Environmental Input-Output Analysis

The accounting of indirect effects in network systems using matrix methods

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I. Motivation

How many greenhouse gas (GHG) emissions are required to generate the Portuguese consumption of clothes (but not shoes)?

To allocate the GHG emissions that occur throughout the economy to one particular class of final output, it is necessary to follow the flow of embodied emissions along each economic transaction, starting from the physical source of direct emissions. Mathematically, this is the same problem as determining the efficiency of electricity production or the impact of government expenditure in job creation.
II. Theory

General framework

There are \( n \) internal sectors, plus sources and sinks. The internal sectors exchange mass* flows among themselves (\( Z \)), receive from sources (\( v \)) and deliver to sinks (\( y \)). The mass* is conserved (\( x \)).

\[
\begin{align*}
x &= Z1 + y \\
x &= Z'1 + v \\
A &= Z \text{ diag}(x)^{-1}
\end{align*}
\]

* This mass can be money, energy, metal, etc. What is important is that each flow is positive and it is conserved along the network.
II. Theory

Conservation of embodied emissions

There are local emissions* \((e^L)\) at each sector and there are embodied emissions transferred along mass flows.  
At each sector the amount of embodied + direct emissions is conserved. Embodied emissions accumulate along the same direction as the mass flows (upstream, \(e^U\)) or in the opposite direction (downstream, \(e^D\)). The sum of upstream emissions embodied in final demand = sum of downstream emissions embodied in primary inputs = sum of direct emissions. 

\[
\begin{align*}
  e^D_2 &= e^D_1 + e^L \\
  e^U_2 &= e^U_1 + e^L \\
  z_1 &\rightarrow i \rightarrow z_2 \\
  e^L &\downarrow
\end{align*}
\]

* These emissions can be GHGs, money, energy, metal, etc. What is important is that each flow is positive and it is conserved along the network.
II. Theory

Emission intensities and computation

If there are multiple mass outputs it is necessary to distribute the outgoing upstream emissions among them. If they are distributed in proportion to the magnitude of the mass flows, then all outputs of a given sector have the same upstream intensity ($m^U$). (Likewise for the downstream case, $m^D$.)

In this case, the intensity is a property of the sector, not the flow.

$$m^U_i = e^U_i / z_i = e^U_{i+1} / z_{i+1}$$

$$m^U_i = e^U_i / z_i = e^U_{i+1} / z_{i+1}$$

For the purpose of computation:

$$e^L = m^L \# x$$
$$e^U = m^U \# y$$
$$m^U = (I-A')^{-1} m^L$$
$$m^U_{i+1} = m^L + A' m^U_i$$
$$m^D = (I-B)^{-1} m^L$$
$$m^D_{i+1} = m^L + B m^D_i$$

$$e^D = m^D \# v$$

$$a_{ij} = z_{ij} / x_j$$
$$a'_{ij} = z_{ji} / x_i$$
$$b_{ij} = z_{ij} / x_i$$
III. Applications

Efficiency of electricity generation in Portugal

Mass flow = current energy (toe); embodied flow = primary energy (toe); Direction: upstream.

What about renewables? And energy degradation?

\[ A = Z \, \text{diag}(x - \text{deg})^{-1} \]

What's the magnitude of direct effects? First-order indirect? Second-order?
III. Applications

Carbon emissions embodied in Portuguese final consumption

Mass flow = currency (euro); embodied flow = GHG emissions (tCO2e); direction: upstream.

Considering direct emissions released from fossil fuel consumption, which sector of final demand has the highest intensity?

And which sector of final consumption has highest emissions?

And what about exports?
III. Applications

Effect of Portuguese exports on labour revenues

Mass flow = currency (euro); embodied flow = final demand (euro); direction: downstream.

A 1 euro increase in final demand of which sector leads to the highest increase in added value?

And of imports?

Which sector provides the energy consumed by households?
IV. Discussion

History

Leontieff (1941) first published a physical IO table. Late on, it became customary to used monetary tables.

Nowadays, IO tables are published by national statistical offices, using UN (1994) guidelines (national accounts).

In the past, the technical coefficients were viewed as fixed production recipes (Harrod-Domar growth model), and the Leontieff inverse was used to calculate the effect of exogenous shocks. Nowadays, IO tables are used to parameterize CGE models, allowing for substitutability between inputs (next class).


IV. Discussion

Comparison

The computation of upstream indirect effects is the “price-push Leontieff model” (Oosterhaven, 1996), which computes the rise in the price of final products given an increase in wages.

The computation of downstream effects (Ghosh model) makes little sense in economics. To compute the effect of a rise of demand in added value, economists compute the rise in total output as $\text{dx} = (\text{I-A})^{-1} \text{dy}$, and then $\text{dv/dx} = \text{v/x}$, assuming that the production recipe (each column of A is kept constant).

Thus, an economic IO model is a prescription of how the economy will function, given a disturbance, while an environmental IO model is a description of what is occurring now.

IV. Discussion

Data processing

IO calculations are conceptually easy, but source data is scarce and often inaccurate, and processing is hell.

Source transaction data comes in symmetric format or supply-use tables. Environmental (NAMEA) and economic data are usually provided in different formats (conversion is often necessary).

Data is often inconsistent and needs to be reconciled (biproportional and least square methods) or estimated (trade share methods). Time-series data needs to be interpolated and deflated.

Multi-regional models are particularly difficult to build (currency conversion, cif vs. fob), since data on international trade is poor (UNcomtrade). Several multi-regional tables are currently available (OECD, GTAP, WIOD, EXIOPOL).
IV. Discussion

Matrix vs. recurrence?

Which method to use to account indirect effects?
If there is a single output: blackbock.
If there are no cycles (production chain): use recurrence expressions.
If there are cycles: matrix expressions.

If using recurrence expressions, it is necessary to consider the effect of truncation.

In LCA, it is customary to consider direct emissions + cascades of indirect emissions, which leads to the problem of double-counting, which never occurs in the present framework.

In environmental IO analysis the crucial problem is data availability, which limits the degree of detail of the analysis.
IV. Discussion

Current work

At IN+/Scientific Area for Environment and Energy – DEM we have worked on the theory of environmental indicators (Rodrigues et al., 2006) and we have produced a multi-regional model from the GTAP6 database (Rodrigues et al., 2010). Currently, A. Marques and T. Domingos are studying the evolution of consumer (upstream emissions embodied in final demand) and producer (downstream emissions embodied in primary inputs) carbon responsibility. J. Rodrigues is applying Bayesian techniques to the quantification of uncertainty in IO analysis.

IV. Task assignment

Homework (4-6)

For every year (1995, 1999, 2005) determine:

During class:
1) The energy efficiency of electricity production;
2) Which class of final consumption has the highest upstream CO2 embodied emissions, using fossil fuel consumption as direct emissions;
3) In which sector will an increase in final demand of 1e lead to higher added value creation.

Homework:
4) The upstream embodied CO2 emissions for each energy type, using the energy balance;
5) The upstream CO2 intensity of each sector (using the results of (4) as direct emissions);
6) In which sector will a decrease in 1 tCO2 embodied emissions in final demand lead to lower higher value reduction.