# Abstract

The accounting for capital in input-output (IO) analysis has been a problematic issue for decades. While it is generally acknowledged that capital transactions should be incorporated in inter-industry matrices when analysing impacts of consumption, issues of data availability have limited efforts of endogenising capital to sporadic efforts at the national scale.

In this paper we present the results from a first attempt at endogenising capital transactions in MRIO tables on a global scale across several years. By combining the detailed environmental accounts from the EXIOBASE3 database with the economic data provided by the EU KLEMS capital accounts, we have created new inter-industry matrices with capital transactions endogenised using the flow matrix method. Results show that the endogenisation of capital transactions leads to substantial reallocations of global consumption-based GHG emissions between countries, which are likely to have important implications for future climate policy development.

# Introduction

Infrastructure development is a well-known driver of economic activity and the associated resource use and environmental impacts (Müller et al. 2013; Chen and Graedel 2015). In terms of the carbon footprints of nations, capital investments constitute a substantial share of the final demand of goods and services: Hertwich and Peters (2009) assign 18% of global greenhouse gas (GHG) emissions to capital investments, while in monetary terms, gross fixed capital formation (GFCF) accounts for almost 25% of the total global final demand.

Nevertheless, it is not well known how capital is being used within societies to provide the infrastructure, industrial assets and communication technologies needed to produce further goods and services. Many countries keep accounts of the total yearly formation of fixed capital, but it is seldom specified in which specific industrial sectors the products are invested; conversely, capital inputs are aggregated into one generic entry as primary inputs (the consumption of fixed capital). Economy-wide models are mainly based on national accounts data, and capital accounts are structured accordingly. Such data is traditionally reported in the form of supply-use tables (SUTs) but is used in analysis in the form of square input-output tables (IOTs), in which GFCF appears as a vector in the final demand, and the consumption of fixed capital as a row vector of primary inputs in the value added. Combining IOTs from different regions yields multi-regional IO tables (MRIOTs), which can be augmented to include environmental extensions that can be used to calculate environmental impacts attributed to the final demand of products and services.

In the System of National Accounts (SNA), gross capital formation includes the “total value of the gross fixed capital formation, changes in inventories and acquisitions less disposals of valuables” (OECD and UN 2009, p198). The definition of GFCF is concurrent across several major standard systems and capital measurement manuals (SNA, Eurostat, UN); the SNA formulates it as “the total value of a producer’s acquisitions, less disposals, of fixed assets during the accounting period plus certain specified expenditure on services that adds to the value of non-produced assets” (OECD and UN 2009, p198). Fixed assets are assets that are used repeatedly in production processes for a period of over a year (Eurostat 2008). The GFCF therefore constitutes a flow of long-term investments purposed to build up or maintain production capacity, and it has therefore been argued that capital transactions ought to be endogenised into the inter-industry matrices of the IO tables, on the basis that capital investments are, ultimately, done in order to facilitate and improve production.

Lenzen and Treloar (2004) discuss the pros and cons of two methods of endogenising capital in IO tables: the augmentation method and the flow matrix method. The augmentation method consists in incorporating GFCF as a separate, additional industry in the inter-industry matrix, thereby creating an artificial sector with a homogeneous commodity “capital”, which is produced using inputs according to the GFCF vector, and consumed according to a row vector of capital inputs (consumption of fixed capital). The flow matrix method, as suggested by Lenzen and Treloar (2004), consists in disaggregating capital expenditures by using sectors and then creating a separate capital flow matrix of the same size as the inter-industry matrix. Hence, a new Leontief inverse can be calculated, which incorporates the fact that capital is used in industries.

Lenzen describes and tests both method and concludes that the augmentation, although being easier to implement, results in systematic distortions in the calculated factor multipliers, mainly due to an unrepresentative allocation of different types of capital, whereas the flow matrix method gives much better results. The main shortcoming of that method is the high data requirements; detailed capital investment matrices are sparsely available and differ in the accounting methodology and classification. However, there have been recent efforts focused on homogenising account data, including GFCF, across countries, and may hence constitute a useful complement towards adopting the flow matrix method and thereby endogenising capital.

One of the reasons that GFCF is aggregated across industries in IO tables is indeed the lack of reliable data. The Eurostat manual (2008) describes a method to approximate the size and nature of capital goods by using the commodity flow method, which essentially consists in reconciling the supply and use sides of commodities by setting fixed allocations based on available statistics on the goods from producers, surveys, etc., which ought to be reviewed every year using updated information. While the method may be suitable for e.g. estimating the share of capital goods that go into intermediate consumption, for homogeneous products that can be allocated more or less uniformly across sectors, the manual maintains that the best approach to collect GFCF is by business surveys, and that the commodity flow approach is an alternative of lower quality.

In this paper, we discuss methods, first results, and implications of endogenising capital in MRIOTs. We begin in Section 2 with a description of MRIO, before describing relevant databases, and methods for integrating the data. Section 3 presents first results, and Section 4 discusses these results and the implications of methodological choices before concluding.

# Methods and data

## Multi-regional input-output analysis

MRIO analysis is a powerful tool for assessing environmental and sustainability impacts of traded commodities and services on a global scale. It is built on a theoretical framework developed by Leontief (1936), which uses previously recorded economic transactions to analyse interdependencies between different sectors of an economy based on records of economic transactions between them. The use of IO methodology for assessing environmental problems began in the late 1960s and constitutes the foundations of current MRIO analysis. Environmentally extended (EE) MRIO is widely used today to study global environmental impacts. Wiedmann et al. (2011) identify five recently developed projects that have compiled large-scale MRIO databases (AIIOT, Eora, EXIOPOL, GTAP and WIOD). Tukker and Dietzenbacher (2013) provide a consistent and recent review of the most prominent databases available today, and Moran and Wood (2014) analyse how the choice of database impacts carbon footprint calculations. We use IO analysis (IOA) to calculate consumption-based environmental impacts such as carbon footprints, and take the approach of linking capital accounts to the MRIO framework.

Figure 1 shows the interrelationships between industries with respect to the production and uses of their products and imports.

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Figure 1: The basic input-output framework, with the vectors of capital investments (GFCF) and inputs (CFC) highlighted*

* $Z$ *n* × *n* transaction matrix, in which element $z\_{ij}$ describes sales from industry *i* to industry *j*
* $Y$*n* × *d* matrix of final demand, i.e. sales to e.g. households, NGOs, government, etc.
* $V$*v* × *n* value added matrix of other financial elements (e.g. consumption of fixed capital).
* $x$ *n* × *1* vector of total output from industries
* $A$*n* x *n* direct requirements matrix
* $L$*n* x *n* Leontief matrix
* $F$*s* x *n* extension matrix containing e.g CO2 emissions, resource use, etc.

The vector **x** consists of both intermediate consumption from the inter-industry matrix **Z** and final demand consumption matrix **Y**,i.e. **x** = **Zi** + **Yi** = **Zi** + **y**, where **i** is a summation vector. In a balanced table, total payments equal total sales, thus we obtain $x$by summing down columns of $Z$and $V$ as well, according to **x**’= **i**’**Z** + **i**’**V**, where **i**’ is a summation row vector. The requirement matrix $A$ can then be computed according to $A=Z\hat{x}^{-1}$, where $\hat{x}$is a diagonalized version of the vector $x$, i.e. in which each element $x\_{i}$ is placed on row / column *i*. Combining these two equations results in $x=Ax+y$,whichcan be written$x=\left(I-A\right)^{-1}y=Ly$, where **I** is the identity matrix. The matrix $L$,known as the Leontief inverse, constitutes a pillar of input-output modelling, as it gives the total (direct and indirect) outputs needed from all industries to produce each unit of final demand, i.e. the change in output for unit change in demand (Leontief 1936; Miller and Blair 2009).

The IO model described above can be scaled up to include several economies / regions which gives the aforementioned MRIO models. By adding an extension matrix **F** containing additional relevant data such as labor accounts, material / energy use and environmental extensions (among which some rows correspond to the carbon footprint (CF), a global warming potential weighted assessment of air emissions), it is possible to calculate environmental impacts associated with a specific final demand. **F** provides total direct territorial impacts per region and industry. By selecting the row corresponding to CF in **F** (that we call $F\_{CF}$)and by normalizing it to form a 1× *n* emission coefficient matrix (or stressor matrix) $S\_{CF}$we obtain the consumption-based CF due to final demand $y$: $d=S\_{CF}Ly$**.**

We can keep the final demand resolution by diagonalizing it and hence obtain a 1×9800matrix of consumption-based CF: $D=S\_{CF} L\hat{y}$. Each element of $D$is then the CF resulting from the purchase of one specific product category in one specific region.

By selecting specific rows in the final demand vector and specific columns in the stressor matrix, we can calculate country-specific impacts. For instance, consider an *n* × *n* MRIO table with *i* sectors and *c* countries, i.e. *n* = *i* × *c*. Consider also a vector $y\_{A}$that contains the final demand data of country A from all other countries. By creating a stressor matrix $S\_{CF}\_{B}$ that contains emission coefficients for country B but with the entries corresponding to other countries set to 0, we can calculate CF that occur in country B due to consumption in country A.

## Databases used

### Exiobase

We use the most recent version of the EXIOBASE database in our calculations (version 3.2). EXIOBASE is based around detailed EE SUTs (Tukker et al. 2013), trade-linked in order to follow global supply chains. The database consists of detailed time series of MR EE SUTs, as well as symmetric MRIOTs (Eurostat 2008), starting from the year 1995 and nowcasted to 2016. The SUTs have been compiled by gathering information from national and international (e.g. Eurostat, UN) statistical offices, and hence contain detailed accounts from 44 countries, covering 90% of the global GDP. The remaining countries are accounted for in five rest-of-the-world (RoW) regions. The EXIOBASE SUT classification contains 163 industries and 200 products, and the symmetric IOTs derived therefrom are hence constructed on a 163- or 200-entry basis. This, along with the high country resolution, make it one of the most detailed MRIO database currently available (Wood et al. 2014b). Moreover, one of the objectives of EXIOBASE is that it should be relevant for environmental policy, and one of its benefits for that aim is the availability of inter-industry requirement matrices and detailed stressor matrices for agriculture, energy and resources. For more detailed information about EXIOBASE, see Wood et al. (2014a).

While EXIOBASE provides global accounts of GFCF disaggregated over 200 asset types, it only lists the investments as one final demand category, in other words giving detailed information on what type of assets GFCF is constituted of, but none regarding the sectors in which capital is being invested in. Other MRIO databases (e.g. EORA, WIOD, GTAP) have the same drawback, the reason being that the upstream source data for all MRIOs are national accounts, which typically do not provide detailed information on capital use per industry.

### Klems

The EU KLEMS Growth and Productivity Accounts are a set of databases containing inputs and outputs of capital, labour, energy, materials and services for 25 European countries as well as five non-European (Australia, Canada, Japan, Korea and USA) (Timmer et al. 2007b; EUKLEMS 2016) . Since many countries provide highly aggregated capital formation matrices, the KLEMS database has settled for a low level of industry and asset type detail, including only eight and 32 categories of assets and industries, respectively.

The KLEMS database does provide additional information regarding where different types of assets are actually being used, which makes it a valuable complement to EXIOBASE. Although it is available for fewer countries, combining the two databases enables us to assign environmental impacts to different industry sectors.

## Endogenising capital in MRIO

The flow matrix method consists in creating a capital requirement matrix $K$with the same dimensions as the inter-industry requirement matrix $A$, where $K=\overbar{K}\hat{x}^{-1}$, with $\overbar{K}$ being a matrix with capital transactions, constructed using capital distribution matrices from KLEMS and capital transactions from EXIOBASE.

In order to combine the capital specifications in KLEMS together with the detailed economic and emissions data of EXIOBASE, we need to make the KLEMS capital accounts compatible with EXIOBASE. First we convert the KLEMS capital data from national currencies to Euros using yearly averages of exchange rates (XE 2015). For the years preceding the introduction of the Euro, the first official exchange rates were used; this is the methodology that the KLEMS database utilizes to harmonize the tables for the countries that have switched to the Euro (Timmer et al. 2007a). Second, we disaggregate the eight asset types in KLEMS into the 200 product categories of EXIOBASE, using a concordance matrix **G**that maps the asset types from KLEMS to relevant product categories in EXIOBASE. When one KLEMS product maps to more than one EXIOBASE product, the value needs to be disaggregated and distributed among the different destinations. In order to obtain a reasonable distribution, a proxy **p**is needed. We use GFCF values from the EXIOBASE as proxy values to distribute the KLEMS asset types over EXIOBASE categories. We normalise the concordance matrix to avoid double counting; that is, the sum of the shares that each asset assigns to EXIOBASE product categories should amount to one. We obtain a new matrix **Gnew** calculated as such:

$$G\_{new}=\left(\hat{Gp+δ}\right)^{-1}G\hat{p}$$

The circumflex attribute on **p** implies a diagonalised vector, and $δ$ is a threshold value that prevents singularities. Multiplying the 8-by-32 matrix of GFCF values $C\_{KLEMS}$ with $G\_{new}$ gives a new 200-by-32 matrix of national GFCF values for each KLEMS country. A similar procedure is performed to convert the industry dimension from KLEMS to EXIOBASE classification.

To make it compatible with EXIOBASE, we need to distribute the GFCF values over all regions to form a 9800-by-200 matrix $C\_{EXIO}$**.** Since KLEMS doesn’t provide information about which country the capital assets are purchased from, we use EXIOBASE proxies to distribute the GFCF expenditures of the KLEMS countries across the 48 EXIOBASE regions (the majority – 85% on average – of assets are assigned domestically). Note these proxies are only used for distribution of GFCF to industries, where the absolute value of GFCF by product is known (as a vector in final demand) for all countries.

In order create capital distribution proxies for the EXIOBASE countries that are not covered by KLEMS, several avenues are possible. As a first attempt, we have created generic distribution matrices by adding all capital transactions matrices of the thirteen available countries covered by KLEMS. This method implies that capital is being used similarly in all other regions of the world and is clearly unrealistic, but it does at least provide a distribution matrix grounded on empirical data and was therefore deemed suitable as a first approach. This generic matrix is then disaggregated across products and industries using, respectively, CFC and GFCF from EXIOBASE as individual country proxies. This results in a 9800-by-9800 $K$ matrix of capital transactions.

In order to obtain a capital requirement matrix we proceed similarly as when calculating the regular inter-industry matrix $A=Z\hat{x}^{-1}$, i.e. by dividing the capital flows by the total output as such: $K=\overbar{K}\hat{x}^{-1}$. From this we calculate a new Leontief inverse based on the a new matrix of inter-industry transactions containing both $A$and$K$:

$$L=(I-\left(A+K)\right)^{-1}$$

The whole procedure is performed for several years, which we then use to calculate time series of carbon footprints of nations.

# Results

We present here an initial sample of the results obtained from our new MRIO tables with endogenised capital. Figure 2 displays the total consumption-based carbon footprint from final demand from each of the EXIOBASE countries, with and without GFCF endogenised, in kg CO2 equivalent. The grey line (right axis) shows the difference between the two approaches. Note that direct emissions are not accounted for, since they are not affected by the different approaches. We see that the carbon footprint of most countries increases when capital is endogenised; only a handful of countries see their footprint decrease. This apparent imbalance is largely due to the fact that China, the world’s largest emitter of GHG emissions, has its footprints reduced by 12%, which offsets the cumulative increase of most all smaller countries. The total carbon footprint of the world remains the same, since emissions are only reallocated.

*Figure 2: Carbon footprint of different countries with and without endogenising GFCF, 2007*

Figure 3 displays time series of the GHG emissions of the world’s two largest emitters of GHG emissions, China and USA, with and without GFCF endogenised. We notice a decoupling between the two approaches for both countries, but in different directions. When GFCF is endogenised, China’s emissions do not increase as fast as they seem to do otherwise, i.e. when using standard consumption-based EE MRIO accounting. On the other hand, USA’s emissions increase much slower without GFCF endogenised. The reallocation of emissions that occurs when endogenising capital hence leads to important changes in the relative contributions to global warming of these two countries, which together account for roughly 40% of global GHG emissions*.*

*Figure 3: Time series of the carbon footprint of the two largest emitters of GHG emissions, China and USA, with and without GFCF endogenised (in kg CO2 equivalent).*

# Discussion and conclusion

Closing the input output system by endogenising capital transactions is not a new idea. The issue is well acknowledged among input output practitioners but has remained unsolved for decades, mainly due to the problem of data availability. Today’s IO databases only provide capital expenditures as a final demand vector, and this is due to the lack of data availability from the national accounts. The EU KLEMS project provides a good starting point for endogenising capital. The relatively low product resolution may seem like a bottleneck, but capital goods tend to be less diverse than e.g. household goods and a higher aggregation can therefore be accepted. However, the nature of capital goods also implies that certain specific products ought to be disaggregated. Such is the case of products from construction, which in EXIOBASE are all aggregated together into one category. Construction goods make up around 50% of all capital investments and a finer resolution would enable more precise environmental assessments.

Another issue of concern with the KLEMS database is that it is still only available for a handful of countries, and the average distribution matrices used in our approach may not provide a realistic representation of capital flows in the remaining countries of the world. Moreover, the countries covered by KLEMS are countries with high levels of GDP per capita, and it is likely that the use of capital in less developed countries may be different.

Calculating capital requirements based on capital expenditures involves the assumption of a steady-state economy. GFCF accounts for capital that is being purchased during a specific year but that will actually be consumed in the future, so to endogenise it in a current inter-industry requirement table assumes that the capital use is similar to the capital investment. This assumption may be considered valid in some cases, for instance in the case of countries that already have a well-established capital stock, since a lot of the capital expenditure will occur to replace old assets, but for countries that are still in the process of building up their infrastructure, the consumption of fixed capital is likely to be different than the capital formation for a specific year. Hence, it would make more sense to endogenise capital inputs rather than capital formation. However, this involves several difficulties regarding how to account for capital inputs, e.g. how to distribute the assets’ use of their lifetimes (which is sometimes referred to as the *fundamental problem of accounting* (Diewert 2005).

Notwithstanding the methodological issues that remain to be dealt with, the methodology applied in this paper constitutes a substantial improvement of the current IO methods and will help the continuous development of MRIO analysis. The task of endogenising the consumption of fixed capital rather than capital formation is the next step we are taking to enhance our methodology further.

The endogenisation of capital in inter-industry requirement matrices shows promising results and the consequences are wide-ranging. The reallocation of emissions that occurs when capital is endogenised changes the global GHG emission distribution substantially, which in turn can have important implications in climate policy development.

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