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Analysis

Effect of aggregation and disaggregation on embodied material use of products in input–output analysis

Arjan de Koning [a,]*, Martin Bruckner [b], Stephan Lutter [b], Richard Wood [c], Konstantin Stadler [c], Arnold Tukker [a]

[a] *Institute of Environmental Sciences (CML), Leiden University, The Netherlands*
[b] *Institute for Ecological Economics, Vienna University of Economics and Business, Austria*
[c] *Norwegian University of Science and Technology (NTNU), Industrial Ecology Program, Trondheim, Norway*

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ABSTRACT

Consumption-based material footprints calculated with multi-regional input–output (mrIO) analysis are influenced by the sectoral, spatial and material aggregations used in the mrIO tables, and lack of disaggregation can be a source of uncertainty. This study investigated the effect of the resolution of mrIO databases on consumption-based material footprints. The effect of aggregation was investigated by constructing input–output tables with different spatial, product and material category resolutions and comparing the calculated material footprints. Our results indicate that the material footprints of countries calculated using the different spatial and product aggregations are in general in the order of a few percent, with outliers in the order of 25% difference. The use of IO models with a low product category resolution (e.g. 60 product categories) to calculate the embodied material use of individual products will likely result in inaccurate estimations of the total embodied material for some product categories. Aggregating the original 46 material categories into 16 categories changes the calculated material footprint of countries by about 30%. This result strongly suggests that the material data used to create the extensions for the IO framework should be collected at the highest resolution that is practically feasible.

1. Introduction

Multi-regional IO systems are currently recognized as constituting a state-of-the art system for the calculation of economy-wide environmental impacts of consumption, including carbon, water, land and material footprints (Bruckner et al., 2012; Tukker et al., 2014; Eisenmenger et al., submitted for publication; Bouwmeester, 2014; Wiedmann et al., 2014). Different multi-regional IO systems (mrIOs) exist, and they differ in their level of resolution with respect to material categories, products/industries and countries/regions (Tukker and Dietzenbacher, 2013). Much of this work on consumption-based accounts with mrIOs has focused on the carbon footprints of countries and products (Hoekstra, 2010; Ahmad and Wyckoff, 2003; Hertwich and Peters, 2009; Davis and Caldeira, 2010), and increasing attention is devoted to factors causing uncertainty in such footprint estimates (e.g. Peters et al., 2012; Wilting, 2012; Lenzen et al., 2010; Moran and Wood, 2014; Stadler et al., 2014). Currently, efforts are being made to use similar approaches to estimate footprint type indicators of material usage for policy applications (EC, 2011; OECD, 2011). An important example of such efforts is the ongoing work of the United Nations Environment Program International Resources Panel (UNEP IRP)[1] and OECD (2008) to develop a harmonized resource extraction database covering almost all countries in the world. In this context, the question is what factors are relevant when creating robust estimates of material footprints. Since the UNEP IRP effort will harmonize much of the primary extraction data, the question we focus on in this paper is: what is the impact of data resolution and aggregation on estimates of material footprints using mrIOs? We focus on this specific question within three particular domains: (1) the resolution of information on material extracted from the environment; (2) the resolution of product groups tracked in the input–output system; (3) the geographic resolution. By investigating these aspects, we have sought to identify a reasonable level of resolution for mrIO work in order to get representative results, and to identify the areas that are most critical to provide detail on when either creating or utilizing mrIO data.

Tukker and Dietzenbacher (2013) provided an overview of the latest developments in mrIOs. Previous work has shown that the resolution in an input–output table (IOT) affects the results obtained. As early as in 1949, Leontief discussed the influence of aggregation (Leontief, 1949). Hatanaka (1952) and McManus (1956) showed that aggregated input–output tables are very likely to yield outputs that differ from

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* Corresponding author.
E-mail address: koning@cml.leidenuniv.nl (A. de Koning).

[1] See the website of the UNEP IRP (http://www.unep.org/resourcepanel/) for completed work and ongoing research.

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that of the original table. The impact of the resolution of IOTs and mrIOTs on footprints of countries and products has until now mainly been investigated for CO_2 or greenhouse gas emissions (e.g. Andrew et al., 2009; Su and Ang, 2010; Su et al., 2010; Lenzen, 2011; Bouwmeester and Oosterhaven, 2013; Steen-Olsen et al., 2014). The conclusion of this work is that a greater level of sector and country resolution generally improves the accuracy of carbon footprints estimates. Bouwmeester and Oosterhaven (2013) concluded that the effect of sectoral aggregation is much larger for water footprints than for CO_2 emissions, highlighting the need for a separate investigation of the influence of aggregation on material footprints. Wood et al. (2015) compared multipliers and impacts embodied in the trade of labor and carbon dioxide, finding significant enough variation to warrant further research into disaggregation. Lenzen (2011) empirically analyzed the question, again for carbon dioxide, finding a clear indication that disaggregation is always preferred to aggregation. Steen-Olsen et al. (2014) concluded that more work is necessary to investigate the relationship between the level of resolution of IOTs and multipliers for other environmental extensions, such as materials. Huysman et al. (2014) looked at the need for disaggregated material extraction data in order to characterize the material footprint by means of a secondary indicator (exergy in this case). Linking pressure indicators such as material extraction to impact indicators that require a characterization of resource use will create a further argument for material disaggregation, which we acknowledge, but do not analyze here.

Work on understanding the uncertainty in material footprint calculations with mrIO is still in its early stages. Eisenmenger et al. (submitted for publication) and Giljum et al. (2014) presented comparisons of the material footprint for Austria, the EU-27, the US and China, calculated using different mrIOs: WIOD (Dietzenbacher et al., 2013; Timmer, 2012), Eora (Lenzen et al., 2013), GTAP (Narayanan et al., 2012), OECD-GRAM (Bruckner et al., 2012) and EXIOBASE (Wood et al., 2015). The material footprints calculated with these mrIOs ranged from 29 to 33 tons per capita for Austria (Eisenmenger et al., submitted for publication), and from 10 to 11 billion tons for the EU-27, 7.5 to 12.5 billion tons for the US, and 7 to 19 billion tons for China (Giljum et al., 2014). It is likely that this range of outcomes is principally due to basic differences in, for example, the material extraction data used (an issue that will be solved by the aforementioned work of the UNEP IRP). However, as was found for carbon footprints, some of the differences can be attributed to differences in resolution, at the level of countries, industry and products, and material categories, as used in the different mrIOs.[2]

Until now the effect of resolution in mrIOs on the material footprint has not been studied in detail. The specific novelty of the present study is its focus on material footprints and the effect of using more or less detail in material categories. As indicated above, the effect of material category resolution is especially interesting for the ongoing discussions at UNEP regarding the set-up of a world-wide material accounting database. While the incorporation of this database in a detailed mrIO can definitively be an argument for a high level of detail, issues such as copyrights or the demand for less detailed data by the majority of users argue for the use of less detailed material extraction data. This paper aims to specifically offer guidance on the effects of having higher or lower resolution in the material data.

We place this research question in a broader context by calculating both material and carbon footprints, and comparing the results regarding the variance of the calculated material footprints with the calculated carbon footprints of countries and products/industries. The carbon footprints serve as a reference with which the material footprints are compared. Is the effect of resolution on the material footprint smaller or larger than on the carbon footprint? The carbon footprint is a useful reference because of the wealth of other studies examining the effect of resolution on carbon footprints. In addition, greenhouse gas emissions are also emitted by many sectors of the economy, in contrast to material extraction, which is by and large concentrated in the agriculture, forestry and mining sectors, leading to much higher concentrations in supply chains.

This study used the recently published version 2 of EXIOBASE (Wood et al., 2015; Tukker et al., 2014). The available multi-regional supply-use tables (mrSUTs) at the highest level of detail were used as the starting material. Subsequently, this set of mrSUTs was transformed to four different mrIOs, each representing a scenario. These scenarios allowed us to investigate the effect of (1) reduced product resolution, (2) reduced spatial resolution, and (3) reduced material category resolution. The basic comparison between the scenarios regards the total material and carbon footprints of countries/regions and the embodied material use and carbon emissions of products per million Euro of the product. In specific cases, the result was broken down into different material categories for further explanation and interpretation.

2. Material and methods

Most of the studies mentioned in the introduction investigated the effect of aggregation of the IOT. However, since the work of Stone and co-workers (UN, 1968) it is generally accepted that the best route to arrive at an IOT is to compile data in the form of a supply-use table (SUT) first. This SUT is then transformed into an IOT for analytical purposes. The purpose of examining the influence of aggregation is to assess the implications of having less detailed data available. Since the basic data for an IOT is given in the form of a SUT, the investigation preferably starts by aggregating the SUT and transforming the aggregated SUT into an IOT. As is shown below, aggregation at the level of an SUT usually results in an aggregated IOT that is different from an IOT created by aggregating the IOT in the same way.

Various SUT to IOT transformation models exist, see for instance Miller and Blair (2009) and Eurostat (2008), but the most commonly used model for product-by-product tables uses transformation according to the industry technology assumption (PxP-ita), which is also recommended by the UN (1993). The PxP-ita IOT always gives positive values and can work with rectangular SUTs like those used in this study. We therefore used the PxP-ita model in this research to transform the SUT into a symmetric product-by-product table.

The basic data used to construct all four scenarios consists of mrSUTs exported from EXIOBASE version 2.2.0.[3] This set of tables represents the EXIOBASE mrSUT data at their highest level of detail for 48 countries/regions, 200 product categories, 163 industry sectors and 46 different material categories. See the Supporting information for a full specification of these classifications. Also included in the set are the three major greenhouse gases (CO_2, CH_4 and N_2O). These were will be used to calculate consumption-based carbon footprints of countries as well as carbon footprints of individual products, and served as a reference with which the material footprint can be compared.

The total material footprint is based on the sum weight of all the individual material categories (only the "used extraction" categories have been taken into account. The "unused extraction" data have not been used). The carbon footprint was calculated based on the global warming potentials of CO_2, CH_4 and N_2O with a 100-year time frame (GWP_{100}). These values are given in the Supporting information.

The construction of the four different scenarios is described below, while a graphical overview is provided in Fig. 1.

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[2] As summarized by e.g. Tukker et al. (2013), not only the mrIO approach but also various other approaches, including co-efficient approaches, can be used to estimate (material) footprints of countries. A co-efficient approach for the material footprint looks at the weight of an imported product according to trade data, and then uses life cycle inventory data to estimate the primary material extraction needed to produce that product (cf. Eurostat, 2012b). Comparison of mrIO and co-efficient approaches is beyond the scope of this paper — see Schoer et al., 2013.

[3] EXIOBASE version 2 can be downloaded free of charge from www.exiobase.eu.