Chapter 11
A Comparison Between Conventional LCA and Hybrid EIO-LCA: Analyzing Crystal Giftware Contribution to Global Warming Potential

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Introduction

The growing concern of European citizens with environmental quality and the European Commission's determination to develop stronger environmental policies has contributed to the development and optimization of environmental management tools to support decision-makers in industry and government. These tools help to pro-actively identify sustainable options, optimized according to environmental, social, and economic criteria.

In line with recent European Commission initiatives, an Integrated Product Policy (IPP) approach is to be considered in any economic sector. IPP addresses the whole life cycle of a product, and seeks to avoid shifting environmental problems from one phase of the product life cycle to another.

This vision has emphasized the role of Life Cycle Assessment (LCA) methods, (see, for example, Guinée et al. 2002), which are frequently used with the purpose of accounting for environmental impacts of products and services. These methods show practical limitations, considering that each industry is dependent, directly or indirectly, on all other industries. Consequently, this approach is expensive and time-consuming because resource input and environmental discharge data have to be estimated for each of the modeled processes of the life cycle of a product or service.

The LCA based model has the following advantages: it is accurate within a defined system boundary; it is independent from price fluctuation, and it facilitates unit process level analysis. The disadvantages of this model are related with its high cost for complex product systems, and inherently, it provides incomplete system

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S. Suh (ed.), *Handbook of Input-Output Economics in Industrial Ecology*, Eco-Efficiency in Industry and Science 23,

boundary, as the process inventory associated to the life cycle analysis has to be broken at a given point, there are no infinite boundaries.

An alternative macroeconomic approach, considering the inter-industry effects of product/process decisions for a diverse set of commodities, makes use of the economic input-output tables and environmental information. This approach is known as Economic Input-Output Life Cycle Assessment (EIO-LCA) analysis, (Hendrickson et al. 1998).

This methodology allows for the use of standard data sources, such as the national sector-based economic input-output tables. The method constitutes a coherent approach to environmental accounting, provided that information on emissions and use of natural resources is added. The use of input-output models is advantageous since they take into account the entire supply chain for a product (including indirect suppliers), allowing for tracing of the full range of inputs to a process, and consequently providing a complete system boundary.

The main limitations associated with this methodology are the poor level of disaggregation of the economy, the linearity of the model, its dependence on cost information, the fact that the result omits environmental intervention associated with capital goods, and the temporal difference may cause additional error. For example, the Portuguese economy characterization within the European System of National and Regional Accounts (ESA 79) is based on a national economic input output table, which includes data from 49 sectors, while the USA economy is divided in 500 commodity or service sectors. Additionally, inherently in EIO-LCA lies the assumption that within one production sector, environmental effects are proportional to the price of the product.

Both LCA and EIO-LCA provide interesting characteristics and complementary advantages. The important question is how can one take the most benefit from the two and reduce both truncation and aggregation errors. An answer that has been confirmed by input-output energy analysts is the hybrid approach, as discussed by Suh and Huppes (2005). This new technique, the HEIO-LCA, (hybrid EIO-LCA), is a process-based methodology analysis that replaces the price-proportionality assumption with an assumption of proportionality according to physical units.

The three methodologies, LCA, EIO-LCA, and HEIO-LCA, are discussed and assessed making use of a case study on the production of crystal giftware. The analysis is focused on the greenhouse gas emissions in the context of the Portuguese economy and, in particular, considering the economic sectors environmental performance. This analysis is used to assess the role of these methodologies to promote sustainable policy making in the context of the Kyoto protocol.

Background of EIO-LCA

Environmental Input-Output (EIO) analysis is based in the work of Leontief ([1985] 1986), and was developed for the US economy at Carnegie Mellon University's Green Design Initiative by Hendrickson et al. (1998), in that they have created a web site where the method is made available: www.eiolca.net.

Economic IO analysis describes the interdependence among sectors of a given economy by "a set of linear equations expressing the balances between the total input and the aggregate output of each commodity and service produced and used in the course of one or several periods of time", Leontief ([1985] 1986).

Considering that the relationship between a sector's output and its inputs, are represented in a matrix constituted by technical coefficients, A. The output required from each sector, X, to satisfy an increase in demand, Y, is quantified by: $X = (I-A)^{-1} Y$, where, $(I-A)^{-1}$, is commonly referred to as the Leontief Inverse and, I, is the identity matrix. Details of the matrix mathematics can be found in appendix.

The EIO-LCA methodology complements the economic input-output analysis by linking economic data with resource use (such as energy, ore, and fertilizer consumption) and/or environmental impact categories (such as greenhouse gases emissions). At a European level, environmental data is available from the National Accounts Matrix including Environmental Accounts (NAMEA), which accounts for the GHG emissions in the form of a matrix (***b***) of gaseous emissions per economic sector.

Considering that **B** represents the vector of different GHG emissions (CO_2, CH_4...), b is a matrix of GHG emissions per monetary unit of each sector's output, environmental impacts can be estimated by:

$$B = b \cdot X = b \cdot (I - A)^{-1} \cdot Y \tag{11.1}$$

Hybrid EIO-LCA Model

The Hybrid model is based on process-based LCA and economic input-output analysis-based LCA, and its motivation is that process-based hybrid analysis replaces the price-proportionality assumption with an assumption of proportionality according to physical units.

As discussed by Suh and Huppes (2005), a few different types of attempts to integrate benefits of process based analysis and input-output model were performed including addition of input-output based results upon process based models and disaggregation of monetary input-output tables, as in Bullard and Pilati (1976) or Wilting (1996). A hybrid model that allows for full interaction between a process based LCA model and an input-output model was suggested by Suh and Huppes (2005), and constituted the basis for the model presented here, that was extended to develop a computer model for the Portuguese economy, which is run to support the analysis performed in the present paper.

In the hybrid method, a new algebraic formulation is adopted that includes in the same matrix the background processes associated with EIO data, and the foreground processes that are specific of the system to be analyzed and provide greater disaggregation to the analysis. These processes are modeled including material inputs, emission outputs, and their interaction with economic activity (the background system). The representation of the foreground and background systems in the new

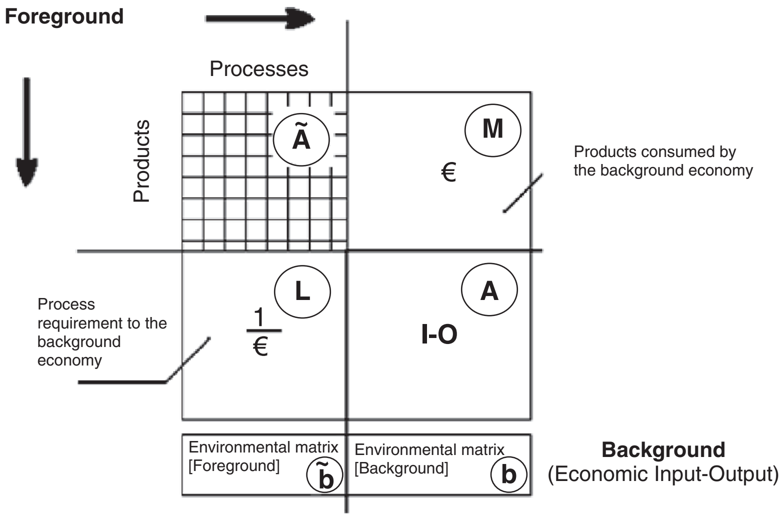

Fig. 11.1 Schematic Representation of the Hybrid EIO-LCA Algebraic Formulation

matrix is represented in Fig. 11.1. Here, the foreground processes are those characteristic of the product life cycle under investigation, and the background correspond to the economic sectors activity, as represented in the national accounting systems.

The integration of the two models has to be done carefully because on one side the foreground and background matrix have different units, and, on the other, it is necessary to avoid duplication of material/processes accounting.

The algebraic formulation of this model is as follows. In the foreground system, let the external demand of process output i be given as $\boldsymbol{k}$, where the use of tilde denotes any activity in the foreground system. If the technical coefficients of the foreground system quantify the products/commodities required in each process, for accomplishing one unit activity level, t, the technical coefficients are denoted by, $\widetilde{\mathbf{A}}$ and:

$$\widetilde{\mathbf{A}} \cdot \mathbf{t} = \mathbf{k} \tag{11.2}$$

This equation can be solved for t (unit activity level required by each process) by inverting the technology matrix $\widetilde{\mathbf{A}}$ and multiplying it with the vector of external demand of process output $\mathbf{k}$.

$$\mathbf{t} = \widetilde{\mathbf{A}}^{-1} \cdot \mathbf{k} \tag{11.3}$$

Considering that the environmental burdens associated with the processes in the foreground system are expressed by $\widetilde{\mathrm{b}}$, as represented in Fig. 11.1, the environmental considerations are expressed in the foreground process as:

$$\mathbf{B} = \tilde{\mathbf{b}} \cdot \widetilde{\mathbf{A}}^{-1} \cdot \mathbf{k} \tag{11.4}$$

The matrix $\tilde{\mathbf{b}}$ is the *intervention matrix*, since its coefficients represent interventions of the different economic processes in the environment: inputs (mainly extractions of resources) and outputs (mainly emissions of chemicals).

If we consider the formulation of the emissions for the foreground system (11.4) with the one for Input-Output (11.1), the Hybrid method can be represented by the following general expression:

$$\mathbf{B} = \left[\tilde{\mathbf{b}} \middle| \mathbf{b}\right] \cdot \left[\begin{array}{c|c} \widetilde{\mathbf{A}} & \mathbf{M} \\ \hline \mathbf{L} & \mathbf{I} - \mathbf{A} \end{array}\right]^{-1} \cdot \mathbf{k} \tag{11.5}$$

According to (Suh and Huppes 2005) the methodology used to create the matrix of coefficients and to normalize the foreground and background units of the process, can be calculated by the expressions (11.6) and (11.7). **L** and **M** denotes inputs from background and foreground systems to one another, respectively. In linking the foreground and background matrix the dimension of elements for **L** and **M** matrices should meet with corresponding rows and columns. **L** shows monetary input to each sector per given operation time, while **M** shows total physical output per total production in monetary term.

$$\mathrm{l_{pq}} = \mathrm{q_{pq}} \times \mathrm{p_p} \tag{11.6}$$

$$\mathrm{m_{pq}} = \frac{-\mathrm{a_{pq}}}{\mathrm{p_p}} \tag{11.7}$$

where:

$\mathrm{q_{pq}}$ = input of sector p in each unit process q,
$\mathrm{p_p}$ = unit price of product from sector p,
$\mathrm{a_{pq}}$ = technical coefficient from economic matrix.

Description of the Case Study – Lead Crystal Giftware Manufacturing

The three environmental analysis tools, LCA, EIO-LCA and HEIO-LCA, were assessed making use of a case study that considers manufacturing 1 kg of crystal giftware, in a notorious Portuguese manufacturer. The environmental burden considered in this analysis was the global warming potential-GWP.

This case study was selected mainly because it includes a complex process, lead crystal manufacturing that is characterized by process specific CO_2 emissions, resulting for chemical reactions characteristic of crystal melting.

The manufacturing processes analysis derived from a detail energy and environmental audit to a Portuguese manufacturer, and a summary of the results obtained are illustrated in Fig. 11.2, where the main production steps are represented together with the respective material and energy flows.

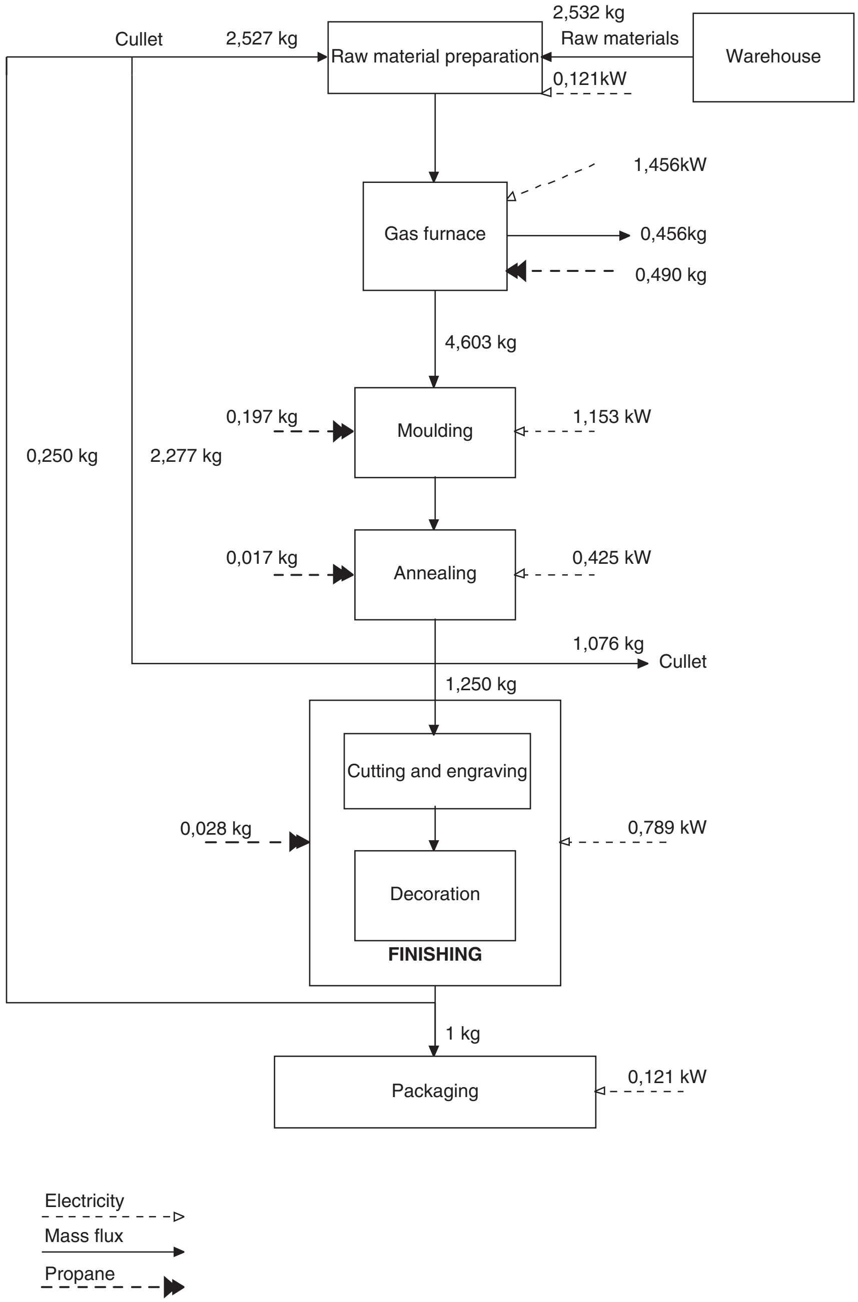

Fig. 11.2 Crystal Manufacturing Flowchart

Full lead crystal is made from a mixture of silica (sand), potash and lead oxide. To be considered "full lead crystal," the content of lead oxide must be at least 24%. After melting in the glass furnace, each piece, created by hand, is worked on by up to 12 craftspeople. First, a "gather" of molten crystal is taken from the furnace by dipping the blowing iron into the molten metal and twisting the iron. The gather is then rotated in a wooden forming block to give it uniformity of shape being produced. The glass is blown to form a bubble. The bubble is then shaped to the basic form by swinging the blowing iron or flattened by spinning. While the crystal is hot, it may be combined with other crystal elements such as handles and stems. After a piece of crystal has been shaped in the blowing room, it must go through a controlled cooling process known as "annealing." This is necessary to prevent internal strains from being set up within the crystal. It is affected by placing the object in a specially constructed oven, known as a "lehr," where it is carried on an endless belt through a series of slowly decreasing temperatures. The annealing of vases or table glass takes 5 to 8 h. Decorating Crystal can consist of hand cutting or engraving with specific designs. By holding the crystal against an abrasive, rotating stone wheel, the crystal can be cut. After decoration, the crystal products are washed and packed.

The GWP resulting from the life cycle (focused on the production phase) of the crystal products analyzed was evaluated using Simapro, an LCA evaluation tool, where specific Portuguese data was built-in. It should be mentioned that detailed manufacturing process was modeled in the LCA software, Simapro, where specific Portuguese energy source data was introduced. However, the boundary established does not include detailed data on the production of the different raw materials required to manufacture the crystal.

In a second step, the EIO-LCA tool was used, considering official data provided by the Portuguese statistical office, in order to enable the analysis of the environmental performance of specific processes and products.

The use of the EIO-LCA tool required the conversion of all the material and energy input along the manufacturing process to be converted in monetary terms, which, in Portugal, was the Portuguese Escudo – PTE, and to be allocated to the economic sector which provided the selected materials. The demand vector which resulted from this exercise is represented in Table 11.1.

The formulation of the hybrid methodology has been implemented in dedicated software developed at IST, (2004). This software enables the user to select

Table 11.1 Demand Vector Corresponding to the Production of 1 kg of Lead Crystal Products. (Only Sectors for Which Demand is Non-zero Are Represented)

Economic sectors	10^6 PTE
Coal	3.80×10^{-5}
Oil	2.74×10^{-4}
Electricity	5.38×10^{-4}
Non metallic minerals	6.90×10^{-6}
Chemical products	1.20×10^{-4}

the products/raw materials/energy sources requested, from a database where more than 12,000 items are available from the Portuguese economy characterization. This data includes the products/raw materials/energy designation, quantities consumed/produced per sector and its average price, information that is crucial to model the purchases of the foreground processes in the background economy.

When the program is run, the following steps have to be followed:

Characterization of the foreground processes, making use of the following information:

Process Available Products – where the available products, raw materials or energy to be consumed in the process are displayed.

Demand – amount of products, raw material or energy chosen to be consumed in the process.

Activity level – amount of the process unit activity used in the functional unit.

Identification of the Input-Output sectors used in the Process: Here the sectors of the input-output matrix that are part of the foreground processes are identified, and the amount used is quantified.

Characterization of the environmental burdens associated with the foreground process.

Once identified the foreground processes and the respective commodities consumed, the program automatically fulfills matrix M in Equation (11.7). These calculations are based on each commodity price, provided by national statistics, which is available in the program databases, and on the technical coefficients in the background system, for the economic sector in which the commodity is classified.

The formulation of the hybrid model has considered nine processes in the foreground system, which interacts with the background economy as represented in Table 11.2, where matrices $\tilde{A}$ and sample rows of matrix L are represented.

In the representation of the foreground processes associated with the bottle production (matrix $\tilde{A}$), each column shows inputs and outputs of each process for a given unit function. Outputs have positive sign while inputs have a negative one. For example, delivering 1 kg of crystal products requires inputs (negative sign) of 2.532 kg of raw materials and 2.527 kg of cullet. The analysis of the furnace shows that the input of 5.059 kg of materials generates 0.456 kg of gaseous emission, and 4.603 kg of melted glass.

Inputs from the background system to the foreground processes show monetary input to each sector, and are represented in the last nine rows of the matrix represented in Table 11.2, which are sample rows from the national EIO Table. For example, obtaining the raw materials required to manufacture the crystal, requires purchases of 3.8×10^{-2} kPTE (1,000 Portuguese escudos) to the coal sector, 2.5×10^{-2} kPTE to the electricity sector, 6.9×10^{-3} kPTE to the non metallic minerals sector and 1.2×10^{-1} kPTE to the chemical products sector.

The results obtained using the three methods, LCA, EIO-LCA and HEIO-LCA, are represented in Fig. 11.3, in terms of each process contribution to the global warming potential.

The results presented in Fig. 11.3 show that process based LCA is limited by the boundary truncations associated to neglecting the raw materials production, the

Table 11.2 Formulation of the Hybrid EIO-LCA Model

	Products	Demand	Foreground processes								
			Warehouse	Raw material preparation	Gas furnace	Moulding	Annealing	Finishing	Packaging	Gas treatment	Landfill
FOREGROUND (kg)	Raw materials	0	2,532	−2,532	0	0	0	0	0	0	0
	Cullet	0	0	−2,527	0	0	3,353	0.250	0	0	−1,076
	Furnace input	0	0	5,059	−5,059	0	0	0	0	0	0
	Melted crystal	0	0	0	4,603	−4,603	0	0	0	0	0
	Raw crystal product	0	0	0	0	4.603	−4,603	0	0	0	0
	Annealed glass	0	0	0	0	0	1,250	−1,250	0	0	0
	Final product	0	0	0	0	0	0	1,000	−1,000	0	0
	Packed Product	−1,000	0	0	0	0	0	0	1,000	0	0
	Gaseous emissions	0	0	0	0.456	0	0	0	0	−0.456	0
BACKGROUND (10^6 PTE)	Raw materials	0	0	3.80E-05	0	0	0	0	0	0	0
	Cullet	0	0	0	−1.40E-04	−1.10E-04	−9.6E-6	−4.3E-6	0	0	0
	Furnace input	0	0	−2.5E-5	−1.5E-4	−2.3E-4	−8.5E−5	−4.3E−5	−4.9E−6	0	0
	Melted crystal	0	0	0	0	0	0	0	0	0	0
	Raw crystal product	0	0	−6.9E-6	0	0	0	0	0	0	0
	Annealed glass	0	0	0	0	0	0	0	0	0	0
	Final product	0	0	0	0	0	0	0	0	0	0
	Packed Product	−1,000	0	0	0	0	0	0	0	0	0
	Gaseous emissions	0	0	−1.2E−4	0	0	0	0	0	0	0

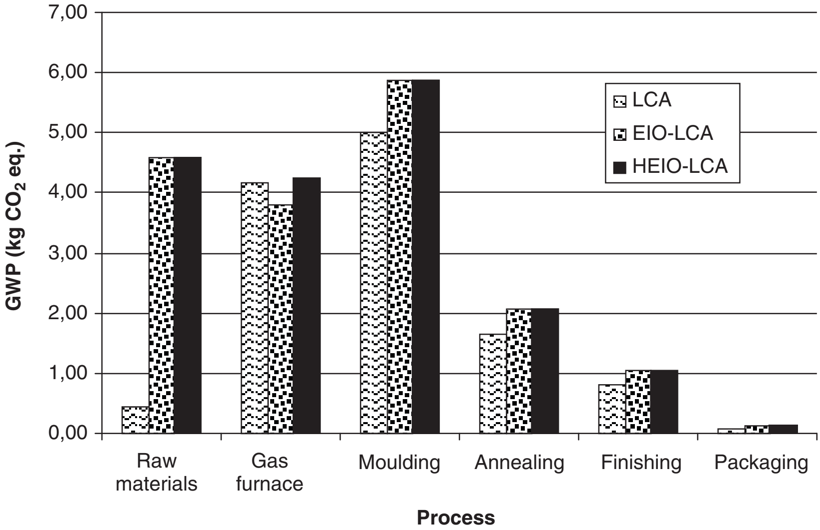

Fig. 11.3 GWP as Evaluated by LCA, EIO-LCA and HEIO-LCA

lubricants consumption in the moulding processes and the cleaning products in the finishing. This is particularly relevant in the raw materials production, as expected, as the process-based LCA clearly under estimate the GWP caused by raw materials production.

The results obtained do also show that EIO-LCA under estimate CO_2 emissions when compared to the HEIO-LCA method. This is because in the last method, the crystal melting process is specifically modeled and considers the emissions of CO_2 that result from the chemical reactions within the raw materials. In the EIO-LCA, this is obviously not modeled, as only the average emissions of the glass and glass products production sector emissions are evaluated. It is clear that the specific nature of the glass-melting process, that has particular CO_2 emissions, cannot be accurately represented by this aggregated analysis. As a consequence, this constitutes a typical situation where the Hybrid methodology may be used with advantage. The remaining sector's environmental burdens were not specifically modeled in the HEIO-LCA analysis and therefore the results obtained coincide with those evaluated in the EIO-LCA model.

These results show that the HEIO-LCA methodology is able to overcome the limitations of the EIO-LCA. Another particularly relevant conclusion is that the results obtained by the HEIO-LCA can contribute to avoid arbitrary boundary analysis decisions in the LCA process analysis and, consequently, avoids truncation that may occur in LCA modeling, when their full range of processes and materials are not properly modeled.

In general, it can be concluded that HEIO-LCA, allowing for process-specific, foreground system models to be inter-linked with national economic system using information on cut-offs, constitute an excellent tool to use when LCA accurate information is required within limited budgets and time scales.

Conclusions

A hybrid model that allows for full interaction between a process-based LCA model and an input-output model is discussed, and a computer model for the Portuguese economy was developed and is run to support the analysis of a case study that compares three environmental analysis tools, namely LCA, EIO-LCA and HEIO-LCA.

Detailed process analyses for the product system of Portuguese lead crystal giftware manufacturer were performed and a process-specific database was created. Compiled process-specific, foreground system is inter-linked with Portuguese national economic data in order to promote the interdependence between the detailed product system and the national industrial system.

The relative merits of LCA, EIO-LCA and HEIO-LCA were discussed considering GHG's emissions in the Portuguese economy making use of the case study. The results obtained show that the HEIO-LCA methodology clearly overcomes the limitations of the EIO-LCA, due to the aggregated nature of EIO data. The analysis of the case study did also show that the HEIO-LCA methodology is able to compensate truncation associated with arbitrary boundary analysis decisions, which may occur in an incomplete LCA analysis. As a consequence, it can be concluded that the HEIO-LCA methodology has provided excellent results, particularly when LCA accurate information is required within limited budgets and time scales.

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Appendix: EIO Matrix Mathematics

Considering the economy divided into n sectors of activity, and if we denote by $\boldsymbol{X}_i$ the total output (production) of sector i and by $\boldsymbol{Y}_i$ the final demand for sector i's product, we have:

$$X_i = z_{i1} + z_{i2} + \ldots + z_{ij} + \ldots + z_{in} + Y_i \tag{A.1}$$

for $i = 1$ to n, and, $j = 1$ to n. The z terms on the right-hand side represent the inter-industry sales by sector i to sector j. Thus, the entire right-hand side represents the inter-industry sales, $\boldsymbol{z}_{ij}$, and, $\boldsymbol{Y}_i$, the demand of sector $\boldsymbol{i}$. Hence, the sum over j represents the total output of sector i.

A fundamental assumption is that the inter-industry flows from i to j depend entirely on the total output of sector j, Leontief ([1985] 1986), which is quantified by a technical coefficient, $\boldsymbol{a}_{ij}$:

$$a_{ij} = \frac{z_{ij}}{X_j} \tag{A.2}$$

The $\boldsymbol{a}_{ij}$'s are fixed relationships between a sector's output and its inputs, and constitute the technical coefficients matrix, A ($\boldsymbol{A}_{ij}$). There is an explicit definition of a linear relationship between input and output. Equation (A.1) can thus be rewritten as:

$$X_i = A_{ij} X_j + Y_i \tag{A.3}$$

The output required from each sector to satisfy an increase in demand $\boldsymbol{Y}$, is quantified by:

$$X = (I{-}A)^{-1}.Y \tag{A.4}$$

where $(I{-}A)^{-1}$ is commonly referred to as the Leontief Inverse. A detailed derivation of the input-output methodology is provided by Miller and Blair (1976) and Leontief ([1985] 1986). Equation (A.4) can be reformulated as:

$$X = (I{-}A)^{-1}.Y = Y + AY + A^2Y + A^3Y + \ldots + A^{\infty}y \tag{A.5}$$

where the component associated with the direct contributions from the different sectors to fulfill the demand, Y, are:

$$X_{Direct} = Y + A\,Y \tag{A.6}$$

and the indirect contributions, i.e. second order are:

$$X_{Indirect} = A^2Y + A^3Y + \ldots + A^{\infty}y \tag{A.7}$$

The indirect contribution accounts for second and higher orders and corresponds to the upstream processes of the inventory associated to a product or service life cycle, inherent to the LCA methodology.