Accounting for raw material embedded in imports by multi-regional input-output modelling and life cycle assessment, using Finland as a study case

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Abstract

The two main methods used to estimate raw material embedded in imports are life cycle assessment (LCA) and multi-regional input-output (MRIO) models. The key advantage of LCA is its higher product resolution but it relies on global or regional averages, which could bias results. Our outcomes suggest that this obstacle could be avoided for primary goods if domestic process data are collected, since the necessary raw materials are mostly extracted from the environment of the direct trade partner. Conversely, for many other products,

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intermediate inputs are produced following a wide range of blueprints and cross multiple borders, which makes it challenging to determine how and where raw materials needed for their production originate. For these products, a method to combine the superior coverage of MRIO with the product resolution of LCA is evaluated here, using imports to Finland as a study case. The analysis provides insights on how to identify critical supply chains and illustrates a relatively simple, replicable solution that can be used in other regions or environmental accounts. Nevertheless, the existing resolution of MRIO models and dissimilarities in classifications between the two tools could constitute a new source of errors if not properly handled.

Keywords

material flow accounting, raw material equivalents, material footprint

1. Introduction

In analyses of the metabolism of socioeconomic systems, all materials required by the economy are ideally taken into account on the basis of mass conservation. To this end, a set of indicators has been developed within the framework of material flow accounting (MFA), so that present and past trends can be analysed and policy targets for a more sustainable future can be set (e.g. OECD, 2011; UNEP, 2011; European Commission, 2011). Standard practice in MFA suggests that all raw material extracted within the boundaries of the system called 'domestic extraction' (DE) and material flows associated with trade need to be accounted for (EUROSTAT, 2013; OECD, 2008). Accounting for DE is relatively straightforward, using official statistics, while there are two distinct ways of incorporating the material flows of traded products in MFA that can give different results regarding the raw material requirements of a given system. On one hand, indicators such as direct material input and domestic material consumption consider only mass of imports and exports ('direct' imports and exports, using MFA terminology). In particular, the direct material input is obtained by adding together the direct imports to the DE, whereas the domestic material consumption is direct material input minus direct exports. On the other hand, broader-scope indicators, such as raw material input and raw material consumption, are based on the concept of 'raw material equivalents' (RME) of imports and exports, which refer to all raw material extracted and used for production of traded products. Thus in the RME approach, all upstream raw materials involved in the production of imports and exports are considered, regardless of the mass that finally crosses the border. Indicators based on direct imports and exports are easier to calculate, but it is acknowledged that they are not able to capture appropriately the existence of dislocation of material-intensive industries and, consequently, burden shifting of raw material extraction among countries. Moreover, evidence of increasing dependence on non-domestic raw material in most rich economies highlights the urgency of including RME-based indicators in resource efficiency policies (Giljum et al., 2014a; Wiedmann et al., 2013). Accordingly, the RME approach appears preferable for assessing the material basis of socioeconomic systems.

However, estimation of RME is challenging because, in contrast to the survey estimation of direct flows, it involves modelling the technology of industries and countries involved in complex supply chains (from extraction to final production) using diverse data sources and strong assumptions, which can have a marked impact on the outcomes. Two broad methods can be distinguished in RME calculations: Life cycle assessment (LCA) and input-output (IO) models. LCA adopts a bottom-up perspective, modelling coefficients of RME for particular products employing process data collected using technical information on (ideally) all upstream production processes in the supply chain. These coefficients are usually first estimated for representative individual products and later adapted or employed for all trade products. In contrast, IO models adopt a top-down approach whereby coefficients of RME are modelled at macro level for broad product groups or industries. This is done by linking physical data about biomass harvested by agriculture and forestry and minerals extracted by mining companies with monetary data about transactions among economic sectors and final consumers, so that raw materials flows can be tracked along supply chains, from extraction to final use. The most promising IO models are multi-regional IO (MRIO) models, which have the highest geographical coverage, since world economies are interconnected via trade and domestic transactions. Furthermore, there is increasing interest in combining approaches in order to take advantage of their main features, in the so-called hybrid or life cycle assessment input-output (LCA-IO) approach.

In this paper, we focus on the issue of the (limited) regional coverage of LCA compared with MRIO models. We begin by assuming that existing LCA-based approaches oversimplify the diversity in technology in exporting regions, which has the potential to bias results (Dittrich et al., 2012), since they are often based on global or regional averages. To this end, we first explore the extent to which including specific process data from exporting nations can improve accuracy, especially for products originating from long, complex supply chains. We then introduce and assess a method making use of the higher degree of detail in the bottom-up perspective and also expanding the system boundaries to full coverage of the world using MRIO.

2. Life cycle assessment vs. multi-regional input-output models in estimation of raw material equivalents

Material flow accounting has become one of the key tools in industrial ecology and ecological economics since its development by Ayres and Kneese (1969), as reviewed by Ayres and Ayres (1998), Daniels and Moore (2002), Daniels (2002) and Fischer-Kowalski et al. (2011). Since the early days of MFA, the relevance of the RME concept has been acknowledged and significant efforts supported by international policy bodies are underway to improve the estimation methods. Below, use of LCA, MRIO and mixed models in RME estimation is compared, focusing on methodological differences relevant for the present analysis.

In the LCA-based approach (also process-based or coefficient approach), RME coefficients (also 'cradle-to-product' or life cycle inventory coefficients) are estimated based on process data for individual products. This approach considers all exchanges between social and natural spheres that occur during the product life cycle, as summarised by the general expression:

$$\mathbf{r} = \boldsymbol{\alpha}'\mathbf{N}\mathbf{m} \tag{1}$$

where lower case letters are vertical vectors, ' denotes transposition, $\mathbf{r}$ is RME of imports, $\boldsymbol{\alpha}$ is a vector of process-based coefficients expressed in kg of RME per kg or euro imported, $\mathbf{N}$ is an aggregation matrix with dimensions number of coefficients by number of imported products with elements 1 and 0 appropriately placed, and $\mathbf{m}$ is the vector of imports. In the literature, RME estimated in this way are also termed 'ecological rucksack' (Dittrich et al., 2012).

Input-output models were introduced to describe technological dependencies between industries and product flows within the economy (Leontief, 1936). An essential feature of these models is the 'Leontief inverse', which consists of direct and indirect inputs required per unit of final demand of each economic sector or product group. To analyse environmental burden flows, information regarding how much raw material is extracted per euro of economic output is included, so biophysical requirements by industry and final user can be obtained. The MRIO model is summarised by the general expression:

$$\mathbf{r} = \mathbf{e}'\mathbf{LNm} = \mathbf{p}'\mathbf{Nm} \tag{2}$$

where $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse ($\mathbf{I}$ being the identity matrix and $\mathbf{A}$ the matrix of technical coefficients) and $\mathbf{e}'$ is the vector of sectoral coefficients of material input (for further details of IO modelling, see Miller and Blair, 2009; European Comission et al., 2014). Elements of the row vector $\mathbf{p}$ represent the raw material multipliers or RME coefficients.

Therefore, assuming that in both cases the imports are the same, differences in RME estimates across methods should derive from differences between components $\boldsymbol{\alpha}$ and $\mathbf{p}$. The pros and cons of each method have been explored previously and it has been concluded that both have their advantages and drawbacks and that there is currently no optimal method (Eisenmenger et al., 2016; Lutter et al., 2016; Schoer et al., 2013).

In the context of the present study, a key shortcoming of LCA-based coefficients is that they are estimated most commonly as representative regional or world averages (which might refer to a particular moment in time or an average), whereas MRIO models can capture more conveniently differences in resource use between countries (Wiedmann et al., 2011). That is to say, it can be assumed that multipliers $\mathbf{p}$ in MRIO models represent divergences in technology between nations. However, MRIO models can be strongly affected by sector or country resolution. These aggregation errors may appear depending on how products/countries are grouped in the model because averaged inputs need to be considered, which could cause distortions that are passed on via the Leontief inverse to multipliers (de Koning et al., 2015; Piñero et al., 2015). Disaggregation of official or basic data could be performed to alleviate this problem, but at the expense of higher uncertainty. In addition, more country resolution does not necessarily mean more accurate outcomes, particularly if based on poor underlying data (Schoer et al., 2013). In contrast, the main advantage of LCA is its high resolution and product coverage (Dittrich et al., 2012), since calculations can be as detailed as the highest product resolution offered by customs statistics offices (or in other words, matrix $\mathbf{N}$ in equation 1 can be suppressed if $\boldsymbol{\alpha}$ is sufficiently detailed). However, this does not mean that process-based coefficients are free from aggregation problems, it being common practice to work with aggregated data (Majeau-Bettez et al., 2011). Furthermore, due to time and resource constraints and to make the model operative, aggregation is frequently applied in RME estimation based on LCA, which involves certain uncertainties as a result of the use of averages for heterogeneous product groups (e.g. the same coefficient may be employed for all types of imported printers, whether a small device intended for home use or professional printing equipment). Moreover, these aggregation problems persist even at the most disaggregated levels of custom statistics (Dittrich et al., 2012) (e.g. because there are multiple models even within the group of printers for home use, with predictably different raw material basis).

Other shortcomings of LCA are that it can be severely affected by boundary setting for the system, e.g. truncation errors can arise as a result of excluding high-order upstream production stages (Lenzen, 2000). In addition, fewer data are available for finished products or services than for raw materials and semi-manufactured goods, because the former involve much complex supply chains and material composition mixes (Dittrich et al., 2012). This extra degree of complexity in downstream production stages is also acknowledged in studies focusing on particular materials, such as aluminium (Cullen and Allwood, 2013), copper (Graedel et al., 2002) or iron (Wang et al., 2007). In contrast, in MRIO models an approximation to such complexity in composition mixes is achieved and the cut-off error is minimised by multiplier estimation itself.

Both LCA (Dittrich et al., 2012) and MRIO models (Arto et al., 2012; Bruckner et al., 2012; Giljum et al., 2014a; Tukker et al., 2014; Wiedmann et al., 2013) have been used to estimate RME embodied in trade products. Although possible, combinations between high geographical coverage MRIO models and process-based coefficients have not been developed so far in MFA studies. However, some mixed models combining features of national or EU IO models and LCA data already exist, for example for the European Union (Schoer et al., 2012b), Czech Republic (Kovanda et al., 2010), Austria (Schaffartzik et al., 2014) and Italy (Marra Campanale and Femia, 2013). These mixed or hybrid models are described in the early works of Moriguchi et al. (1993), Joshi (2000), Treloar (1997), Suh et al. (2004), Suh (2004) and Suh and Heijungs (2007). In the remainder of this paper such models are referred to using the acronym LCA-IO, because the term hybrid is also applied to mixed units (physical and monetary) in IO models. In the literature, mixed model approaches are also referred as LCI-IO or LC-IO, from life cycle inventory or life cycle, respectively.

All approaches model the same reality (i.e. upstream raw material requirements of traded products) and hence the results should be similar. In reality, there are a number of methodological differences which might explain differences in the outcomes. To date, only a few studies have compared existing methods. An evaluation of a LCA-IO method and a MRIO model focusing on the EU found that discrepancies at more aggregated levels remain within 5-10% for RME of imports, although they are significantly higher for broad groups of materials (Schoer et al., 2013). This gap is reduced when further steps are taken to attenuate methodological differences. Another comparison between three MRIO models and one LCA-IO method found that RME of trade products deviate markedly across models, especially when considering disaggregated material groups (Giljum et al., 2015). In addition, strong deviations between economic sectors or product groups have been reported, whereby the more disaggregated the comparison, the higher the discrepancies. Using Austria as a case study, six methods have been compared and discrepancies of around 30-40% in aggregated RME-based indicators have been reported (Eisenmenger et al., 2016). In that study, the sign of the physical trade balance (RME of imports minus RME of exports) changed for some raw material categories depending on the approach, which implies some vagueness about whether Austria plays the role of net importer or net exporter of environmental loads in the international arena. Although the studies by Schoer et al. (2013) and Giljum et al. (2015) highlight that deviations at more aggregated level are manageable and that uncertainty does not compromise current policy applications of RME-based estimates, dissimilarities reported for some countries correspond with the results for Austria and call for a more profound understanding of existing methodological differences.

Overall, there are a number of other differences (such as monetary versus mass units, time window in the functional unit, how capital stocks are modelled etc.) that can explain discrepancies in outcomes and which should also be considered in the choice of approach. In order to improve estimation of RME, in this study we attempted to incorporate the superior coverage of supply chains by MRIO models into more detailed LCA-based approaches. Due to the differences between these two tools and the particularities of the models and databases employed, many obstacles had to be overcome, using rough assumptions in some cases and ad-hoc correspondences between products and materials in others. In this manner, the benefits and risks of combining LCA and MRIO methods for RME estimation in a systematic manner were analysed.

3. Material & Methods

Three models were used in the analysis: the Envimat Imports model, the Eurostat RME tool and the Exiobase MRIO model. The Envimat Imports model (Koskela et al., 2013, 2011; Seppälä et al., 2011) was chosen to represent the LCA approach, since RME of all imported goods are modelled using process-based coefficients and only services are estimated using the IO technique. The Eurostat RME tool (Eurostat, 2015; Schoer et al., 2012a) was selected because is the most popular LCA-IO model for RME estimation. Although different MRIO models exist, with different product and country coverage (Tukker and Dietzenbacher, 2013), in this study Exiobase was chosen because of its high detail in extractive sectors and its focus on the EU (Tukker et al., 2014; Wood et al., 2015). Main features of each of these models are explained in the subsection

Model specifications. Full product and material classifications, correspondence tables, model specifications and complementary mathematical descriptions and results are available in Supporting Information.

The results are described in two sections. Section 4.1 (Raw material flows in international supply chains) examines the question of how much domestic raw material extraction occurs in direct trade partners compared with extraction in third countries. For the sake of replicability, this analysis was performed using only Exiobase data (for the year 2007). Section 4.2 (Country-specific information from the Exiobase MRIO model in LCA-based approaches) attempts to refine original RME coefficients from the Envimat (LCA) and Eurostat (LCA-IO) models by accounting for country/regional variations in the embodiments. Finland was chosen as a study case for this purpose and 2010 data as the base, because those are the most recent IO data available for Finland. Further explanations and mathematical details are presented in the subsection The Method.

At this point, two issues regarding MFA principles require clarification. First, in this study only the 'Used' fraction of raw material extraction is considered, i.e. only materials entering the economy via prices are studied. Other materials removed but not bought or sold, such as mining overburden or fishing by-catch ('Unused' raw materials), are excluded. The reason is to keep calculations simple, since the method developed would be similar in both cases. Second, estimation of RME of imports for a country depends on whether or not intermediate imports for production of exporting products are included in the calculations. If the goal is to measure environmental pressure exerted by a given domestic final demand, then these loads are usually reallocated to those end-user countries receiving those exports (this approach is applied e.g. by Giljum et al. (2015b) and in the cited studies using MRIO models). However, in the present study, all imports as recorded by customs offices were included, because making a distinction would involve extra effort and probably detract from the focus of the analysis.

3.1. Model specifications

In the Envimat Imports model (hereafter 'Envimat'), basic data in physical and monetary units are obtained mostly from foreign trade statistics compiled at combined nomenclature (CN) eight-digit product resolution and then converted to the Envimat classification system for products (ETTL), which distinguishes around 490 goods and is derived from the classification of products by activity (CPA) 2008. In addition, a hierarchical classification of 85 types of raw materials is made in the Envimat resource classification. Furthermore, process-based coefficients are calculated for goods on a mass basis, i.e. kg RME per kg of goods imported, while for services kg RME per euro imported is used. Most of these coefficients represent world average values, although in some cases they refer to European averages or to particular countries (e.g. natural gas from Russia). Basic data are mainly retrieved from the life cycle inventory database Ecoinvent version 3.0 (Wernet et al., 2016) and, for some products, a direct correspondence with data available in Ecoinvent and ETTL products can be drawn. For other products input data from technical and academic literature is used to build streamlined LCA systems (full description in Supporting Information).

The Eurostat RME tool (Eurostat, thereafter) comprises 166 product groups and 52 raw material categories, since standard MFA classification is further disaggregated for metals, through the so-called ‘metal model’. Basic calculation was carried out using an IO table for the EU27 region, in which monetary flows of fossil fuels, metal concentrates and base metals are replaced by physical flows (fossil raw materials in oil equivalent tons and metals in tons). In addition, for some raw materials and basic products (metals, oil and gas), LCA data is utilised. For other imported products, manufacturing and services, the so-called ‘domestic technology assumption’ is followed, i.e. the technology for import production was assumed to be the same as in the importer region (EU27 in this case). The model is based on CPA 2002 and coefficients represent EU import average values.

Exiobase is a MRIO database that includes data for 200 products and 48 countries or world regions, more precisely 27 EU countries, 16 non-EU countries and five regions. Single countries considered (43) cover 90% of global gross domestic product (GDP). In short, the database harmonises official IO tables and material extraction data using auxiliary information from international agencies, such as the Food and Agriculture Organization (FAO) and International Energy Agency (IEA). The product classification uses the CPA 2002 scheme with high resolution for extractive products (33 product groups) and data currently available are for the years 2000 and 2007. Publicly available data are in various formats, but for this study ‘product by product’ tables were chosen for two reasons: i) errors dependent on the version chosen are reported to be small (Marin et al., 2012) and ii) the product by product approach gives easier correspondence between models and trade data.

Lastly, it should be stressed that the emphasis in this study was on goods and therefore services were excluded from the calculations, so a fixed amount of RME associated with imported services was included in all models. The reason is twofold: i) customs data for services are more incomplete and ii) services are less relevant than goods as raw material extraction drivers. For instance, in 2010, imported services reached almost 17 050 million euros according to IO data from Statistics Finland, whereas imported services included in customs data were a mere 182 million euros. Unfortunately, the former data do not specify country of origin of service companies. In addition, it has been pointed out that services only accounted for 3.4% of total RME embodied in Finnish imports in 2005 (Seppälä et al., 2011).

3.2. The Method

Raw materials extracted and used for production of same type of product differ between countries, i.e. producing a watch in Switzerland and in China differs in raw material terms, since technology and production blueprints vary from country to country (in the Supporting Information, dispersion statistics for multipliers of the full Exiobase are presented). Customs statistics usually report where goods are dispatched, so assuming that those traded products are entirely or mostly produced in the dispatching country, which is typically the case for primary products, allows process data including technology particularities of those countries to be gathered and RME coefficients to be estimated. In the Envimat and

Eurostat models, this approach is followed for some products. However, production of more sophisticated products often takes place in more than one country, so raw material extraction might happen in country A, further processing in countries B and C, and final export to Finland by country D. Therefore, to study the fraction of RME of imports from a particular product and country that has been extracted domestically or elsewhere, multipliers of full Exiobase were aggregated according to this criterion.

As mentioned previously, there is extensive literature on combining LCA and IO approaches. Such studies have, at their core, the definition of system boundaries, consideration of possible miscounting or double counting and the importance of sectoral, regional and time frame details, depending on the object of the study. In the present study, a method for including MRIO information from Exiobase in the Envimat and Eurostat models was developed. The method is based on a correction matrix $\mathbf{C}$ dimension number of countries by number of products, the elements of which are the ratio between full Exiobase multipliers and those from an averaged Exiobase version that describes world or EU average values, re-arranged in country by product form. Thus c_{ij} informs for product j about deviations of country i in relation to the regional average under consideration (i.e. if $c_{ij} > 1$, RME for product j coming from country i are above average, while if $c_{ij} < 1$, the opposite occurs). Using algebra, matrix $\mathbf{C}$ can be estimated as:

$$\mathbf{C} = \mathbf{P}\hat{\mathbf{p}}_{\mathbf{A}}^{-1} \qquad (3)$$

where $\mathbf{P}$ is a multiplier matrix whose elements are disposed in country by product form (i.e. p_{ij} is the RME coefficient for product j from country i)

and $\hat{\mathbf{p}}_{\mathbf{A}}$ indicates the diagonal matrix of $\mathbf{p}_{\mathbf{A}}$, which is the vector describing average multipliers for products.

Matrix $\mathbf{W}$, which describes coefficients corrected including MRIO information in country by product form, can then be calculated as:

$$\mathbf{W} = \mathbf{C}\hat{\boldsymbol{\alpha}} \tag{4}$$

where w_{ij} describes the 'MRIO-refined' RME coefficient for product j imported from country i.

After refining original RME coefficients, RME embedded in imports can be estimated considering technological differences among countries: if matrix $\mathbf{M}$ is an imports matrix re-arranged in country by product form, then matrix $\mathbf{R}^*$ can be obtained using the Hadamard product denoted by $\circ$ as:

$$\mathbf{R}^* = \mathbf{W} \circ \mathbf{M} \tag{5}$$

where r^*_{ij} informs about RME embedded in imports of product j from country i.

Finally, to obtain RME after correction by product $\mathbf{r}^*_{\mathbf{p}}$, $\mathbf{R}^*$ can be pre-multiplied by a row vector of ones, i.e. $\mathbf{r}^*_{\mathbf{p}} = \mathbf{i}'\mathbf{R}^*$. Similarly, raw material embedded after correction by country $\mathbf{r}^*_{\mathbf{c}}$ can be calculated following $\mathbf{r}^*_{\mathbf{c}} = \mathbf{R}^*\mathbf{i}$.

Hereafter, the MRIO-corrected versions of the Envimat and Eurostat models are referred to as 'Envimat-MRIO' and 'Eurostat-MRIO', respectively. For the Envimat-MRIO version, refinements refer mainly to global averages, although EU values are also employed for some products. Conversely, country-specific coefficients are not corrected. For the

Eurostat-MRIO version, EU averages are mostly utilised, except for minerals and fossil fuels, for which world averages are used. Both corrections are based on values from Exiobase for 2007, and therefore it is assumed that variations between countries within a particular year are not greatly affected by price changes.

In addition, RME of imports using original versions of Envimat and Eurostat are presented. The calculation is straightforward: imports from customs statistics in CN eight-digit resolution in mass (Envimat) or mixed units (Eurostat) are appropriately converted using correspondence tables and multiplied by a set of RME coefficients.

4. Results & Discussion

In this section, we first present results for countries with the lowest and highest domestic (vs. foreign) extraction, and their shares by product group and by type of extraction. These results provide insights and rules for types of extraction and justify the integration performed in the Envimat-MRIO and Eurostat-MRIO models for some products and countries.

4.1 Raw material flows in international supply chains

Tables 1 and 2 list exporting countries with the lowest and the highest percentage domestic extraction, respectively, per euro imported to Finland in 2007 (aggregated regions excluded). As Table 1 shows, small countries with high population/GDP density tend to have low domestic extraction in their exports. On the other hand, countries endowed with significant amounts of natural resources (usually also large in area and population size) show high domestic extraction. An interesting exception is Denmark, for which a high score was obtained. This score is better explained by Figure 1, in which percentage domestic extraction in RME and country falls into broad groups of raw materials (biomass, metals, fossil fuels and other minerals). The dot size indicates RME by country in absolute values for 2007. The x-axis follows the Exiobase ordering of countries, with the EU countries displayed from left to centre and other economies to the right. It can be seen that the high domestic extraction of Denmark is due to other mineral products exported to Finland, broken or crushed stones and chalk mainly, as reflected in publicly available custom statistics. Overall, Figure 1 informs modellers about when to use LCA based on national data or MRIO combined models in RME estimation. It can be observed that, in general, EU countries have low domestic extraction of metals and fossil fuels in their exports (with the exception of Sweden for metals and Estonia for fossil fuels). Therefore, in these cases, modelling RME via LCA would involve an extra degree of complexity, particularly for some key trade partners such as Germany and Belgium. In contrast, for other products, most of the raw materials come from the direct partner. In addition to Sweden and Estonia, this is the case for Russia for fossil fuels, for China, India and Spain for other minerals and for Brazil for biomass embodied in agricultural and forestry products. Therefore, it could be argued that, for these countries, performing a LCA based on national data would potentially improve RME estimates with less effort than in previous examples.

Tables 1 and 2.

Figure 1.

Table 3 depicts the percentage of domestic extraction by industry embodied in imports. It can be seen that extractive sectors (agriculture, forestry and mining), along with electricity and food production, show high domestic extraction per euro imported in direct partner countries. The relative importance of the extractive sector means that, overall, almost 73% of all raw materials embedded in Finnish imports in 2007 were extracted from the environment of direct trade partners. Regarding manufacturing, there are a wide range of domestic extraction forms, although most sectors have an approximately equal share. Accordingly, if only sectors C1 to C10 are considered, total DE in direct partners drops to 53%. In Figure 2, the percentage of domestic extraction in RME by industry is plotted by raw material type. As can be seen from the diagram, the domestic share of metals seems lowest for most products (between 8% and 42%), while other minerals and biomass show a wider dispersion of shares across products. Moreover, considering their volume and low domestic extraction share, LCA modelling of products belonging to C7 (Basic metals and fabricated metal products) seems particularly problematic.

Both pieces of information, on industry and country of origin, help modellers in identifying possible sources of bias and also open the way for improvement of MFA indicators, since it is clear that for large countries with highly developed extractive profiles, the LCA-based approach has the potential to refine the calculations. Furthermore, similar procedures can be applied for simple supply chains, i.e. for those trading schemes involving a reduced number of countries and industries. To that end, our combined approach could be complemented with existing techniques, such as production layer decomposition (see e.g. Giljum et al. (2016), where the underlying logic is equivalent to that applied in this study) or structural path analysis (see e.g. Lenzen, 2007), which could bring more detail, regarding the importing countries and sectors across the whole supply chains. On the other hand, the existence of highly complex supply chains and process data constraints at country level for many products exemplifies the limitations of process-based approaches and the importance of integrating precision from LCA with global coverage from MRIO, as described in the following section.

Tables 3 and 4.

Figure 2.

4.2 Country-specific information from the Exiobase MRIO model in LCA-based approaches

In Figure 3, the original Envimat and Eurostat models are compared with the versions extended with MRIO information. Direct imports obtained from official statistics are also shown, as a dashed line. Total direct imports were 57.1 Mt, while raw materials embedded in Finnish imports amounted to 233.9 Mt (original Envimat), 268.7 Mt (Envimat-MRIO), 144.2 Mt (original Eurostat) or 212.9 Mt (Eurostat-MRIO). The significant differences between direct imports and RME estimates support the idea that the latter concept is important, particularly for metals and other minerals and, to a lesser extent, for fossil fuels. However, it is worth mentioning that these global estimates sometimes mask other differences that are less evident in aggregations. Moreover, there are marked differences in RME figures depending on the method chosen, calling for a deeper understanding on this matter, as mentioned in previous studies. Tables showing most important differences between coefficients by product group and country (see Supporting Information) were used for describing the deviations in the following.

Figure 3.

In Figure 4, the comparison between original Envimat and Envimat-MRIO is disaggregated for broad groups of products. It can be seen that the two most important deviations at this level arise in metals and other minerals. For metals, the almost non-existent difference between both models shown in Figure 3 is revealed to be an offset effect: Envimat-MRIO tends to increase material embedded in extractive products but decrease that in metal products (Sector C7 in Figure 4). In Table 4, changes in multipliers and the most important deviations for metals and other minerals between the two model versions are shown. As can be seen, increases in extractive products occur mainly in 'Iron ores' and 'Copper ores and concentrates', whose coefficients notably increase in Envimat-MRIO. Regarding iron ores, 97.7% of exports to Finland in 2010 were from its neighbour Sweden. In the Supporting Information, the ratio of DE per euro imported is shown for all countries and products (based on 2007 data). For iron ores from Sweden, 99% of raw materials required were extracted from the Swedish environment and in that case process-based estimation based on national figures would clearly be advisable. In the case of copper, 49.2% of imports to Finland in 2010 came from Peru and Chile, both categorised in Exiobase as ‘Rest of America and Caribbean’. In this case too, almost 100% of materials were extracted domestically and a LCA-based estimation considering Peruvian and Chilean technological particularities would be desirable. The reason why the increases described are offset at the macro level can be seen in Table 4. Because Envimat has higher resolution, refinements of metal products in Table 4 were performed using multipliers for three corresponding Exiobase products: ‘Basic iron and steel and of ferro-alloys and first products thereof’, ‘Other non-ferrous metal products’ and ‘Copper products’. In the Supporting Information, it can be seen that percentages of metal DE for these three products can vary significantly between countries. Focusing on key Finnish trade partners in Table 4, for basic iron and steel products Exiobase delivers 1% metal DE for German products, whereas it increases to 47% for Swedish products. For copper and other non-ferrous metal products, the percentage of metal DE embedded varies from almost 0% for Spanish nickel products to almost 100% for Russian, Brazilian and ‘Rest of Africa’ products. Considering that Spanish nickel mining and the content of iron from German mines in basic iron and steel products are both negligible, performing a process-based estimation would involve substantial extra effort. Nevertheless, since their mineral intermediate inputs coming from third countries can be followed using MRIO, the method developed in this study could be utilised. In contrast, for copper products coming from Russia, nickel products from Brazil and cobalt products from the Democratic Republic of Congo (which is the other main non-ferrous metal product coming from Africa), LCA-based data estimation would be desirable. For Swedish iron and steel products, an intermediate solution might be best.

For other minerals, it is revealed in Figure 4 that the increases in the MRIO version occur mainly in the sectors mining and quarrying and C5 (Other chemical products). The rise in mining is because of 'Clays and kaolin' products, mostly coming from India and the United Kingdom. Consulting publicly available disaggregated customs data reveals that the reason for the high score for India is from exports to Finland of 'Bentonite' (6.1 million kg imported in 2010). Including MRIO information greatly increases the original coefficient for clays and kaolin for India (see Table 4), explained by existing high analogous differences between world average and Indian values using Exiobase. This enormous difference could be an error in Exiobase original data and might be related to the difficulties in data gathering in India reported by the database's developers (Giljum et al., 2014b). However, it serves to illustrate how the existence of outliers or unexpectedly high values can cause errors in the refined method proposed in this study. In addition, Finland imports a high volume of kaolin (927.6 million kg in 2010), as an input for the paper industry, from three countries: UK (36%), US (33%) and Brazil (29%). The Envimat original coefficient for clays and kaolin increases to 37.6 kg/kg for the UK in Envimat-MRIO, while it increases only slightly or decreases for the other two key trade partners, which leads to a significant RME allocation to imports from the UK (-12140.4 Mkg bias). These examples exemplify the two possible causes of re-allocation in the method proposed: high multiplier dissimilarities between original and MRIO versions (India), and less significant variations for substantial import flows (UK). Lastly, most notable deviations in other chemical products occur in imports from Norway of ‘Other inorganic basic chemicals’ and ‘Peptones, modelling pastes, activated carbon, finishing agents, pickling preparations etc.’ (see Table 4). The increase in both cases is caused by the differences between multipliers in Exiobase for ‘Chemicals not elsewhere classified (nec.)) and salt DE comparing Norway and world-average values. For other inorganic basic chemicals, customs data show that two products are mainly responsible for this increase: ‘Calcium carbonate’ and ‘Sodium hydroxide (caustic soda)’. Total imports of calcium carbonate to Finland in 2010 were 674.9 million kg, of which 99.3% came from Norway, whereas imports of caustic soda were 149.7 million kg, of which 19.8% came from Norway. Although alternative routes exist, calcium carbonate is mainly produced from lime and carbon dioxide (European Commission, 2007). Therefore including MRIO country-specific information could bias allocation of salt DE, rather than refining outcomes. In contrast, caustic soda is mostly produced by electrolysis from sodium chloride solution with mercury, and it is clear that importing caustic soda implies significant amounts of salt embedded, which is also one of the main contributors to the overall environmental burden of the production process (Hong et al., 2014). Similar considerations apply to the second group of products, which mainly refer to finishing agents for the paper industry imported from Norway.

Figure 4.

Table 4.

For the Eurostat models, including MRIO information from Exiobase also caused significant deviations in extractive and metal manufacturing products. However, in this case, both estimates were higher in the Eurostat-MRIO model. This situation is mainly explained by the significant growth taking place in metal embedded in imports of 'Other non-ferrous metal products' as can be observed in Table 5, which shows the main deviations between original Eurostat and Eurostat-MRIO. This happens because the correction is based on an EU average, whereas for Envimat-MRIO a global average is used. This outcome shows that average EU RME embedded per kg imported are significantly lower than global and African values. However, two related issues need to be considered: i) this refers to an 'Other' products category, where many diverse products are included, and ii) it belongs to a 'Rest of' MRIO category. Other notable increases in metal products occur in 'Basic iron and steel products' from Russia and other partners. Thus, in comparison with the outcomes from Envimat-MRIO, these results suggest that, if global values are used (Envimat), RME tend to be overestimated, whereas if EU averages are employed (Eurostat), they seem to be underestimated.

For other minerals, more than 50% of the higher quantities obtained with Eurostat-MRIO compared with the original Eurostat model are due to 'Ceramic products and other non-metallic mineral products' coming from the United States (C6: Other non-metallic mineral products) in Figure 4). According to customs statistics, this is mostly due to 'Carbon fibres and articles of carbon fibres, for non-electrical purposes'. However, the refinement was performed considering multiplier dissimilarities for disaggregated non-metallic DE of Exiobase's 'Other non-metallic mineral products', in particular differences in DE of 'Building stones', which is three orders of magnitude above the average for US multipliers according to Exiobase. Therefore, it seems clear that product aggregation into a single 'Other non-metallic mineral products' category, in combination with the above-average building stones intensity in US multipliers, cause inaccurate re-allocation of raw materials in Eurostat-MRIO. A high domestic share of raw material extraction of other minerals for this product in the US (around 80%, see Supporting Information) suggests that a process-based estimation considering domestic particularities would be a better choice.

In biomass flows, deviations are caused by increases in biomass embedded in 'Animal and vegetable oils and fats', along with 'Fruit, nuts, beverage and spice crops' (see Table 5). The increase for the former refers mainly to imported palm crude oil from Malaysia, which comprised about 385 million kg in 2010, to which an extra load of raw material is allocated based on multiplier differences for Exiobase's 'Products of vegetable oils and fats'. However, since agricultural products typically involve shorter supply chains (98% of biomass is domestically harvested for this product in the Rest of Asia and Pacific region, see Supporting Information), process data could be used to cross-check this outcome. A similar situation arises for fruits, nuts etc. from Brazil and other Latin American countries.

Finally, for fossil fuels, the increase observed is mainly because including MRIO information raises RME embedded for products coming from Russia, in particular for 'Petroleum oils and oils obtained from bituminous minerals' (explaining the growth observed in mining and quarrying in Figure 5), and 'Other basic chemicals' and 'Fertilizers and nitrogen compounds' (explaining the increase in other chemical products in Figure 5). Therefore, in this case, the correction proposed increases the raw material requirements of more fossil fuel-intensive Russian exports of the petrochemical industry.

Figure 5.

Table 5.

5. Conclusions

This study examined the theoretical connection between life cycle assessment (LCA) and input-output (IO) methods. Although there has been more than a decade of key development and application of these tools, there is still a need to provide simple and effective rules for improving the estimation of raw material equivalents (RME) embedded in imports. In particular, this study examined domestic (vs. foreign) extraction contents for countries and products, developed in order to help modellers overcome limitations imposed by the use of averages in LCA-based approaches. One of the conclusions that can be drawn is that domestic process-based data are preferable for primary mining and biomass products and for manufacturing products, which rely heavily on natural resources from the domestic environments of direct trade partners. This involves mixing physical and monetary flows and coupling bottom-up with top-down methods. It also requires access to detailed custom and LCA data for key trade partners and the development of correspondences between product, country and material classifications.

For products involved in longer trade chains, or for which domestic LCA data are not available, a refined method providing a systematic way of analysing the embodied contents of RME based on multi-regional IO (MRIO) was developed. The results suggest that comparisons between original (based on regional averages) and MRIO-refined models could give valuable insights into iteratively correcting possible errors or biases. However, there are also methodological limitations, due to different products or raw material classifications and aggregation into miscellaneous products or material groups (such as ‘Other’, ‘nec.’ or ‘Rest of’ categories) that need to be handled carefully when applying our method. Moreover, the products and regions that serve as reference in MRIO models need to be chosen with care and should be the closest in coverage to the original process-based coefficient being split. Depending on data and resource availability, our approach is equally applicable to more distant tiers of the supply chain (e.g. trade partners of direct trade partners) and can be combined with existing IO tools for assessing chain length and complexity.

Our method may be applicable in the study of exports to any other country and, since the multipliers used for corrections are of a very general nature, they are applicable to other regions or product specific studies. For this reason, basic data for the refinements are offered for all countries (except Finland) in the Supporting Information. Similar comparisons have previously been made between top-down and bottom-up approaches for other environmental accounting tasks, e.g. for water flows in Feng et al. (2011) and for ecological footprint in Weinzettel et al. (2014). Thus the methodological developments presented here are also of interest outside the material flow accounting community. However, more work is needed to explain the differences between current databases and models and to support future developments that make use of the detailed product resolutions from LCA and the higher coverage of supply chains in MRIO models.

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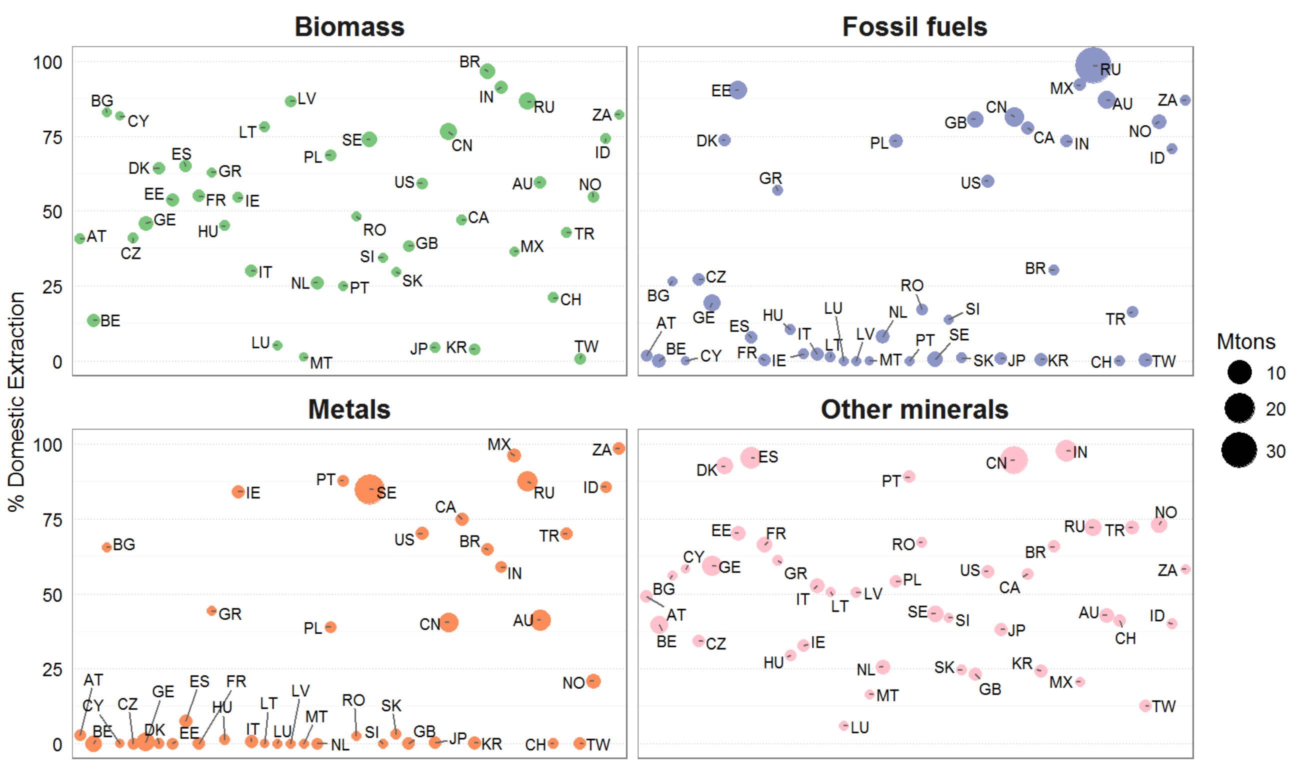
Table 1. Domestic extraction by the ten lowest countries			
Code	**Country**	**Domestic (%)**	**Other (%)**
LU	Luxembourg	3	97
TW	Taiwan	3	97
MT	Malta	8	92
KR	South Korea	8	92
SK	Slovak Republic	13	87
JP	Japan	15	85
NL	Netherlands	19	81
BE	Belgium	19	81
HU	Hungary	22	78
SI	Slovenia	22	78

Code = country code used in Exiobase. **Country** = country name used in Exiobase. **Domestic** = % of Domestic extraction of exports to Finland. **Other** = % of extraction in other countries of exports to Finland.

Table 2. Domestic extraction by the ten highest countries			
Code	**Country**	**Domestic (%)**	**Other (%)**
RU	Russian Federation	95	5
IN	India	94	6
ZA	South Africa	93	7
MX	Mexico	90	10
DK	Denmark	84	16
BR	Brazil	83	17
ES	Spain	83	17
CN	China	82	18
PT	Portugal	79	21
EE	Estonia	77	23

Code = country code used in Exiobase. **Country** = country name used in Exiobase. **Domestic** = % of Domestic extraction of exports to Finland. **Other** = % of extraction in other countries of exports to Finland.

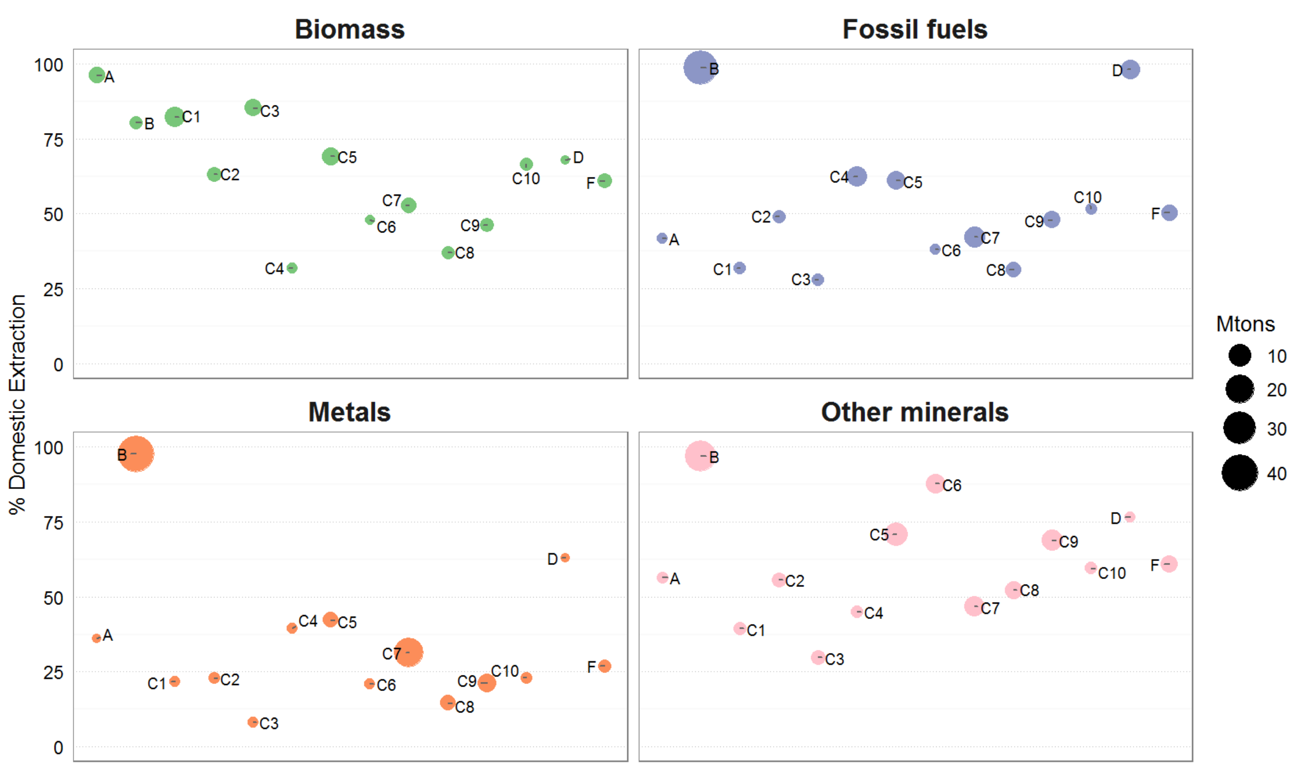


European Union Countries (left to centre): AT = Austria, BE = Belgium, BG = Bulgaria, CY = Cyprus, CZ = Czech Republic, GE = Germany, DK = Denmark, EE = Estonia, ES = Spain, FR = France, GR = Greece, HU = Hungary, IE = Ireland, IT = Italy, LT = Lithuania, LU = Luxembourg, LV = Latvia, MT = Malta, NL = Netherlands, PL = Poland, PT = Portugal, RO = Romania, SE = Sweden, SI = Slovenia, SK = Slovak Republic, GB = United Kingdom. Other countries (right): US = United States, JP = Japan, CN = China, CA = Canada, KR = South Korea, BR = Brazil, IN = India, MX = Mexico, RU = Russian Federation, AU = Australia, CH = Switzerland, TR = Turkey, TW = Taiwan, NO = Norway, ID = Indonesia, ZA = South Africa. Mtons denotes million tons of RME of imports by each raw material.

Figure 1. Percentage domestic extraction per euro imported to Finland in 2007, by country and raw material equivalents (RME) of imports.

Table 3. Percentage domestic extraction by product group			
Code	**Product group**	**Domestic (%)**	**Other (%)**
A	Products of agriculture, forestry and fishing	87	13
B	Mining and quarrying	98	2
C1	Food, beverages and tobacco products	71	29
C2	Textile, clothing and leather products	54	46
C3	Wood, pulp and paper products	58	42
C4	Petroleum refining products	59	41
C5	Other chemical products	66	34
C6	Other non-metallic mineral products	82	18
C7	Basic metals and fabricated metal products	37	63
C8	Electrical and electronic products	50	50
C9	Machinery and transport equipment	37	63
C10	Other manufacturing products	55	45
D	Electricity and water supply	96	4
F	Services	54	46

Code = product group code developed for presenting results. **Product group** = product group name developed for presenting results. **Domestic** = % of domestic extraction of exports to Finland. **Other** = % of extraction in other countries of exports to Finland.



A = Products of agriculture, forestry and fishing, B = Mining and quarrying, C1 = Food, beverages and tobacco products, C2 = Textile, clothing and leather products, C3 = Wood, pulp and paper products , C4 = Petroleum refining products, C5 = Other chemical products, C6 = Other non-metallic mineral products, C7 = Basic metals and fabricated metal products, C8 = Electrical and electronic products, C9 = Machinery and transport equipment, C10 = Other manufacturing products, D = Electricity and water supply , F = Services. Mtons denotes million tons of RME of imports by each raw material.

Figure 2. **Percentage domestic extraction per euro imported to Finland in 2007, by sector and raw material equivalents (RME) of imports.**

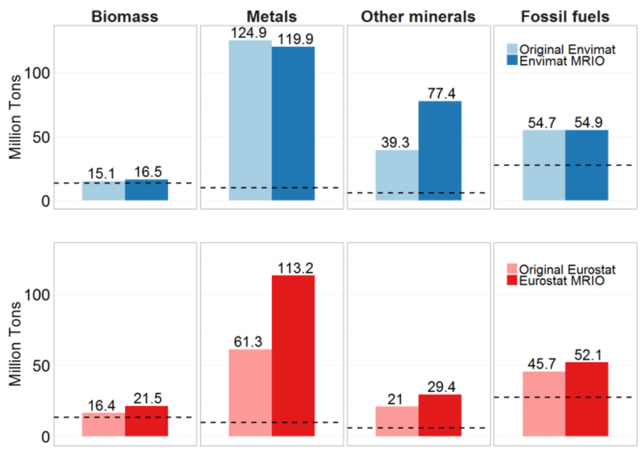
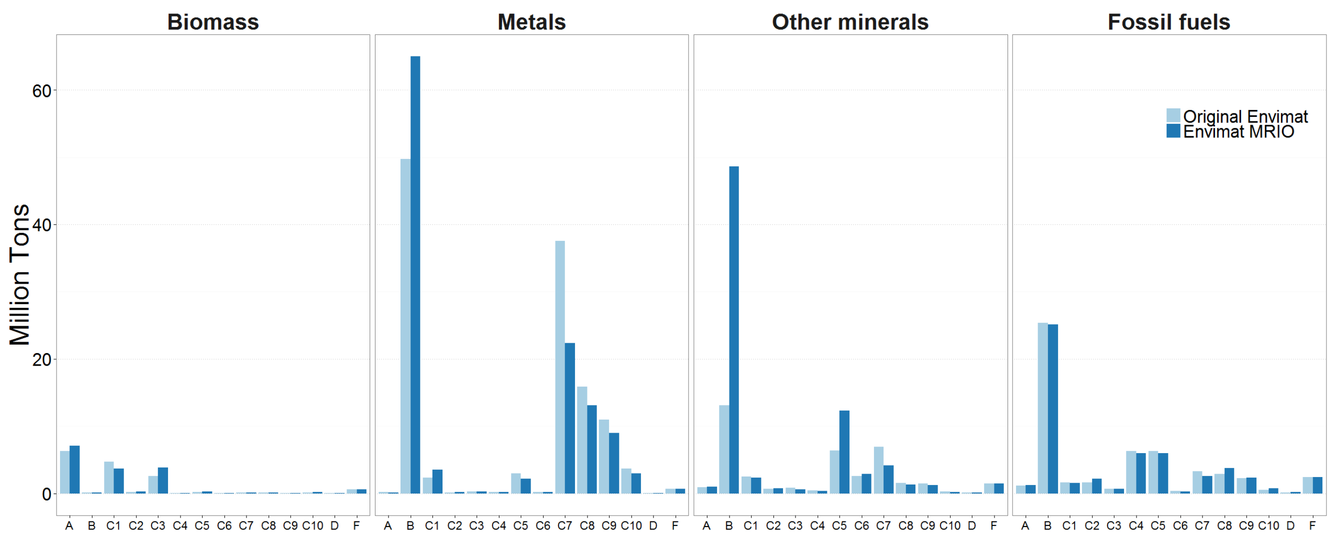


Figure 3. Raw material equivalents (RME) of imports to Finland in 2010, by material for original and multi-regional input-output (MRIO) refined models.



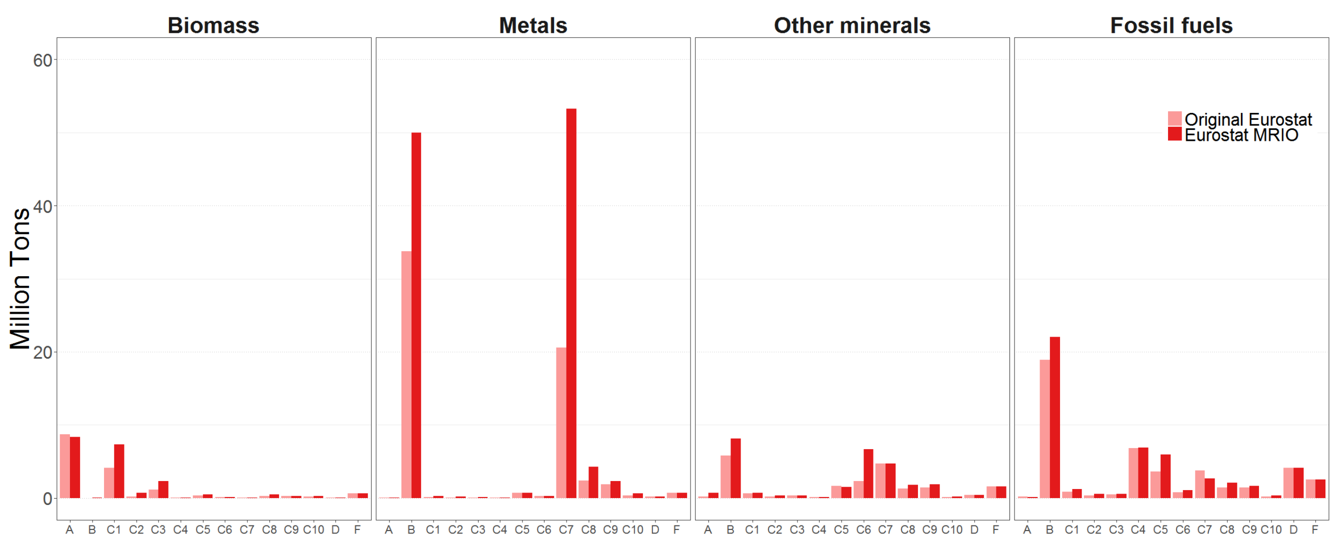
A = Products of agriculture, forestry and fishing, B = Mining and quarrying, C1 = Food, beverages and tobacco products, C2 = Textile, clothing and leather products, C3 = Wood, pulp and paper products , C4 = Petroleum refining products, C5 = Other chemical products, C6 = Other non-metallic mineral products, C7 = Basic metals and fabricated metal products, C8 = Electrical and electronic products, C9 = Machinery and transport equipment, C10 = Other manufacturing products, D = Electricity and water supply , F = Services. Mtons denotes million tons of RME of imports by each raw material.

Figure 4. Raw material equivalents (RME) of imports to Finland in 2010, by material and product groups for original Envimat and Envimat-multi-regional input-output (MRIO) models.

Table 4. Changes in multipliers and the most important deviations in metals and other minerals comparing original Envimat and Envimat-multi-regional input-output (MRIO) models

Product	**Imports** (Mkg)	**Original Envimat** (kg/kg)	**Main partner** (kg/kg)	**Main partner bias** (Mkg)	**Total bias** (Mkg)
Iron ores	3053	1.7	5.4 (SE)	-11007	-11301
Copper ores and concentrates	458	44.1	107.6 (WL)	-14307	-7378
Primary materials of iron and steel	1089	6.4	1.4 (SE)	4726	5154
Nickel, unwrought semi-finished products of nickel or nickel alloys	32	125.4	28.6 (ES)	1669	3027
Nickel mattes, nickel oxide sinters and other intermediate products of nickel metallurgy	34	125.4	47.3 (BR)	2156	1921
Flat rolled products of steel	548	4.9	1.2 (SE)	524	1478
Tubes, pipes, hollow profiles and related fittings, of steel	535	5.1	2.2 (GE)	746	1459
Other non-ferrous metals and articles thereof; cermets; ash and residues, etc.	33	110.9	164.7 (WF)	-1330	-1407
Semi-finished products of copper or copper alloys	45	108.8	56.1 (RU)	415	1399
Clays and kaolin	997	4.5	7303.4 (IN)	-18054	-30150
Other inorganic basic chemicals	1876	1.1	4.6 (NO)	-2874	-3846
Peptones, modelling pastes, activated carbon, finishing agents, pickling preparations etc.	282	2.7	13.2 (NO)	-2396	-2487

Product = product name used in Envimat. **Imports** = total imports to Finland in 2010, in million kg. **Original Envimat** = coefficient kg of material RME per kg imported for the broad raw material type under consideration. **Main partner** = coefficient kg of material RME per kg imported for the main deviations by country: SE = Sweden, WL = Rest of America, ES = Spain, BR = Brazil, GE = Germany, WF = Rest of Africa, RU = Russia, IN = India, NO = Norway. **Main partner bias** = most important deviation between partners, in million kg. **Total bias** = total bias by product, in million kg. Sign in bias denotes under- or over-estimation.



A = Products of agriculture, forestry and fishing, B = Mining and quarrying, C1 = Food, beverages and tobacco products, C2 = Textile, clothing and leather products, C3 = Wood, pulp and paper products , C4 = Petroleum refining products, C5 = Other chemical products, C6 = Other non-metallic mineral products, C7 = Basic metals and fabricated metal products, C8 = Electrical and electronic products, C9 = Machinery and transport equipment, C10 = Other manufacturing products, D = Electricity and water supply , F = Services. Mtons denotes million tons of RME of imports by each raw material.

Figure 5. Raw material equivalents (RME) of imports to Finland in 2010, by material and product groups for original Eurostat and Eurostat- multi-regional input-output (MRIO) models.

Table 5. Changes in multipliers and main deviations in biomass, metals, other minerals and fossil fuels comparing original Eurostat and Eurostat-multi-regional input-output (MRIO) models

Product	**Imports** (Mkg or Meuro)	**Original Eurostat** (kg/kg or kg/euro)	**Main partner** (kg/kg or kg/euro)	**Main partner bias** (Mkg)	**Total bias** (Mkg)
Animal and vegetable oils and fats (e)	416	2.0	7.7 (WA)	-1390	-1496
Fruit, nuts, beverage and spice crops (m)	301	1.0	6.6 (WL)	-477	-1283
Iron ores (m)	3053	1.2	3.9 (SE)	-7951	-8164
Copper ores and concentrates (m)	458	34.8	78.1 (WL)	-9751	-4427
Other non-ferrous metal products (m)	31	189.8	1162.7 (WF)	-24067	-28099
Basic iron and steel products (m)	3354	2.2	6.4 (RU)	-1348	-2474
Ceramic products and other non-metallic mineral products (e)	338	5.1	836.6 (US)	-4109	-4294
Petroleum oils and oils obtained from bituminous minerals (m)	11212	1.1	1.4 (RU)	-3174	-2888
Other basic chemicals (e)	2341	1.0	4.2 (RU)	-987	-1349
Fertilizers and nitrogen compounds (e)	228	1.5	6.7 (RU)	-862	-912

Product = product name used in Eurostat RME tool, (e) denotes economic flow and (m) mass flow. **Imports** = total imports to Finland in year 2010 in million kg or million euros. **Original Eurostat** = coefficient kg of material RME per kg or euro imported for the broad raw material type under consideration. **Main partner** = coefficient kg of material RME per kg or euro imported for the main deviations by country: WA = Rest of Asia and Pacific, WL = Rest of America, SE = Sweden, WF = Rest of Africa, RU = Russia, US = United States. **Main partner bias** = most important deviation among partners in million kg. **Total bias** = total bias by product in million kg. Sign in bias denotes under- or over-estimation.