extraction (supply) in one country to the point of further processing (use) in several other countries. Such physical models, from which 'use extensions' to a MRIO can be derived, have already been presented for the case of agriculture (Bruckner et al., 2019), forestry (Arto et al., 2022) and iron/steel (Wieland et al., 2021). Work is currently ongoing to develop such models also for other material categories.

55. This option brings clear benefits, in particular in cases where material footprints are calculated with a MRIO database of limited sector resolution. However, it should also be emphasised that compiling such detailed physical accounts for a integrating in a global MRIO model is a complex and data intensive task, because each sector transforms materials into products and waste, making a mass-balanced tracing necessary to achieve a consistent implementation. Further, applying use extensions only resolves aggregation errors at the first stage of the supply chain. If the down-stream processing sectors are represented only in aggregated form, this can also cause distortions of resulting material footprints (Schör et al., 2021).

56. The simplest form of a 'use extension' can be applied for the case of non-metallic construction minerals. These materials are often a magnitude larger compared to metal ores and other industrial minerals and can be allocated directly to the construction sector 'using' them, instead of the mining sector 'supplying' them. Earlier OECD studies (Giljum et al., 2017) found that through this modification of the material satellite, results generated with the sectoral aggregated ICIO database more closely aligned to the sectoral results generated by EXIOBASE and Eora, which show more disaggregated extractive sectors.

3.5. Step-by-step technical procedure

57. This section contains a step-by-step description of the procedure to calculate demand-based material flow indicators following the MRIO approach. We split the calculation procedure into five main steps.

Step 1: Choose indicator of interest

58. Next to the headline material use indicator DMC, Domestic Material Consumption, which is production-based, the main demand-based indicator for material flows is the material footprint, also termed 'Raw Material Consumption (RMC)'. The material footprint comprises all used raw material extraction occurring within the domestic economy and in other economies, which are directly and indirectly required to satisfy domestic final demand.

Step 2. Select a MRIO database

59. Selection of the applied MRIO database should follow the specific research interests and priorities. For detailed database characteristics and guidance for selection, consult Section 3.2 of this report.

- ***Geographical scope***: Is the country/region of interest covered?
- ***Temporal scope***: Are the years of interest covered?

- ***Detail required***: Is an assessment of relatively aggregated total material footprints sufficient, or shall material categories and/or sectoral footprints be distinguished? In the latter case a MRIO database with high resolution of extractive sectors should be selected (e.g. EXIOBASE, GLORIA).
- ***Underlying data and consistency with national accounts***: How important is the close adherence to national statistics (e.g. the case for ICIO, FIGARO and WIOD) and transparency of input data? How acceptable are inferred data in favour of higher resolution (e.g. balancing algorithms for high country and sector resolution of EXIOBASE, Eora, GLORIA)?

Step 3. Calculate basic input-output analysis objects

60. Input-output analysis requires matrix algebra to derive material footprints. Please note that matrices are generally depicted as bold upper case letters (e.g. $\mathbf{A}$), vectors with lower case letters (e.g. $\mathbf{x}$), except for the material footprint being lower case bold letters $\mathbf{mf}$. A circumflex indicates a diagonalised vector, a negative unity exponent a matrix inverse. The summation vector i is a column vector of 1's, which when post multiplied with a matrix returns the matrices row sum. Please also note that multiplications * herein generally refer to matrix multiplications.

61. The basic structure of a MRIO table contains the inter-industry transactions matrix $\boldsymbol{Z}$, also called intermediate use matrix and the final demand matrix $\boldsymbol{Y}$, whose sum is the total monetary output of the economy $\mathbf{x}$, see also Figure 1 above. Here, we describe the basic calculation steps starting from the $\boldsymbol{Z}$ and $\boldsymbol{Y}$ matrices, to derive the technology matrix $\boldsymbol{A}$ and Leontief inverse matrix $\boldsymbol{L}$, which are necessary to calculate material footprints. Note that the basic calculation procedure can be extended in several directions.[3]

62. First, total gross output of the economy can be set up as the sum of all intermediate uses $\mathbf{Z}$ and final uses $\mathbf{Y}$ as described in Equation (1). i is a summation vector which upon multiplication yields row-sums.

$$x = \boldsymbol{Z} * i + \boldsymbol{Y} * i \quad (1)$$

63. The technical coefficient matrix $\boldsymbol{A}$ is then calculated by dividing the elements of the intermediate use matrix by total output of each sector as shown in Equation (2). This thus represents the direct monetary input-requirements per unit of monetary gross output:

$$\boldsymbol{A} = \boldsymbol{Z} * \hat{\mathrm{x}}^{-1} \quad (2)$$

64. Depending on whether MRIOs are available as inter-industry flow matrices $\mathbf{Z}$, or as technical coefficient matrices $\boldsymbol{A}$, gross output can also be calculated via Equation (3):

$$x = (\boldsymbol{I} - \boldsymbol{A})^{-1} * Yi = \boldsymbol{L} * \boldsymbol{Y} * i \quad (3)$$

where $\mathbf{I}$ is the identity matrix (a matrix with only 0's except for the main diagonal containing 1's), and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is the so-called Leontief inverse matrix $\boldsymbol{L}$ (Miller and Blair, 2022). The Leontief inverse captures both direct and indirect inputs over the whole supply chain required to satisfy one unit of final demand in monetary values, fully allocating all economic activity without double counting or truncation errors. It is thus the key for calculating footprint-type

[3] For example, in some input-output approaches, an improved reflection of flows of materials through the economic system in the *Z* matrix is achieved by creating so-called "mixed-unit input-output tables". These tables represent the interactions between sectors not entirely in monetary units, but integrate physical use data for selected sectors, for example, where different industry purchasers of the same product pay different prices. Other approaches internalise capital investment into the inter-industry matrix or introduce non-square matrices to increase the sector detail, see, for example, Lenzen (2001); Hertwich and Wood (2018); Eurostat (2021); Hertwich (2021).

indicators. When these basic elements have been calculated, the environmental data to extend the model with environmental information can be selected.

Step 4: Construct material satellite/extensions

65. The environmental satellites are the environmental data with which the monetary MRIO is extended to calculate footprints (yellow row vector in Figure 1 above). These satellites first need to be constructed from environmental data. For material footprints, the domestic extraction of raw materials is used. The standard database to use for global MRIOs is the UNEP IRP 2021 database which shows raw material extraction for 80/13/4 material categories and countries world-wide (see sub-section on MFA database in 3.4).

66. This raw material extraction data needs to be matched to the MRIO sectors. The common type of extension to match extraction data to MRIO sectors is a so-called supply extension. For the supply-extension, raw material extraction data is allocated to the sector that extracts the respective raw material, ‘supplying’ it to the rest of the economy. Depending on the resolution of the raw material extraction data and the number of extractive sectors in the input-output tables, the raw material categories in the original data might need to be aggregated to achieve a complete matching. Generally, it is preferable to retain as much detail as feasible. While this approach in most cases allows for plausible assignment of the resources extracted to appropriate sectors, this step risks inaccuracies when MRIOs only offer highly aggregated extractive sectors, as in the case of ICIO or FIGARO (see Section 3.2 above).

67. An alternative route for achieving robust results also for MRIOs with highly aggregated extractive sectors is to consider constructing so-called ‘use extensions’. From a use perspective, raw material extraction is not allocated to the extractive sectors, but to the sectors further processing or ‘using’ them in both the domestic and foreign economies (see Section 3.4.3 above).

Step 5. Calculate material footprint

68. Once the basic elements of input-output analysis have been calculated and a materials extraction extension has been constructed, the factors of production matrix $\boldsymbol{E}$ can be calculated from raw material extraction satellite matrix $\mathbf{S}$ via Equation (4). $\boldsymbol{E}$ is a matrix of domestic material extraction (in tonnes) per unit of monetary sectoral gross output, with the resolution of the material extraction sectors $\boldsymbol{i}$ that are disaggregated in the respective MRIO database.

$$\boldsymbol{E} = \boldsymbol{S} * \hat{\mathrm{x}}^{-1} \qquad (4)$$

69. In a last step these factors of production E are multiplied with the Leontief inverse $\mathbf{L}$, yielding so called total multipliers, i.e. the direct and indirect raw material requirements per one monetary unit of final demand, e.g. tonnes / $ (Equation 5). Multiplication of these total multipliers with the final demand matrix Y yields the vector $\mathbf{mf}$, which states the material footprints (or Raw Material Consumption) aggregated over all sectors of the economy, but per raw material category (derived from the number of material extension categories which were constructed). The $\mathbf{mf}$ represents all domestic and foreign material extraction ultimately serving domestic final demand.

$$\boldsymbol{mf} = \boldsymbol{E} * \boldsymbol{L} * \boldsymbol{Y}i = \boldsymbol{E} * (\boldsymbol{I} - \boldsymbol{A})^{-1} * \boldsymbol{Y}i \qquad (5)$$

70. If one is only interested in total aggregate material footprints without distinction of raw material categories, the column vector $\mathbf{mf}$ can be summed to one single value by aggregating over all material categories. If one is interested in material footprints by category of final demand, post multiplication with specific columns of the final demand matrix $\mathbf{Y}$ instead of vector Yi can be conducted (for instance the column of private consumption). If one is interested in material footprints per sector, the final demand vector $\mathrm{Yi} = \mathrm{y}$ in Equation (5) can be diagonalised to $\hat{y}$.

71. Note that for EXIOBASE, a particularly convenient python package has been published to allow for easy calculation of environmental footprints, including the material footprint indicator (Stadler, 2021). However, these procedures are also easily implemented directly in python using, for example, NumPy, or in other common platforms like MatLab or R, while Excel generally struggles when handling the very large matrices of state-of-the-art MRIOs.

4. Example results from material footprint analyses with ICIO

72. This section provides an overview about which types of results can be derived from a MRIO model that is applied to calculate material footprints. The illustrations are adapted from the latest OECD material footprint report (Lutter et al., 2019), where the 2018 version of ICIO was used (see ENV/EPOC/WPEI(2019)8). Note that this version only separated two material extraction sectors, causing aggregation errors as will be illustrated below for selected countries. The example results feature material footprints by main material categories and sectors, trade-related indicators as well as decoupling assessments. All figures refer to 2015 as the latest year, but could be updated using the 2021 versions of ICIO and UNEP's material flow database.

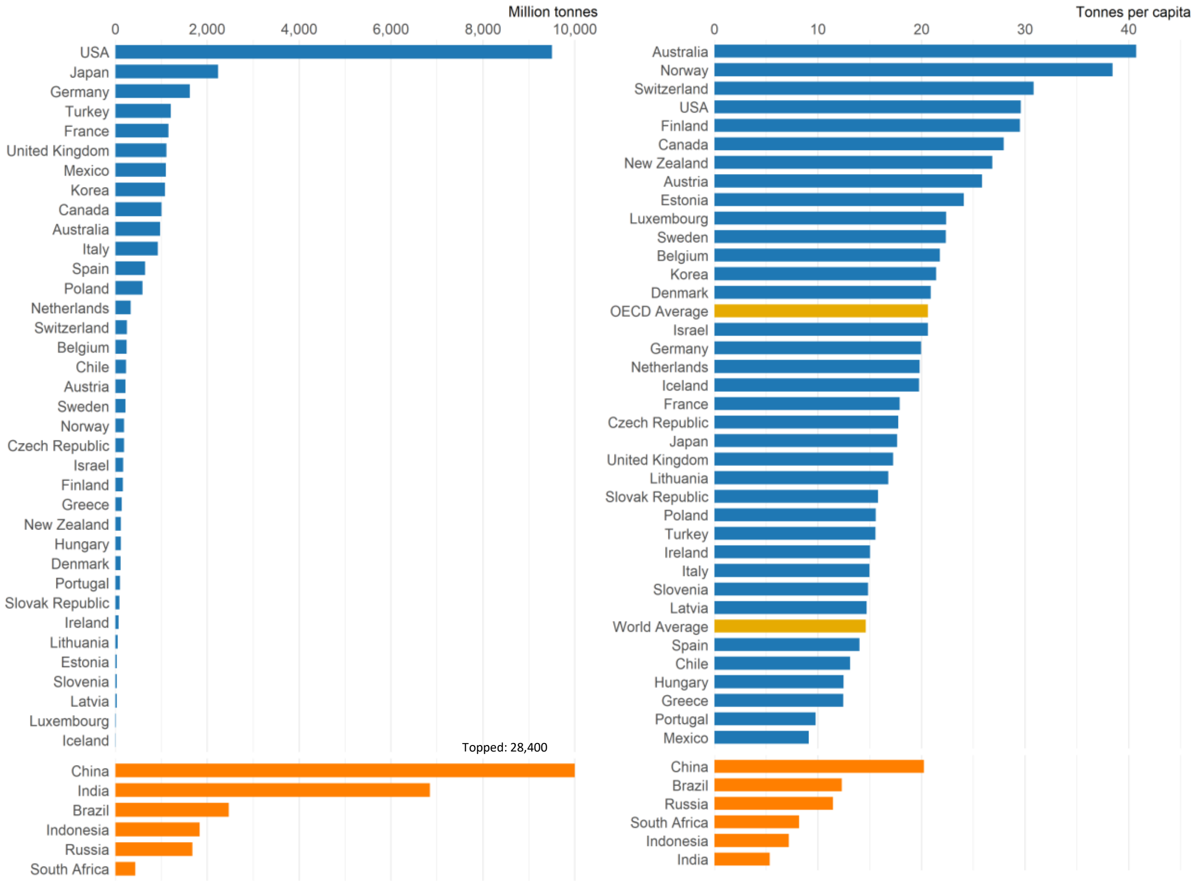
4.1. Material footprints

73. Figure 2 illustrates the material footprint indicator for all OECD countries and the BRIICS countries in the year 2015, both in absolute and per capita terms. Within the group of OECD countries, the USA had by far the highest MF with 9.5 billion tonnes, followed by Japan and Germany with 2.2 and 1.6 billion respectively. In comparison, China's MF of 28.4 billion tonnes exceeded the MF of all OECD countries together (26.3 billion tonnes in 2015). India's material footprint amounted to more than two thirds of the USA value, and Brazil exceeded the OECD second, Japan.

74. Absolute values are driven by the size of the countries' socio-economic system, in terms of both population and economic activity (GDP). The high values of China and India can be partially explained by their large population. However, China also recorded significant per-capita increases during the last 15 years due to rapid economic growth, leading to a per-capita footprint that equalled the weighted OECD average in 2015. Within the OECD, the per-capita ranking was headed by Australia with a per-capita MF of more than 40 tonnes, followed by Norway with 38 tonnes. Issues such as low population densities and high levels of affluence are among the explaining factors for these high numbers. The weighted OECD average was 21 tonnes per capita in 2015, with the lowest values of less than 10 tonnes in Portugal and Mexico.

Figure 2: Material footprint, absolute (left) and per capita (right)

year 2015, OECD countries and BRIICS

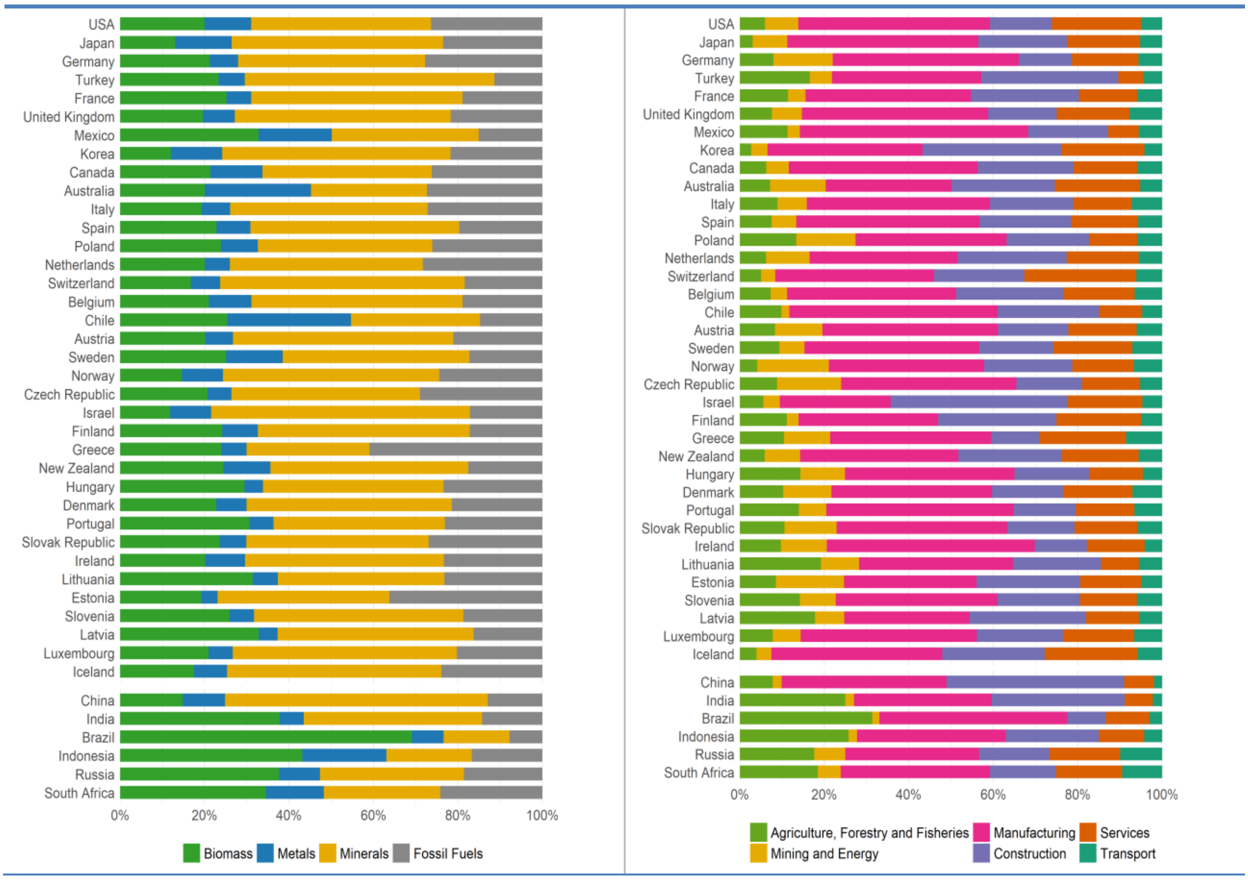


75. Using a MRIO model to calculate material footprints allows disaggregating the result in various ways. Figure 3 shows two options: a disaggregation by main material category on the left side and by main consuming sector on the right side.

76. In general, minerals play the most prominent role in the MF of almost all analysed countries. On average, within the group of OECD countries, minerals accounted for 45% of a country's MF. Greece with a very low and Israel with a very high share of minerals (29% and 61% respectively) reflected a certain diversity within the OECD. For the BRIICS countries, it can be seen that China's MF was strongly dominated by minerals (62%), indicating the high importance of construction activities to build up housing, energy and transport infrastructure. In comparison, except for China, BRIICS countries showed a higher relative importance of the biomass sector than OECD members (on average, 44% when excluding China).

Figure 3: Material footprints, by main material category (left) and main final demand sector (right)

year 2015, OECD countries and BRIICS



77. Some results also point to issues related to the high aggregation of extraction sectors in ICIO and related problems for the calculation of demand-based indicators of material flows (see Section 3.2 above). For instance, Chile is characterised by large extractions of copper and other metal ores, with a high share dedicated for exports. The fact that in ICIO 2018, all abiotic resources are being added up into one theoretically homogenous sector for mining and quarrying, leads to mis-allocations, as specific abiotic materials have different use structures across industries and different shares being exported versus domestically used. For Chile, for example, an excessively large fraction of the extracted metal ores (29% of total MF, while on average metal extraction only contributes about 10%) is allocated to domestic final demand, while in reality, the largest parts are exported to other countries. This illustrates the necessity to use a higher sector disaggregation, in order to reduce uncertainty of the MF results.

78. The right part of Figure 3 illustrates the shares of six different aggregated final demand sectors in the total MF of OECD and BRIICS countries in 2015. On average of all countries analysed, OECD and BRIICS, the manufacturing sector contributed most to the MF (38%), followed by the construction sector (27%), agriculture (15%), and the service sector (11%). Looking only at the BRICS countries, again, the manufacturing sector contributed 38%, but with 36%, construction activities were more important than in the OECD country context. Among all countries analysed, Brazil showed by far the largest contribution of the agricultural sector (31%), followed by Indonesia (26%) and India (25%). These values were considerably above the OECD average of 15%. In Mexico (54%) and Chile (49%), manufacturing was the dominant sector. In contrast, in China and Israel (42% each), the construction sector contributed most to the national MF.

4.2. Material trade balances

79. The MRIO framework allows calculating foreign material extractions embodied in domestic final demand as well as domestic material extraction embodied in foreign final demand. The respective trade balance called ‘Raw Material Trade Balance’ (RTB, UNEP, 2021) illustrates whether a country is a net-importer of direct and indirect material flows related to its international trade activities.

80. Figure 4 shows the RTB for the different OECD and BRIICS countries disaggregated by the four main material groups. Further, it offers a comparison how these structures have changed for each country from 2005 to 2015.

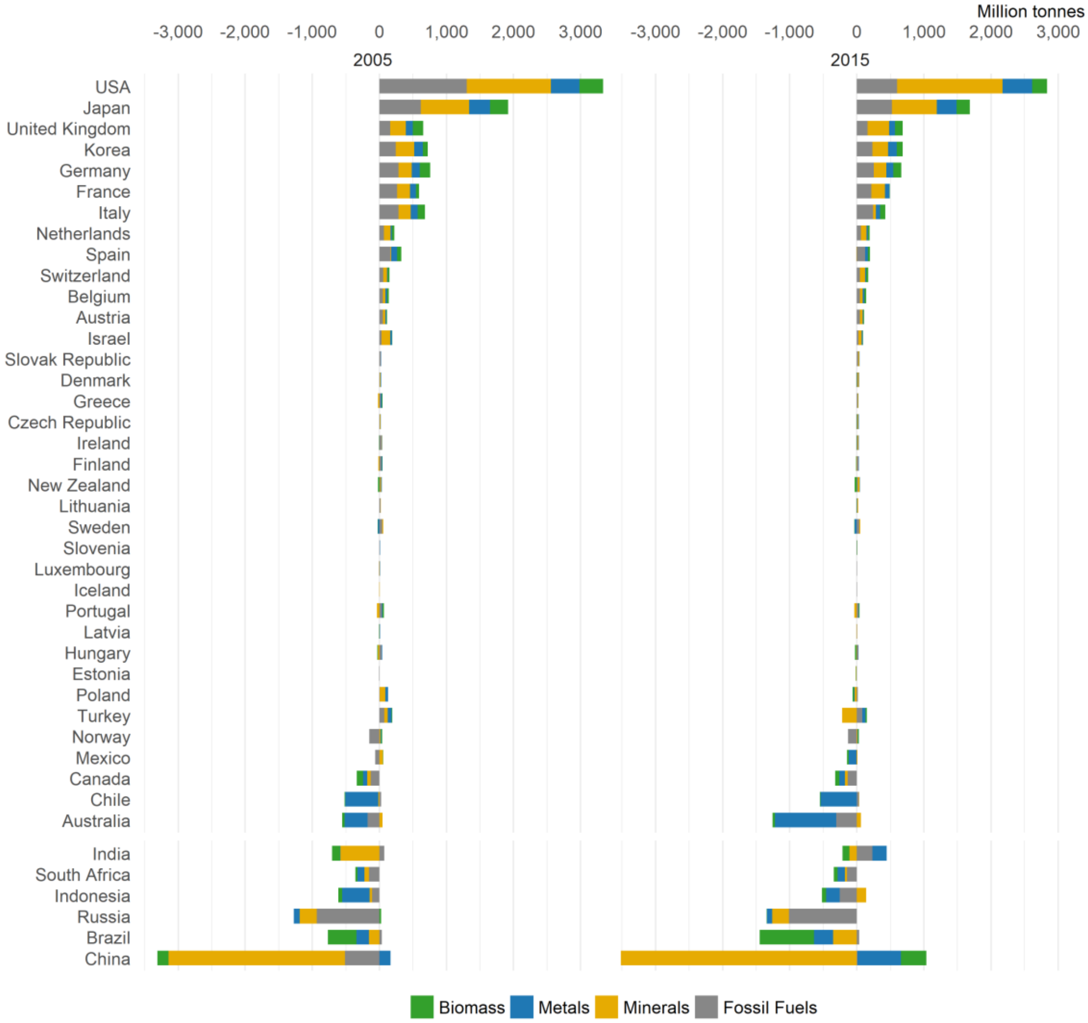
81. While OECD countries such as USA, Japan, France and Italy reduced their import dependency from 2005 to 2015, the BRIICS members China, Indonesia and India decreased their export surplus. Hence, for some countries, a convergence process from 2005 to 2015 could be observed, where net imports and export became less accentuated. At the same time, net exports of other countries, such as Australia and Brazil increased most (by around 100%).

82. For other countries, a turnaround in RTB is observed. Poland and Turkey developed from net importers to net exporters, while India clearly turned its RTB from negative to positive hence becoming a country where extraction and imports from abroad become more relevant for the country than exports of domestically extracted materials.

83. On the level of material groups, China is a very interesting case, as it is an important indirect exporter of minerals, especially through the export of manufacturing products, which require huge construction efforts to building-up mineral-intensive infrastructure. In the period 2005-2015, Chinese net exports of minerals increased by 33%. In contrast, China depends on high imports of metals and net metal imports almost quadrupled in the observed 10-year period. Furthermore, while China was still a net exporter of biomass and fossil fuels in 2005, it became a net biomass importer until 2015 and its export surplus regarding fossil fuels vanished.

Figure 4: Raw Material Trade Balance (RTB), by material categories

years 2005 (left) and 2015 (right), OECD countries and BRIICS



84. For OECD net-exporting countries, the important role of metal ores (e.g. Chile and Australia) as well as of fossil fuels (e.g. Australia, Canada, and Norway) can clearly be seen. India, in contrast, developed from a net exporter in 2005 to a net importer in 2015 mostly due to major net imports of metals ores, while the net exports of minerals decreased sharply during that period.

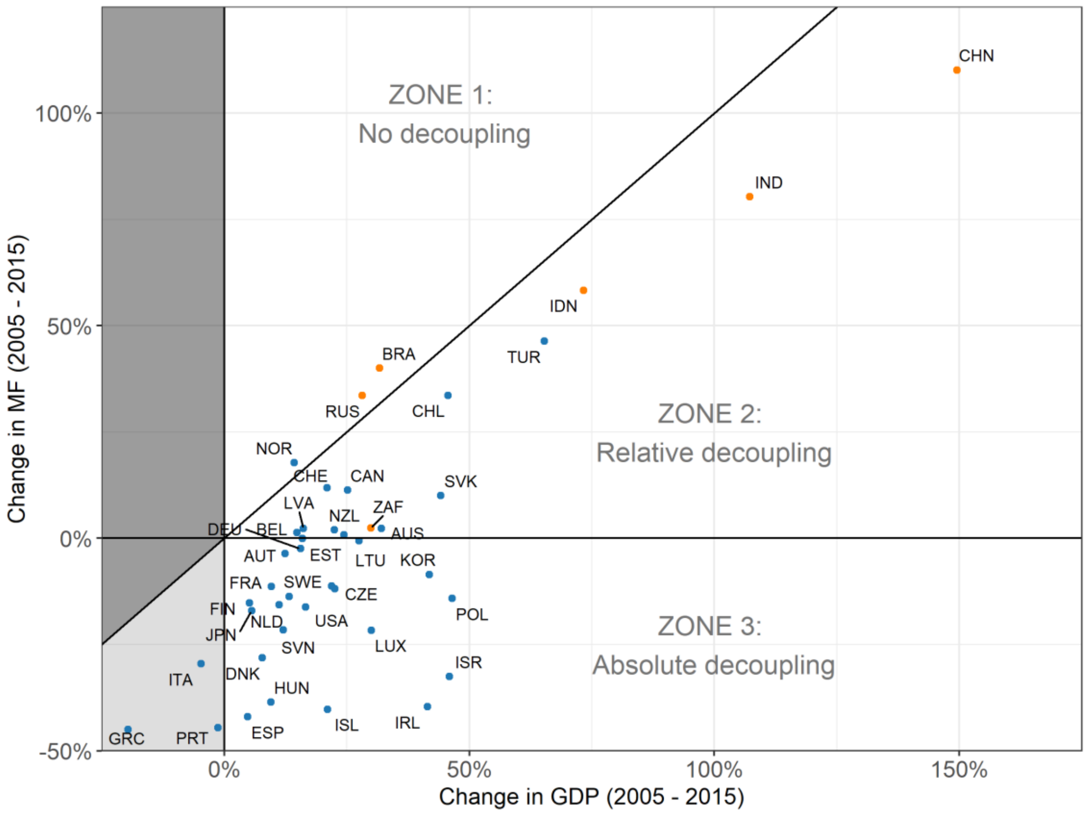
4.3. Decoupling

85. The material footprints can also be set into relation to GDP, in order to investigate, whether a decoupling of demand-based material use from economic growth occurred. Figure 5 illustrates a comparison between changes in GDP (in constant 2010 USD) and changes in material footprints for all OECD and BRIICS countries for the period 2005 to 2015. Three specific zones are identified: Zone 1 shows larger growth in MF than in GDP and hence no signs of decoupling; in Zone 2, GDP grew more rapidly than MF, which still increased, representing relative decoupling; and Zone 3 contains countries with absolute decoupling, as their MF is decreasing absolutely while GDP is increasing. In the grey area to the bottom left, countries have both decreasing GDP and RMC. For more detailed discussions on the issue of

decoupling, we refer to several recent reviews of the decoupling literature (Haberl et al., 2020; Vadén et al., 2020; Wiedenhofer et al., 2020; Vadén et al., 2021).

86. According to these calculations, a major fraction of OECD countries managed to achieve absolute decoupling in the investigated period of 2005 to 2015, including the USA with the highest level of absolute MF among the OECD member countries. Other economies with large absolute MF numbers such as Japan, Germany and France are also located in Zone 3. While this positive development to some extent might be explained by policy efforts towards resource efficiency and decoupling, most likely the decreases in MF can also be attributed to the after effects of the global financial crisis in 2008/9. The crisis affected global production, consumption and investment and therefore significantly shaped material requirements.

Figure 5. Decoupling trends, 2005–2015, OECD countries and BRIICS



87. No BRIICS country achieved absolute decoupling in the observed time period. China, India, Indonesia and South Africa, as well as OECD countries such as Turkey and Chile achieved relative decoupling and are hence located in Zone 2. From these, China and India registered very high GDP growth rates during that period (100% and 150%, respectively), but also high increases in MF. Finally, Italy, Greece and Portugal registered decreases in both MF and GDP. All three countries were affected considerably by the global financial crisis in 2008/2009 and the policy measures at that time and in the following years.

88. The trend of many OECD countries showing absolute decoupling of material consumption from GDP in the observed 10-year time period is in contrast to many other material-related decoupling studies that investigated longer time periods (Giljum et al., 2015a; Wiedmann et al., 2015; Cibulka and Giljum, 2020; Haberl et al., 2020). To evaluate whether the observed decoupling trends continued towards the more recent past or if they were only a temporary crisis-driven phenomenon, an update to the new ICIO

version (with 2018 as the final year) would be particularly pertinent, as well as cross-validations with more detailed MRIO models.

5. Summarised recommendations for users

89. The final section of this document condenses the information presented in previous chapters to concrete recommendations for users, who aim at calculating material footprint indicators. Countries and institutions at different levels of skills and different priorities regarding specific criteria have several options to perform material footprint analyses. Figure 6 provides a stylised decision tree for countries approaching the issue of demand-based indicators on material flows.

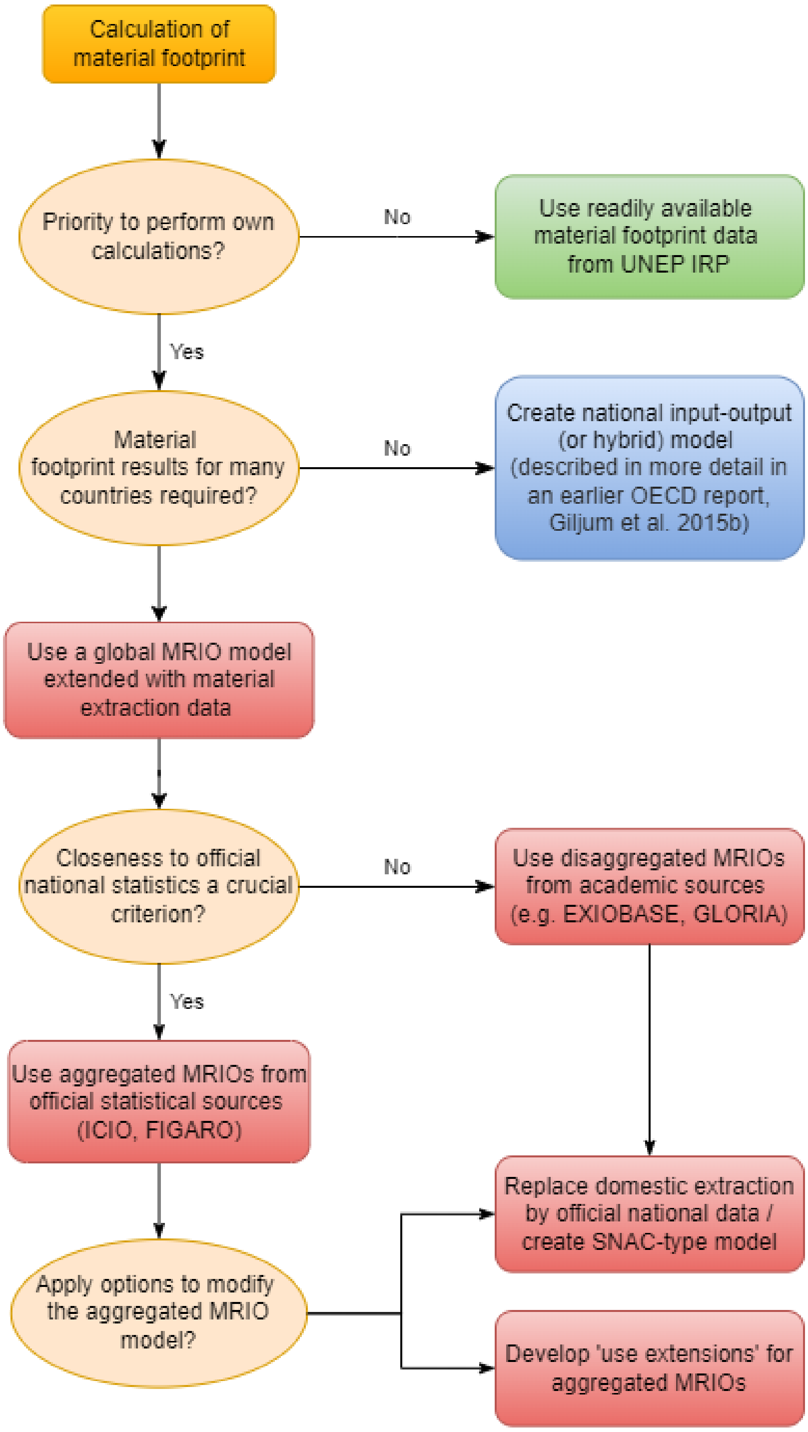
90. Countries which do not put a priority in investing into own model developments to perform material footprint calculations are advised to use the readily-available material footprint data which is part of UNEP's International Resource Panel (IRP) efforts in developing a comprehensive, multi-indicator material flows database (see green box in Figure 6). The material footprints are calculated using the GLORIA MRIO database that was combined with the 2021 release of the material extraction data to calculate material footprints for 160 countries in a time series from 1990 to 2018. The material footprint data can be downloaded from www.resourcepanel.org/global-material-flows-database and is available for visualisation at www.materialflows.net.

91. If countries aim to perform their own calculations and consistency with national statistics is a high priority, they are advised to create single-country input-output or hybrid models (see section 2 above), which can integrate a number of national data sets (input-output tables, trade data, material flow data) (see blue box in Figure 6). This type of model is not further explained in this document, but has been in the focus in previous OECD material footprint reports (Giljum et al., 2015b). Further, detailed documentations are available for existing hybrid models, including the EU model of Eurostat (Eurostat, 2021).

92. All red boxes in Figure 6 refer to various options to use MRIO databases for calculating consistent material footprint indicators across a wide range of countries. They differ regarding their source data from statistical versus academic sources and apply different levels of sophistication to adapt the system. It is generally recommended to use IRP's global material flow database as the main source to derive the material extension for the MRIO model.

93. If closeness to national statistical data is not a crucial criterion in the selection of the MRIO database, it is recommended to apply one of the existing detailed MRIO models from academic sources, i.e. EXIOBASE or GLORIA. These MRIO databases generally provide robust estimates due to their high resolution of extractive and material processing sectors.

Figure 6. Options for calculating demand-based indicators on material flows



94. If maximum use of and adherence to official data is a priority, OECD's ICIO or Eurostat's FIGARO are the preferred choice. However, when selecting one of these databases, critical attention has to be paid to the limitations for interpreting results due to sector aggregation bias (see above). As discussed in this document, several options exist to modify the aggregated MRIO model, in order to increase the robustness of results.

- The first option is to replace domestic material extraction data in the MRIO model and use official national statistics instead of data from the global material flow database. Further along this line is the creation of a 'SNAC-type' model, where also the input-output tables and trade data of the country in focus are aligned with national statistics and embedded in the global MRIO data framework (Edens et al., 2015).

- Another option is the development and application of so-called 'use extensions' for some material categories, which have a high potential to distort material footprint results in an aggregated MRIO framework. As a very simple form of a use extension, the extraction of construction minerals could be removed from the aggregated mining and quarrying sector and allocated directly to the construction sector. Other major material categories (such as iron ore, coal or fodder crops) should also be considered to be treated with a modified sector attribution to improve the accuracy of results.
- A third option is to collect physical data to replace parts of the monetary data in the MRIO tabel by physical data and thus create mixed-unit inter-industry tables. Applying physical sales structures, for example, for agricultural and forestry products, energy carriers or non-metallic mineral products, is an appropriate alternative to increasing the number of sectors in the monetary MRIO model (Schör et al., 2021).

95. In the medium future, it would be highly desirable, if one harmonised reference MRIO database could be developed from official institutions, for example, based on ICIO and FIGARO. To enable calculating robust material footprint indicators, the OECD, EUROSTAT and other relevant players should reflect on options to further increase the detail of the material extraction and processing sectors in their MRIO database. Furthermore, such a reference database could serve as the starting point and benchmarking framework, based on which more disaggregated MRIO databases and hybrid and/or mixed-unit models could be developed.

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