UNIVERSITAT ROVIRA I VIRGILI

INPUT-OUTPUT ANALYSIS FOR USE IN LIFE CYCLE ASSESSMENT: INTRODUCTION TO REGIONAL MODELLING

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in partial fulfilment of the requirements for the degree of Doctor
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părinților mei

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Abstract

The sustainable management of the environment and its resources needs a multidisciplinary research to describe the structure of the technical society and its interactions with the environment. A good approach for this objective are the environmental Input-Output (IO) models, based on the IO tables and the national emissions accounts compiled periodically by each country, combined with Life Cycle Inventory (LCI), which quantifies the environmental impacts of a product, process, service or activity across its whole life cycle. In this line, the objective of this thesis is to study both methods and connect them into a common framework which gives the regional/national picture meanwhile conserving process details. On the LCI side, we tested its compilation in matrix form which allows further link to IO models. Our results show that it gives comparable results to the "classic" method using process-flow diagram and to SimaPro, commercially available software. On the IO side, we perform two types of analyses at national scale. In the first one, using an economic decomposition technique, Structural Path Analysis, we describe how the pollution is transmitted throughout the Spanish economy and identify key sectors in air pollution. In the second type IO analysis, we focus only on greenhouse gas (GHG) emissions and investigate how exogenous changes in sectorial demand, such as changes in private consumption, public consumption, investment and exports, affect the relative contribution of the six major GHG regulated by the Kyoto Protocol to total GHG emissions. Based on these results, we propose different IO methods to calculate the emissions of a specific process-plant and compare their results to those obtained by LCI. The simplest one is to assume the plant is only a final consumer, calculating the emissions generated to produce the inputs necessary to the plant for its production. As the on site emissions of the plant are important, we considered adding them to the previous results, but this approach implies a double-counting. To correct it, we disaggregate the Spanish economy to include a new sector represented by the plant. In this way we can model the interactions of the plant with the rest of the economy and with the final demand. Furthermore, we introduce the concept of shared producer-consumer responsibility and compare its results with those of the above mentioned methods. The method considering the plant as a new sector in the Spanish economy and the shared producer-consumer responsibility gives results closer to the LCI results. We test also two hybrid models, specifically the tiered-hybrid and the integrated hybrid methods, which integrate IO and LCA into a single model. Our results show that applied to end-of-life processes, the two methods give the same results meanwhile the tiered hybrid model is easier to apply in practice.

Altogether, the results we obtained show a promising way for a further development of regional models IO-LCA. Given the poor data availability for detailed analyses at regional/national level, we suggest starting with a "traditional" IO analysis together with a Structural Path Analysis to identify the most polluting sectors and the paths through which the pollution is propagated. For the identified most polluting sectors, LCA data should be collected and fed into a tiered-hybrid IO-LCA model which gives the regional picture meanwhile conserving process details.

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INTRODUCTION, OBJECTIVES AND OVERVIEW OF CHAPTERS

1. Introduction

The last 20 years were characterized by a demographic explosion, an increasing industrialization and, at the same time, an increasing concern on the future of the human kind. Words like “sustainability” and “sustainable development”[1] were often used and a multitude of tools were developed to operationalize them. According to Agenda 21, the concept of sustainability is multidimensional, as it includes ecological, social and economic objectives. Some of the key characteristics of sustainability that are often mentioned in the literature and policy documents are intergenerational equity (including social and geographical equity and equity in governance), protection of the natural environment (and living within its carrying capacity), minimal use of non-renewable resources, economic vitality and diversity, community self-reliance, individual well-being and satisfaction of basic human needs (EEA, 2001).

In the early 1990s through the Fifth Environmental Action Programme, the European Union established a common strategy on environmental policy. The programme aimed to achieve sustainable development through the integration of the environmental dimension into all policy areas, the widening of the range of policy instruments (information and education, technological development, introduction of environmental costs in prices, etc), and the shared responsibility among all the polluters, public or private. But to achieve a sustainable development, goals must be assessed. This has challenged the scientific community to provide efficient and reliable tools. In the recent years, a multitude of tools and methods have been developed and sustainability assessment has been increasingly associated with impact assessment tools as Environmental Impact Assessment and Strategic Environmental Assessment (Devuyst, 2000; Pope *et al.* 2004). However, sustainability is a broader concept including environmental, economic and social goals. After a review of the actual sustainability assessment tools, Ness *et al.* (2007) consider that the purpose of a sustainability assessment is to “provide decision-makers with an evaluation of global to local integrated nature-society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society more sustainable”. To provide this information, it is important to know the structure and functioning of the modern technological society and its relationships with the environment.

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[1] “Sustainability” and “sustainable development” have very closed meanings and are often used interchangeably in the literature. A way to distinguish between them is to think of sustainability as describing a desirable state or set of conditions that persists over time. In contrast, “sustainable development” implies a process by which sustainability can be attained.

There is a multitude of tools that can be used to describe and/or quantify the structure of the technical society and its interactions with the environment. Ness *et al.* (2007) divide them in three main groups: regional or national sustainability indicators and indices, product-related tools, and integrated assessment tools. The first group represents measurements of the economic, social or environmental state of a region or nation. The indicators and indices are continuously measured and calculated and therefore allow for describing long-term sustainability trends from a retrospective point of view. Some well known examples of this group are: Material Flow Analysis, focused on the consumption of natural resources, Substance Flow Analysis, with the goal of reducing the load of certain substances, Energy analysis, which analyses the flows of energy between different industries in an economy, The Index of Sustainable Economic Welfare (Daly and Cobb, 1989), The Human Development Index, used by United Nations Development Programme (UNEP), etc. The second group is more specific as focuses on the flows related with the production and consumption of goods and services. The goal of these tools is to evaluate the consumption of natural resources and emission of environmental loads along the production or consumption chains or through all the life cycle of a product or service. Examples from this group include Life Cycle Assessment, which evaluates the environmental impact of a product or a service over all its life cycle, Life Cycle Costing, which covers "total costs of a product, process or activity discounted over its lifetime" (Gluch and Baumann, 2004), Product Material Flow analysis based on the Material Input per unit of Service index expressed in weight and Product energy analysis that quantify the energy required to manufacture a product or a service (Herendeen 2004). The third group, integrated assessment tools, includes in the analysis the three pillars of sustainability and allows analyses at regional level. Examples are Risk Analysis, Multi-criteria Analysis, Cost-benefit Analysis, Impact Assessment,[2] etc. that can be applied interdisciplinary to assess different aspects of sustainability.

The development trends of these tools are somehow contradictory as there is an increasing demand for more case- and site-specific assessment tools that at the same time should be accessible to wider categories of users. It is intended to standardize these tools in order to obtain more transparent results, with an easier and clearer interpretation. It is not within the aim of this work to analyse and compare tools of sustainability assessment, nor to add a new tool to the list of the existing approaches. We intend to study the applicability of a process-assessment tool, namely Life Cycle Assessment (LCA), for sustainability assessment at regional or national scales. The idea behind is to use process-specific information as far as possible and to supplement the missing specific information with other more aggregated data at regional or national level.

LCA is the most developed tool in the category of process-related tools. It is hard to determine which was the first LCA study; Following Vigon *et al.* (1993), one of the first works in LCA was performed by Harold Smith, project general manager for the Douglas Point Nuclear Generating Station, Canada. In 1963, at the World Energy Conference, Smith reported his calculation of cumulative energy requirements for the production of chemical intermediates and products. The next studies aimed to optimise energy consumption in a context where strong energy consumption represented a constraint for

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[2] A good review of existing environmental tools can be found in Sonnemann *et al.* (2003).

the industrials (increasing costs, possible boycott, etc). It followed a transition from straight energetic consumption analyses to studies that took into account the raw materials and energy resources consumption, materialized in two important reports "The Limits to Growth" (Meadows *et al.*, 1972) and "A Blueprint for Survival" (Club of Rome, 1972). The first multicriteria study was realized for Coca-Cola by Harry E. and Teastley Jr. on the use of plastic vs. glass bottles for packing. For the first time, all the life-cycle of the product (here bottles) was taken into account. Contrary to all expectations, the study revealed the plastic bottles as being less polluting than the glass bottles. The complete results of the study were never published, except a summary that appeared in April 1976 in Science Magazine. These partial results raised discussions on the validity of comparisons and led the scientific community to think to a standardisation process. As results, in 1984, EMPA publishes an "Ecological report of packaging materials" and in 1989 the Society of Environmental Toxicology and Chemistry (SETAC) is constituted; but it took almost 20 years to appear the first standard on LCA: NF X30-300, published in France in 1996. Nowadays LCA is standardized through the ISO 14040 series: 14040, 41, 42, 42 and 43, which define the different stages of an LCA study. For an optimum use of LCA results, it is essential to communicate them as clear and transparent as possible. In 1999-2001 appeared ISO 14020, 25, 48 and 49 series of standard and technical documents regarding the communication of LCA results, the directions of environmental declaration and working methods.

Originally, SETAC's "Code of practice" distinguished four components for an LCA analysis: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle improvement analysis. With the edition of the first international standard ISO 14040 (1997), the last component, life cycle improvement analysis was no longer considered as an individual component, but as part of each of the first three components and a new forth component was introduced: life cycle interpretation. While improvements continue to be brought to the LCA methodology, the ISO 14040 series are generally accepted as providing a consensus framework for LCA:

- ISO 14040:1997 on principles and framework of LCA,
- ISO 14041:1999 on the definition of goal and scope and inventory analysis,
- ISO 14042:2000 on life cycle impact assessment, and
- ISO 14043:2000 on life cycle interpretation.

In 2006 come out the Final Draft International Standards (FDIS) versions of the new ISO 14040:2006 and ISO 14044:2006 that technically revise, cancel and replace the four mentioned standards ISO 14040 series. These new standards reconfirm the validity of the main technical content of the previous standards.

LCA maps the environmental impacts of a product, process, service or activity across its whole life cycle (i.e. from cradle to grave) from raw material extraction through production, use and final disposal (see Figure 1). A LCA practitioner tabulates the environmental exchanges (emissions released and natural resources consumed) at every relevant stage (phase) in a product's life cycle. The complete life cycle together with its associated material and energy flows is called "product system". A LCA can be conducted to generate environmental information on the life cycle investigated, or on the consequences of changes that may be operated in the product system.

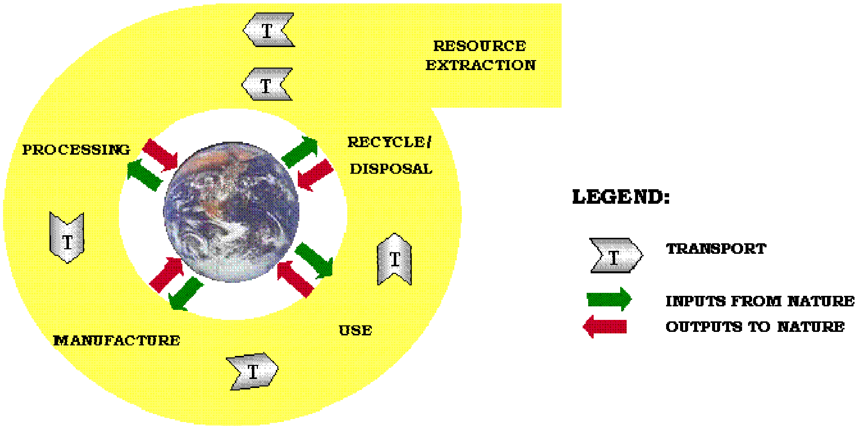

Figure 1. Schematic representation of a generic life cycle of a product

The most time and resources consuming step of LCA is the inventory analysis, one of the focuses of this work. It involves the compilation, tabulation and quantification of all environmental exchanges (emissions, resource consumptions, etc.) of a given product system throughout all its life-cycle. In other words, during the inventory phase are estimated the consumption of natural resources and the generation of solid and liquid wastes and air emissions attributable to a product's life cycle. The processes within the life cycle and the associated material and energy flows as well as other exchanges are modelled to represent the product system with all its inputs and outputs from and respectively to the environment (see Chapter I of this thesis for methods of inventory compilation). All the quantities are reported by functional unit[3] of the product system (e.g. for a power plant the functional unit may be "kWh produced electricity"). Several difficulties may arise at the compilation of data for an inventory analysis:

- An LCA study usually consists of a large number of unit processes, hence requiring good communication between different companies, usually outside of the regular business interaction.
- Specific technological information may be difficult to obtain, as some companies may consider it as "confidential". This problem can be overcome by using industry averages or default approximations.
- The quantity of product, emissions, resources, etc. needs to be measured in the same way in each unit process along the life cycle of a product. Also, the nomenclature used to denote flows and environmental exchanges has to be consistent throughout all the product system.
- In any process providing more than one function, the practitioner has to decide on how to distribute the overall inputs and outputs between the different functions. This process is called "allocation" and has been topic of many scientific papers and PhD theses. (Azapagic and Clift (1999), Ekvall (1999), Ekvall and Finnveden (2001), Frischknecht (1998), Heijungs and Frischknecht (1998), Heijungs and Suh (2002), Huppes and Schneider (1994)).
- Data are available from different sources which use different methods to measure and report them. Data precision is often unavailable.

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[3] The functional unit is a quantitative description of the performance of the system under study.

- Many times the costs of data compilation are not covered by the benefit of the results.

Further examples are given by De Beaufort-Langeveld *et al.* (2003), Middleton and McKean (2003) and Rebitzer *et al.* (2004). All these practical difficulties on compiling a complete inventory conducted to the use of simplified LCA, especially when a rapid decision is required or when an approximate overview of the system is required in order to decide on further investigations.

The main difficulty of applying LCA at regional level is the availability of data that makes impossible the acquisition of a minimum set of data necessary for the inventory step. Provided the absence of detailed data on all the material and energy flows within a region, we thought on alternative databases. On this aspect, the Input-Output (IO) tables are a powerful source of information as they describe both the flows between the sectors of a region or a country (domestic flows) and the flows between the production sectors of a region/country and other regional or national economies (imports and exports or foreign flows). For example, if we are interested on electricity production in a given region or country, IO tables give information on all the inputs of the electricity production sector from domestic and foreign sectors as Cement Manufacturing, Fuel Refining, Coke Extraction, etc. The IO tables also show the destination of the produced electricity within the region under study, e.g. which sectors consumes it locally, and in which amount it is exported. After a general presentation of IO tables and their history, we will discuss the ways IO data can be used in LCA.

Input-Output (IO) analysis is a linear modelling technique widely used in economic research to represent the functioning of an aggregated economy. The first attempts to represent schematically an aggregated economy are traced back to the XVIIth century when the French doctor François Quesnay elaborated the first “Tableau Economique”. The table contained a classification of economic agents and a description of the flows established between them. Other contributions in this field are attributed to the French Boisguillebert and the Irish Cantillon. The simplicity of Quesnay’s Tableau Economique acted against of a major dissemination and use of the model and in the next centuries there were not registered any progresses. It was only in the XIXth century when, due to the advances in the Economic Theory and the generalization of mathematics applications in economic analysis, the economist L. Walras formulated for the first time a general equilibrium model in mathematical language. He defined the interdependencies between the elements which integrate an economic system. Nevertheless, it was the Russian Nobel Prize Wassili Leontief, author of “The Structure of the American Economy, 1919-1939”, who developed and implanted the IO tables in the form we know them nowadays. His model combines the economic vision of century’s XVII thinkers with the mathematical rigor of Walras. From 1940 to nowadays, the Leontief model was developed and extended by numerous authors headed by Leontief himself who received in 1973 the Nobel Prize for conceiving the IO tables.

The IO tables are a statistic instrument that breaks down the National Production between the sectors (or industries) which originate it and the sectors which absorb it. The term “output” designates the products that come out from a company or industry; “input” gathers the factors or resources needed to realize this production.

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Table 1. Simplified structure of the supply table

SUPPLY	**Sectors**	**Imports**	**Total supply**
Products	production by product and economic sector	imports by product	total supply by product
Total	total supply per sector	total imports	total supply

The IO tables formed from the supply and use tables show the total production (output) of each productive sector and which is the destination of this production: how much from the produced goods or services are absorbed by the final consumer and how much are absorbed by each of the others productive sectors. In particular, the supply table describes by product group the production of goods and services used by different industries in an economy and their imports from abroad (Table 1). Use tables describe by product group the use of goods as intermediate products by different industries, final uses, and exports abroad (Table 2). The IO tables are more useful as the number of sectors in which an economy is disaggregated is bigger. The ideal would be the IO tables to have so many sectors as services and goods are produced by the economy. But it would be too expensive due to the difficulty to gather all the necessary data and the complexity of calculations to compile all the data together.

The supply and use tables represent an intermediate stage between the basic statistics and the symmetric IO tables which are more useful in economic analysis. A symmetric IO table is derived from the supply and use matrices by assuming that all products (whether principal or secondary) produced by an industry have the same input structure (they are produced using the same technology). This assumption is known as "the industry technology assumption".[4]

Table 2. Simplified structure of the use table

USES (INPUTS)	**Sectors**	**Exports**	**Final consumption**	**Gross capital formation**	**Total uses**
Products	consumption by product and economic sector	exports by product	expenditure in final consumption	gross capital formation	total uses by product
Value added components	value added per sector				
Total	total uses per sector				

The simplified structure of a symmetric IO table is given in Table 3. Such a table gives an overview of trades in a national economy. It shows how products are sold by the producing industries to either be used in other industries or by the final consumers.

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[4] To derive the symmetric IO table, it can be also assumed that a product has the same input structure in whichever industry it is produced (known as "the commodity technology assumption"). Although this assumption makes more economic sense than the industry technology assumption, its automatic mathematical derivation sometimes produces results that are unacceptable, e.g. negative technical coefficients.

Table 3. Simplified structure of the symmetric IO table

	Sectors	**Exports**	**Final consumption**	**Gross capital formation**	**Total**
Sectors	intermediate transactions matrix	exports by product	expenditure in final consumption	gross capital formation	total uses by sector
Value added components	value added per sector				
Total domestic inputs	domestic inputs				
Imports	imports				
Total	total supply per sector				

The supplying/producing sectors, represented in the rows of Table 3, are divided into a number of domestic production sectors, *n*, and foreign producing sectors (imports). The demanding sectors, represented in columns, are divided in different categories of final demand and the same *n* domestic sectors as the supplying sectors. The sectors included in "final demand", e.g. government, households, foreign trade, etc, are purchasers that use products as such and not as inputs to an industrial process.[5] "Value added components" include wages and salaries, gross operating surplus (benefits from production) and net taxes on production.

The information given by a symmetric IO table can be used for various economic analyses. In this work we use IO to assess environmental impacts from changes in production (see Chapters II and III of this book for different types of IO analyses at national level). As the most commonly used IO model considers the market economy driven by the final demand, to assess impacts from changes in production it is necessary to determine the connection between production and final demand. To this end, let us consider a hypothetical economy divided into two sectors. Table 4 shows a simplified version of the symmetric IO table of a two sectors economy.

Table 4. A simplified two sectors IO table; hypothetical example

		Sectors		**Final demand**	**Total output**
		1	**2**		
Sectors	**1**	15	50	35	**100**
	2	20	10	170	**200**
Payments sector		65	140		
Total		**100**	**200**		

Table 4 shows that the production or the total economic output of sector **1** is of 100€. Reading the first row, the distribution of this output is as follows: 15€ are used internally in sector **1**, 50€ worthing goods go to the sector **2**, and 35€ to the final demand. To

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[5] The demand of sectors considered as final demand is determined by considerations that are independent of the magnitude of production in the productive sectors, and therefore it is considered exogenous to the production; e.g. the car demand of households is determined by the purchasing power of people, the availability of gasoline, etc. and not by the production of car manufacturing sector.

produce this output, sector **1** needs goods in value of 15€ from itself (internal delivery), 20€ from sector **2** and 65€ from the payments sector[6] (this is found reading the first column). To put this information in equations, let us denote the final demand of industry *i* as y_i, its total output as x_i, and the monetary flows from an industry *i* to industry *j* as z_{ij}. Then, we can write for the two sectors:

$$\begin{aligned} x_1 &= z_{11} + z_{12} + y_1 \\ x_2 &= z_{21} + z_{22} + y_2. \end{aligned} \tag{1}$$

In other words, the total output of each sector is equal to the sum of the deliveries of this sector to other productive sectors and to its final demand (row sums in Table 4). Considering the hypothetical example values, we obtain:

$$x_1 = 0.15 * 100 + 0.25 * 200 + 35 = 100$$
$$x_2 = 0.20 * 100 + 0.05 * 200 + 170 = 200.$$

To further simplify the calculations, we can divide the values in Table 4 by the total output of each sector (see Table 5). The resulting matrix is called the direct or technical coefficients matrix, usually denoted as *A*. Its elements, a_{ij}, in columns show the amount of inputs from other industries necessary to produce 1€ of output of the sector in column. They are calculated as:

$a_{11} = 15/100 = 0.15;$ $a_{12} = 50/200 = 0.25;$ $a_{21} = 20/100 = 0.20;$ $a_{22} = 10/200 = 0.05.$

Table 5. Technical coefficients matrix; hypothetical example

		Sectors	
		1	**2**
Sectors	**1**	0.15	0.25
	2	0.20	0.05

This operation is a fundamental assumption in IO analysis, as it implies that during a period (normally 1 year), there is a fixed relationship between a sector's output and its inputs; e.g. to produce 1€ worth output of industry **1**, it needs 0.15€ inputs from itself and 0.20€ from industry **2**. The main way in which IO coefficients are used for analysis is as follows. We assume the numbers in Table 5 represent the structure of hypothetical economy during a year, meaning that during this time we consider the inputs to production as unchanged. Given this structure of the economy, we can find what happens if, for example, the final demand of sector **1** would increase to 60€ and would decrease to 150€ for sector **2** in the next year.

If we write the deliveries to other productive sectors, z_{ij}, as function of technical coefficients: $z_{ij} = a_{ij} * x_j$, equations (1) become:

$$\begin{aligned} x_1 &= a_{11} * x_1 + a_{12} * x_2 + y_1 \\ x_2 &= a_{21} * x_1 + a_{22} * x_2 + y_2. \end{aligned} \tag{2}$$

Rearranging the terms in equations (2) we obtain:

$$\begin{aligned} (1 - a_{11})x_1 - a_{12} * x_2 &= y_1 \\ -a_{21} * x_1 + (1 - a_{22})x_2 &= y_2. \end{aligned} \tag{3}$$

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[6] For simplicity, the payments sector includes only the salaries of workers in sector 1.

Equations (3) help us to calculate the new productions of sectors **1** and **2** required to meet the new final demands. For $y_1 = 60€$; $y_2 = 150€$ and the values from the hypothetical example we have:

$$\begin{aligned}&(1-0.15)x_1 + 0.25 * x_2 = 60\\&0.20 * x_1 + (1-0.05) * x_2 = 150,\end{aligned}$$ and from here $x_1 = 124.75$; $x_2 = 184.16$.

Compared to the initial situation when $x_1 = 100$, $x_2 = 200$ for final demands $y_1 = 35$, $y_2 = 170$, to meet the new final demands, sector **1** has to increase its production to 124.75€ and sector **2** has to decrease it to 184.16€. The new values of x_1 and x_2 are a measure of the impact that changes in final demands have on the economy.

For the general case of a economy divided into *n* sectors, equations (3) will become a set of *n* linear equations with *n* unknowns: $x_1, x_2, ..., x_n$. In matrix notation we have:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & & & \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix},\ X = \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix},\ \text{and } Y = \begin{bmatrix} y_1 \\ y_2 \\ \dots \\ y_n \end{bmatrix}$$

and equations (3) become:

$$(I - A)X = Y, \qquad (4)$$

where the matrix $(I - A)$ contains on its main diagonal the elements $(1-a_{11}), (1-a_{22}), ..., (1-a_{nn})$, all the other elements being negative. Equation 4 can be rewritten to give:

$$X = (I - A)^{-1} Y, \qquad (5)$$

which expresses the dependence of production in each sector on the values of each of the final demands. Given a final demand, it is possible through the inverse matrix, $(I - A)^{-1}$, to calculate what output levels would be required to meet the specified demand.

For the given hypothetical example we have:

$A = \begin{bmatrix} 0.15 & 0.25 \\ 0.20 & 0.05 \end{bmatrix}$; $Y = \begin{bmatrix} 60 \\ 150 \end{bmatrix}$; and following equation (5) we obtain a vector of new sectoral outputs: $X = \begin{bmatrix} 124.75 \\ 184.16 \end{bmatrix}$, the same results as by solving the equation system (3).

Matrix $(I - A)^{-1}$ is often referred as the Leontief inverse or the total requirements matrix as it shows the production required both directly and indirectly per euro of delivery to final demand. The effect of an increase in demand for a certain product does not end with its required direct intermediate inputs. It generates a long chain of interactions in the production processes since each of the products used as inputs needs to be produced, and will, in turn, require various inputs. One cycle of input requirements requires another cycle of inputs, which in turn requires another cycle (see Figure 2). The sum of all these chained reactions is shown in the inverse matrix. To see the contribution of each layer of suppliers, the Leontief inverse can be decomposed as follows:

$$(I - A)^{-1} = I + A + A^2 + A^3 + ..., \qquad (6)$$

where the first term represent the effect on the production due to direct requirements for an industry product (stage 0 in Figure 2), the second term represents the effect of the first layer of suppliers (stage 1 in Figure 2), etc.

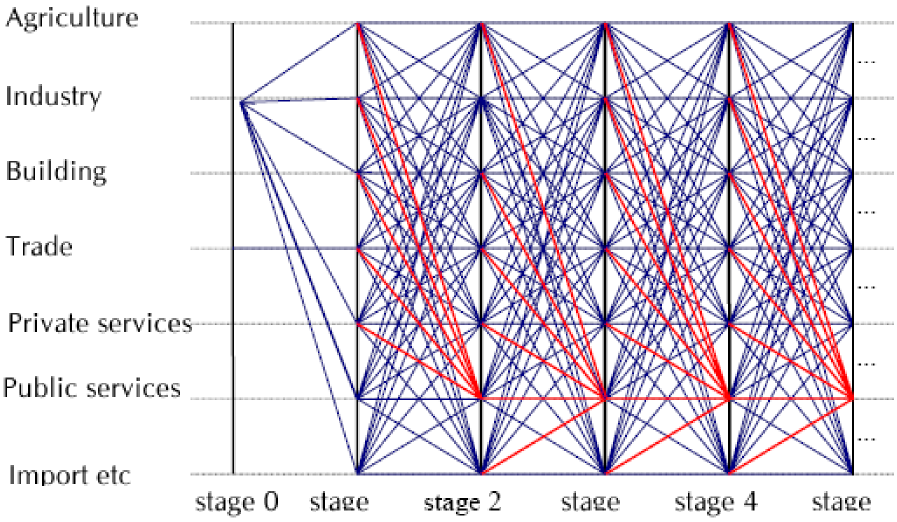

Figure 2. The direct requirements for an industry product and the related indirect demands for all the sectors. Figure based on Treloar (1998)

IO analysis can help LCA in two ways. Firstly, it can offer a solution to the selection of boundaries in LCA, and secondly, it can be used for the estimation of environmental flows of the processes left out from the LCA evaluation. The current LCI methodologies and standards by the International Standards Organization (ISO 14040 Series) impose practical difficulties in setting the system boundaries for an LCI study. The decision on which processes to be left out of the analysis is made on a subjective base, many times based on the data availability than on objective cut-off criteria. IO techniques, particularly Structural Path Analysis (SPA), can help to decide which processes to include or leave out of analysis. SPA allows identifying key sectors in air pollution (or other environmental interventions as water or soil pollution, water consumption, etc.) and describes how the pollution is transmitted throughout an economy. To describe the pollution chain, SPA uses the decomposition of the Leontief's inverse presented in equation 6 and the atmospheric pollution accounts at regional or national level. To illustrate the information given by SPA, let us analyze the example of an incinerator. Figure 3 describes the main SO_x polluting inputs to the incineration plant. We can see that the direct suppliers of the plant are the sectors of Cement, lime and plaster and Transport (represented by continues arrows). However, it can be seen clearly that indirect suppliers in the second level (stage), depicted by interrupted arrows, are also very important in SO_x pollution terms. This information helps to orientate the data gathering for a complete inventory of incineration (see more details of such analysis in Chapter IV of this thesis).

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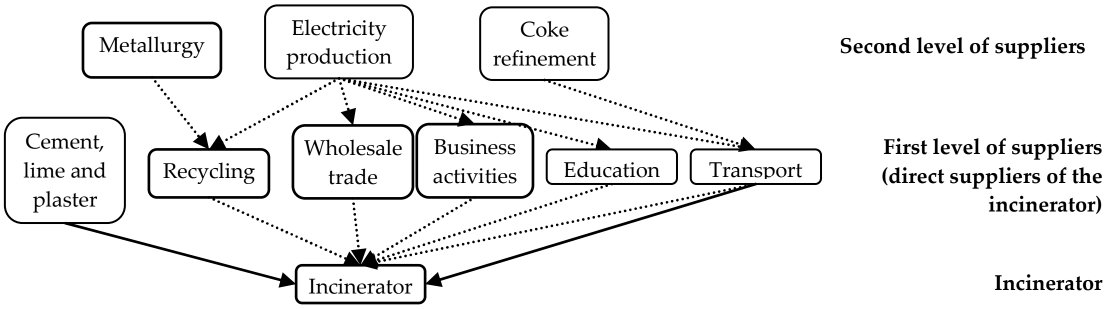

Figure 3. Top 10 paths for the SO_x emissions generated by an incinerator

IO tables can also be used to supply an LCA study with data. In this case, IO analysis and LCA are combined together. The first combination of process-specific data with IO average data was suggested by Bullard *et al.* (1978) in the field of energy analysis. They calculated the energy cost of an atypical product that cannot be represented by an aggregated industrial sector (e.g. a power plant) by using process-specific data supplemented by IO average data. The IO data cover processes far upstream from the process that delivers the product under study (electricity), meanwhile process-specific data cover the processes near the studied production process (see Figure 4). Following Suh and Huppes (2005), this type of approach is referred to as a “tiered hybrid method”.

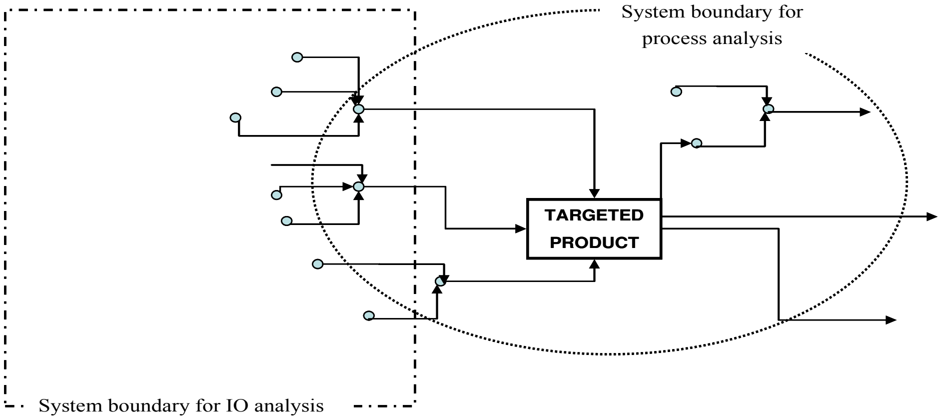

Figure 4. System boundaries for process and IO analyses

Using the same approach, Moriguchi *et al.* (1993) analysed the CO_2 emissions of a car. Their application used IO for the pre-consumer stages and LCA for the use and end-of-life stages of a car. Then, the total emissions are obtained by summing up the results of the IO part with those of LCA (see more examples in Chapter IV). By using together IO and LCA, the boundaries of the analysis are wider, but the upstream system boundary could not yet be reached specially for economies that strongly rely upon imports. To overcome this problem, Hondo *et al.* (1996) used process-modelling for far upstream processes not covered by the Japanese IO tables (e.g. coal mining) and IO for the remaining sectors.

There appear several problems when using together LCA and IO results:

- The different computational structures of IO and LCA imply separated analyses. IO is computed in a matrix form and LCA uses the graphical representation of the processes within the boundaries of the assessment. This problem is overcome by computing LCA in a matrix form (see Heijung and Suh (2002) for the description of the matrix method for computing LCA and Chapter I of this book for a comparison of the matrix method with other computation methods);

- IO can only account for the pre-consumer stages of a product life-cycle;
- The type of data used in IO is different of those used in LCA: monetary vs. physical units, environmental loads per unit of sectoral output vs. environmental loads per unit of product (kg, kWh, hour of washing, etc.);
- The flows accounted in process-analysis are already included in the data in IO tables used in the IO-part; hence a summation of LCA and IO results implies a double-counting. This inconsistency can be overpassed by using the concept of shared producer-consumer responsibility. It recognizes that in every transaction there are always involved two groups: the producer and the consumer and therefore, the responsibility for the impacts of production has to be shared between them (see Chapter IV of this book for a detailed description of the concept and implementation of shared consumer-producer responsibility);
- If the analyst applies other analytical tools (e.g. uncertainty and sensitivity analyses) to the results of assessment, the calculations are to be performed separately.

All these problems make difficult the modelling of interactions between LCA and IO. A change in the process-analysis is not reflected in the results of the IO part, unless the later is reformulated and adapted to the change. Therefore, Suh (2004) proposed a hybrid model which integrates not only the results of LCA and IO, but also their computational structures within a consistent framework. This approach is known as "integrated hybrid analysis" and is presented and applied to a real case study in Chapter V of this thesis.

2. Objectives of the current work

The main research question of the current work is:

Is it possible to use a process-assessment tool, namely Life Cycle Assessment (LCA), for the assessment of sustainability at regional or national scales?

There are two underlying themes related to the computational structure of LCA and the availability of data to perform a regional or national LCA.

The computational structure of LCA

As the revised LCA standard ISO/FDIS 14040:2006(E) states, "[…] there is no single method for conducting LCA. Organizations have the flexibility to implement LCA as established in this International Standard, in accordance with the intended application and the requirements of the organization" (p. 9, ISO/FDIS 14040:2006(E)). No further guidance is provided. So every user has the flexibility to implement LCA practically, based on the specific application and the specific requirements of the user. The easiest and fastest way of LCA compilation is by using a commercial software, e.g. SimaPro, TEAM, Umberto, Regis, PEMS, etc. The main limitation of these software packages is that their databases are specific to the country where they were developed, or they contain average data. If we would like to perform a regional study in Catalonia, for example, by using one of these packages we would obtain only average results, unspecific to the region under study. Other method to compile a LCA is based on material and energy balance sheets. However, at regional level, it would imply an exhausting work although we would have all the data to perform the study. A simple and quick method would be the matrix compilation of LCA, used by some available software packages, e.g. SimaPro. The question is: does it provide the environment to perform a regional LCA? This has led us to the other important question:

Availability of data for a regional or national LCA

Without a doubt, the main difficulty on applying LCA at regional level is the availability of data. Provided the absence of detailed data on all the material and energy flows within a region, we thought on alternative databases. On this aspect, the Input-Output (IO) tables are a powerful source of information. There are several questions to be answered before using IO data for a LCA study:

- What type of data uses IO and how could they be used for LCA?
- What kind of analysis can be performed by using IO and how can be used their results for LCA?
- Can be used IO to evaluate the environmental impact of a plant?

The solution to these questions led us to the last question addressed by the present work: "Is it possible to combine IO and LCA? If so, which are the methods to do it?

All these questions are addressed and discussed the chapters of this book.

3. Overview of chapters

The information in the current document is structured in five chapters and 6 annexes.

- Chapter I presents the methodology of LCA, focusing on the compilation of the inventory. The main problem of LCA is the data availability, increased by the inadequate mathematical structure of the "classical" way of LCA compilation that does not allow a straight connection with other type of data. This chapter describes different methods of inventory compilation, with special focus on the matrix method that allows a future connection of LCA data with IO data. To illustrate these methods, the case-study of a municipal solid waste incinerator is presented.
- Chapter II deals with the application of IO techniques to environmental problems. It presents the methodologies of IO and SPA and, based on Spanish atmospheric pollution and macroeconomic data, identifies the main drivers of atmospheric pollution in Spain and describes the paths through which the pollution is propagated.
- Chapter III continues on the field of application of IO techniques for decision-making on environmental issues. It investigates how exogenous changes in the sectorial demand affect the emission of the six greenhouse gases regulated by the Kyoto Protocol and their relative contribution to the total greenhouse emissions.
- Chapter IV is divided into two parts. The first one is concerned with the calculation of direct and indirect emissions of a plant by both LCA and IO analysis. The concept of shared producer-consumer responsibility is also

introduced and compared with the above methods. The second part describes how can help IO the boundaries definition in LCA.

- Chapter V presents two different methods to combine LCA and IO analysis in a common framework and apply them to the same case-study of a real incinerator.

For an easier reading, all the references and annexes are grouped at the end on this thesis.

CHAPTER I

METHODS FOR LIFE CYCLE INVETORY OF MUNICIPAL SOLID WASTE INCINERATION

Abstract

Modern solid waste incinerators generate electricity or convert water into steam to fuel heating systems besides reducing the volume of non-recycled municipal solid wastes. In spite of its positive aspects, waste incineration is criticised for the release of air pollutants and generation of secondary waste streams (slag and fly ash) that need to be taken care of as efficient as possible. In this study we apply Life Cycle Analysis to evaluate the environmental burdens of a municipal solid waste incinerator. We compare two scenarios of functioning of the incinerator, before and after the installation of an advanced acid gas removal system. To compile the Life Cycle Inventory of the incineration system in the two scenarios, we use different methods: the "classic" method using process-flow diagram and Excel-based calculations, the matrix method using exact mathematical equations, and finally a commercially available software, SimaPro. We describe the three different ways of compiling a LCI and discuss the differences between their results with particular attention to the matrix method that allows future links to other sources of data for solving the data availability in LCA; e.g. economic data available in the national Input-Output tables.

Keywords: Life Cycle Inventory (LCI); process-flow diagram; matrix method; municipal solid waste (MSW) incineration.

1. Introduction

In the early 1990s through the Fifth Environmental Action Programme, the European Union established a common strategy on environmental policy. The programme aimed to achieve sustainable development through the integration of the environmental dimension into all policy areas, the widening of the range of policy instruments (information and education, technological development, inclusion of environmental costs in prices, etc) and the shared responsibility among all the polluters, public or private. Concerning waste management, the priorities were ordered as follows: reduce the volume of waste, increase the reuse and recycling, incinerate with heat recovery, and reduce as much as possible landfill. Besides reuse and recycling, incineration is a good method to reduce the volume of wastes. In addition, properly equipped combustors can generate electricity or convert water into steam to fuel heating systems. Despite its positive aspects, waste incineration also creates problems through the release of air pollutants and generation of secondary waste streams (slag and fly ash) that need to be taken care of as efficient as possible.

A large number of methods and tools have been developed for describing the environmental implications of waste treatment systems. In this study, we use Life Cycle Assessment (LCA) to evaluate the environmental performance of a municipal waste incinerator. We perform all the calculations for the case of SIRUSA[7] incinerator, located in Constantí, Tarragona. It is a public plant operated since 1991. In order to ensure the compliance with the European legislation on waste incineration (particularized in the Spanish RD 1088/92 Directive and also the regional Catalan Directive 323/1994), in 1997 an advanced acid gas removal system was installed. Its function is mainly to reduce the emissions of heavy metals, particulates, As, Cd, HCl and SO_x. Hence, in this chapter we analyse both situations: the operation of the plant until 1996 (situation 1) and the current operation with the advanced acid gas removal system working (situation 2).

LCA maps the environmental impacts of a product, process, service or activity across its whole life cycle (i.e. from cradle to grave) from row material extraction through production, use and final disposal (ISO 14040). There is not a single method for conducting an LCA study, so every user has the flexibility to implement LCA practically, based on the specific application and the specific requirements of the user. Among the applications of LCA to environmental evaluations of waste management strategies and specifically to incineration systems we can name the works of Finnveden and Ekvall (1998), McDougall *et al.* (2001), Sonnemann *et. al* (2003), Finvedden *et. al* (2005), den Boer *et. al* (2005), Morselli *et. al* (2005), and Güereca *et. al* (2006). In our research group, previous evaluations of the environmental impact of an incinerator (Alonso 1998; Nadal 1999; Sonnemann 2002) used the classical formalism based on material and energy balances. Their calculations used the eco-vector formulation described in Castells et al. (1995). The new part brought by this work is the mathematical formalism as all the computational structure of LCA is formulated in terms of explicit mathematical equations. This method of computation is also known as the "matrix method". The main reason for which we chose this way of computation is to enable later the connection of LCA data with Input-Output (IO) data, described in Chapter V. Although LCA is very detailed and specific, it has the disadvantage of needing big amounts of data. As not all of these data are available, the user has to decide on which processes to cut-off from the analysis. Besides providing information on the processes cut-off from the analysis, IO analysis also can help the LCA practitioner to decide which processes to include in the analysis (see Chapter III). In order to check the results of the matrix method, we compare them with the results obtained by using a "classic" LCA based on an Excel spreadsheet model and a simulation with commercial software, SimaPro.

According to ISO 14040 series, a LCA evaluation consists of four steps: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment, and Life Cycle Interpretation (see Section 2 for their description). In contrast to the previous evaluations of the environmental performance of a municipal solid waste incinerator, we are interested here only in the first two steps of the LCA. Furthermore, as our final intention in Chapter V is to link LCI to IO, we study here only the atmospheric emissions of the incineration system, although the methodology can be extended to emissions to water and soil and land-use.

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[7] SIRUSA is an acronym standing for "**S**ervei d'**I**ncineració de **R**esidus Sòlids **U**rbans de Tarragona, **SA**" (Service of Municipal Solid Wastes Incineration, Tarragona, SA)

The chapter is structured as follows. In Section 2 we make a brief description of LCA methodology and present our sources of data. Sections 3 contains the description of the three methods we employ to compile a life cycle inventory and Section 4 presents the results obtained by applying the three methods to the incineration system and the assumptions we considered in the calculations. Finally, we conclude with some remarks on the models we used to compile the inventory.

2. Life cycle assessment methodology

Life Cycle Assessment (LCA) is an analytical methodology used to provide information on a product's or service's energy, material, wastes and emissions from a life cycle perspective (from "cradle to grave"). The technique examines every stage of the life cycle of the product, from raw materials acquisition, through manufacture, distribution, use, possible use/reuse and recycling and then final disposal (ISO 14040 (1998), Guinée *et al.* (2002)). If real environmental improvements are to be made, it is important to use LCA so that any system changes do not cause greater environmental deteriorations at another time or location in the life cycle. According to the ISO 14040 series (14041-43), LCA consists of four steps: (1) Goal and Scope definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment, and (4) Life Cycle Interpretation.

2.1 Definition of the goal and scope

The first step of an LCA is the definition of the goal and scope of the study, which are equivalent with the definition of the objectives and the selection of the boundaries of the study. This study aims to compare two scenarios of incinerator functioning: the operation before the installation of the advanced acid gas removal system (situation 1) and the current operation with the gas cleaning system working (situation 2). For both scenarios we consider as *functional unit* 1TJ of electricity co-produced in the incineration[8]. The time horizon is one year of functioning of the plant.

The components of the incinerator before the installation of gas-cleaning system are presented schematically in Figure 1. The functioning of the plant before the installation of gas-cleaning system is as follows: mixed municipal solid wastes (MSW) transported from the surrounding cities to the incinerator are fed into a hopper. First, all metals are removed and then the waste is fed into the first incineration chamber where the temperature varies between 950ºC and 1000ºC. In the secondary, post-combustion chamber the temperature is 650-720ºC and the output temperature of the flue gas is 230-250ºC. The minimum required incineration conditions are two seconds incineration time at 850ºC with 6% minimum oxygen excess. The combustion process is controlled by on-line measurements (CO_2, O_2) and visually with the help of TV-monitors (Nadal, 1999). The heat resulted from the combustion of waste is recovered to produce steam (subsystem B in Figure 1) which is used to generate around 7.5MW of electricity per year. About 80% of the total electricity produced is sold and 20% is used for the operation of the plant itself. The products of the incineration are solid bottom ashes, which represent around 25% of

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[8] In ISO terminology, the functional unit is electricity co-produced by the incineration of MSW and the reference flow is 1TJ.

the initial MSW weight, much finer fly ashes caught up in the flue gases (air and gaseous combustion products) and slag. The main pollutants in the flue gases are dioxins, acid gases, nitrogen oxides heavy metals and particulates.

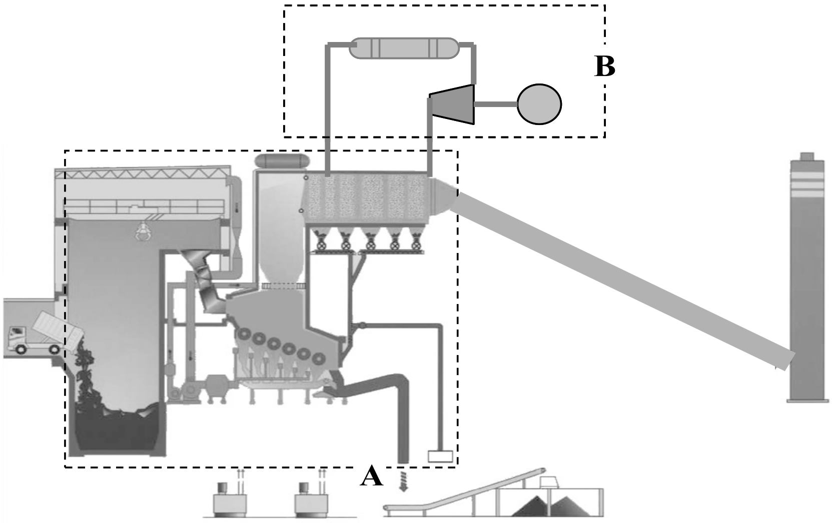


Figure 1. The components of the incinerator SIRUSA before the installation of the gas-cleaning system (A: waste incineration system; B: the co-production of electricity)

To reduce the amount of particles, acid gases and heavy metals, in 1997 a gas-cleaning system was installed (subsystem C in Figure 2). The flue gas cleaning process is a semi-dry process consisting of an absorber of Danish technology (GSA). The acid compounds of the flue gas, such as HCl, HF, SO_2 are neutralized with lime, $Ca(OH)_2$. The reaction products are separated in a cyclone and after that the gases are treated with injected active carbon to reduce dioxin and furan concentrations. The last cleaning step, a bag filter house, secures that the total emissions meet the legislative emission limits mentioned in Section 1.

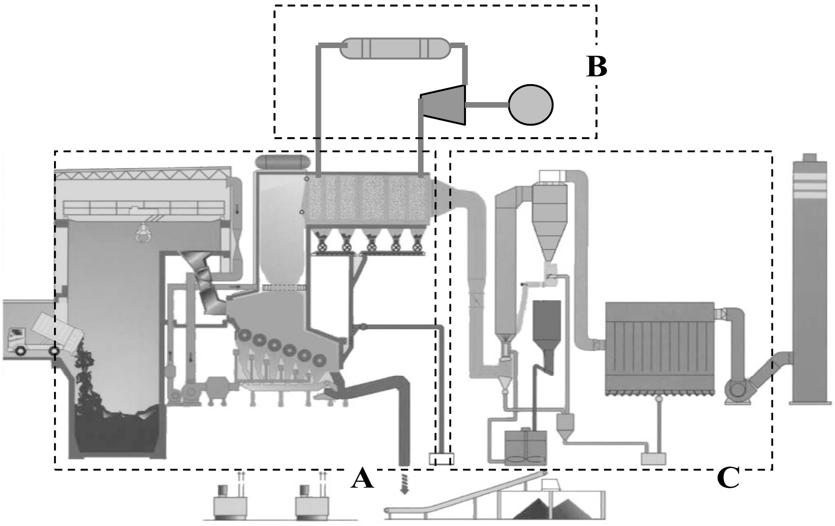


Figure 2. The components of the incinerator SIRUSA: current situation (A: waste incineration system; B: the co-production of electricity; C: acid gas-removal system)

The life cycle of municipal solid wastes (MSW) incineration begins with the disposal of the municipal waste. The system boundary includes (see Figure 3) besides the incineration process also the transport of MSW to the incinerator and the transport of ashes and slag resulted form incineration to their corresponding waste treatment units. The production of utilities is also included in the system. This includes the demineralisation of water necessary in incineration (by osmosis), the refrigeration of water used for the co-production of electricity and the purification of water resulted from incineration. The purified water is recirculated in the system.

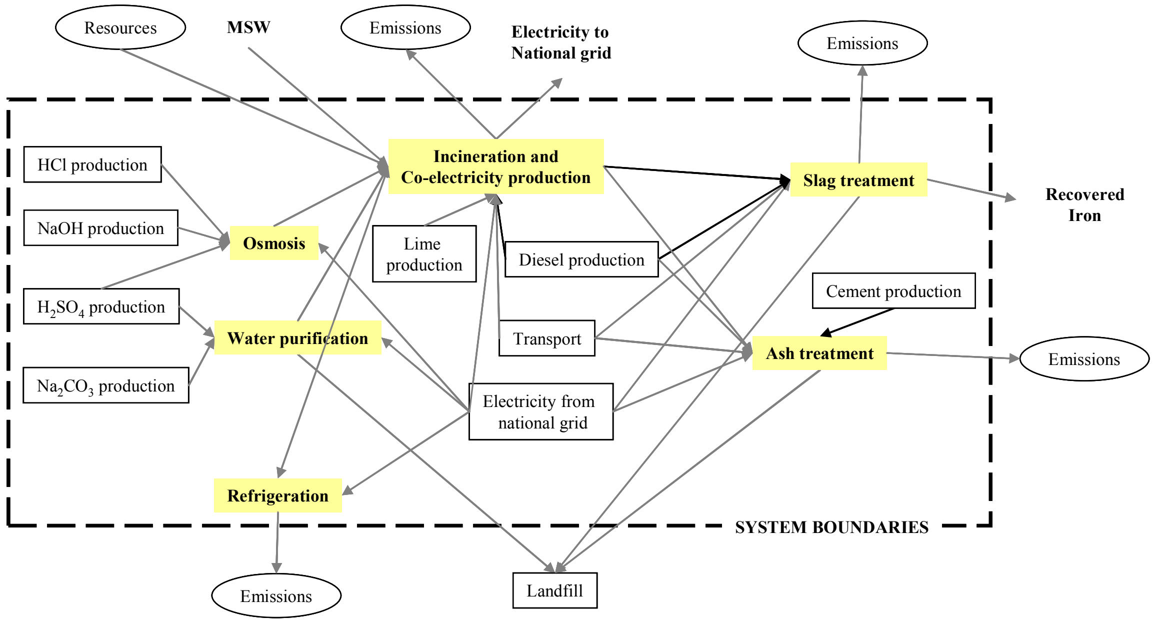


Figure 3. System boundaries and life cycle stages taken into account

Part of the residues resulted from incineration goes to landfill, that is not included in the system because of the absence of specific data. As landfill is not included in any of the two scenarios, it will not influence the comparative results. Emissions produced during the construction of facilities of incineration, utilities production and ashes and slag treatment are not considered in this study as we considered they are negligible compared to those emitted during the functioning of the system.

2.2 *Inventory analysis*

LCI is the phase on an LCA in which the material and energy flows are compiled and quantified (ISO 14040). In this step, environmental burdens from several sources are evaluated as follows:

Emissions from the system under study

The structure of the system and the flows of material and energy that cross the system boundary are shown in Figure 3. We represent in bold letters and yellow background all the processes for which SIRUSA provided us with data. Tables A1.1, A1.2 and A1.3 in Annex 1 present all the technical data obtained from SIRUSA, TRISA (plant of ashes treatment) and LYRSA (treatment of slag). For the other processes included within the boundaries of the incineration system, represented by rectangles, we use data from

Ecoinvent 2000. The average composition of the municipal waste incinerated in SIRUSA is shown in Figure 4.

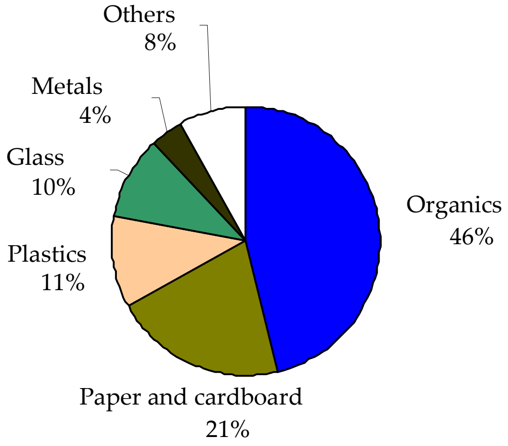


Figure 4. The average composition of MSW (Nadal 1999)

Following Figure 3, resources (including energy) and MSW are flows that enter the system, and emissions and wastes for landfill leave the system. There are no water emissions as SIRUSA is provided with a unit of water purification. The residues resulted from the purification of water are sent to landfill. The emissions resulted from the "refrigeration" unit are residual water vapours. Besides electricity, the only positive output of the system (not environmental burden) is the steel recovered in the "slag treatment" unit.

CO_2 emissions resulted from the incineration of natural organic materials are not considered in the analysis because they are part of the carbon cycle in nature. Nevertheless, CO_2 emissions generated by the combustion of non-renewable organic materials (e.g. plastics, rubber, etc.) contribute actively to the greenhouse effect. Therefore, to calculate the total amount of CO_2 resulted from incineration (Em_{CO_2}) we do not use the emission values reported by SIRUSA but we calculate them as a function of percentage of plastics in MSW by using equation (1):

$$Em_{CO_2} = \frac{m_{MSW} * p_{plastics}}{2.0691 * 100} * V_{em}, \qquad (1)$$

where m_{MSW} is the amount of wastes incinerated per year, $p_{plastics}$ is the percent of plastics in MSW, and V_{em} is the volume of air emissions from the incineration process. We assume an 11% of plastics in MSW and a 56.43% of carbon in plastic.

Emissions from transportation

SIRUSA is located in Constantí, in an industrial area, approximately three kilometres outside of Tarragona. The main roads, such as the motorway A7, provide excellent access to the plant from the surrounding cities Tarragona, Reus, Valls, Salou, Cambrils, Vila-Seca and Constantí. The treatment of residues resulted from incineration is made by TRISA (treatment of ashes) located in Constantí, and by LYRSA (treatment of slag) located next to Madrid. We include in the study both the transport of MSW to the incinerator and the transport of ashes and slag to their corresponding units of treatment. We assume all wastes are transported using 16-ton trucks. The average distance for MSW is considered 9km, for ash 4km and for slag 534km (all of them are one-way distances).

2.3 Impact assessment

The impact assessment phase of LCA is regulated by the international standard ISO 14042 and consists of the following steps:

- Definition of impact categories: here the potential problem areas, where environmental impact may be observed, are described;
- Classification: LCI results are assigned to the impact categories chosen in the first step;
- Characterisation: the results form the inventory analysis are transformed into a number of contributions to environmental impact categories, such as resource depletion, global warming, etc; and
- Weighting (optional): is a quantitative measure of the relative importance between different impact categories.

As we are interested only in the methods of LCI computation, we do not cover the phase of impact assessment.

2.4 Interpretation

According to ISO 14040, interpretation is the phase of life cycle assessment in which "the results of a life cycle inventory analysis and – if conducted – of a life cycle impact assessment are summarised and discussed as a basis for conclusions, recommendations and decision making in accordance with the goal and scope definition". The main aim of this phase is to formulate the conclusions that can be drawn from the LCA study. Here, as we don't cover the phase of impact assessment, the results are reported as quantities of emissions to air, water or soil. As our objective is to compare the environmental profile of the incineration before and after the installation of the advanced gas cleaning filters, we present these results as differences between the situation 1 without filters and situation 2 with filters (see Section 4) and draw the conclusions from the LCI study.

3. Methods to compile Life Cycle Inventories

This section is concerned with the description of the three methods we employed to perform the inventory of the incineration, with emphasis on the matrix method. All the calculations are based on real data from the system. The matrix method of LCI compilation is based on the mathematical formalism described by Heijungs (1994) and Heijungs and Suh (2002). Its results are compared to other two methods of compiling a LCI: a commercial software for calculation of LCA, SimaPro, and an Excel spreadsheet based calculation.

Matrix-calculation

Given a product system, a unit process is the smallest portion for which data are collected when performing a LCA. All the process units are interconnected by material and energy flows forming a process-tree in interaction with the environment and with the rest of the economy. In the matrix method, the process-tree is represented into a matrix. A process is represented by a column vector, where the upper part ($a_1 \ldots a_r$) contains the economic inputs and outputs, and the lower part the inputs from and the outputs to the environment ($b_1 \ldots b_s$).

$$\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} a_1 \\ \vdots \\ a_j \\ \vdots \\ a_r \\ b_1 \\ \vdots \\ b_k \\ \vdots \\ b_s \end{pmatrix}.$$

Here the inputs are considered negative and outputs positive. The economic inputs and outputs represent exchanges with the economic system, such as the purchases or sales of intermediate goods (materials, machinery, etc.) or services (transport, waste treatment, telecommunication, etc.). The exchanges with the environment (inputs from and the outputs to the environment), such as extraction of natural resources (e.g. petroleum extraction, fishing) and direct emissions to the air, water and soil, are known as environmental burdens. They are represented in the lower part of the vector ($b_1 \ldots b_s$).

By numbering processes with an index *i* and by placing them in a matrix such as the data on each input or output is presented in a row, we obtain:

$$\begin{pmatrix} A \\ B \end{pmatrix} = \begin{pmatrix} a_{11} \ldots\ldots a_{1i} \ldots\ldots a_{1q} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ a_{j1} \ldots\ldots a_{ji} \ldots\ldots a_{jq} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ a_{r1} \ldots\ldots a_{ri} \ldots\ldots a_{rq} \\ b_{11} \ldots\ldots b_{1i} \ldots\ldots b_{1q} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ b_{k1} \ldots\ldots b_{ki} \ldots\ldots b_{kq} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ b_{s1} \ldots\ldots b_{si} \ldots\ldots b_{sq} \end{pmatrix},$$

where: *A* is the technology matrix (represents the flows within the economic system), *B* is the environmental loads matrix (contains the environmental loads of unit processes), and *q* is the number of processes in the process tree. Rows represent flows of one type (e.g. TJ of electricity) and columns represent processes (e.g. diesel production).[9]

The next step is to create a model of that part of the economic system which comprises all the processes required to produce a certain good or to deliver a certain service. By calculating the inverse of matrix *A*, provided that *A* is square and non-singular, we get the cumulative demand of intermediate goods and services needed to produce each of the unit process. The conditions of invertibility are normally met in a real product system.[10] The cumulative amounts of resource extractions and emissions are then calculated by:

$$g = B * A^{-1} * f, \tag{2}$$

---

[9] We conserve the same notations as Heijungs and Suh (2002).

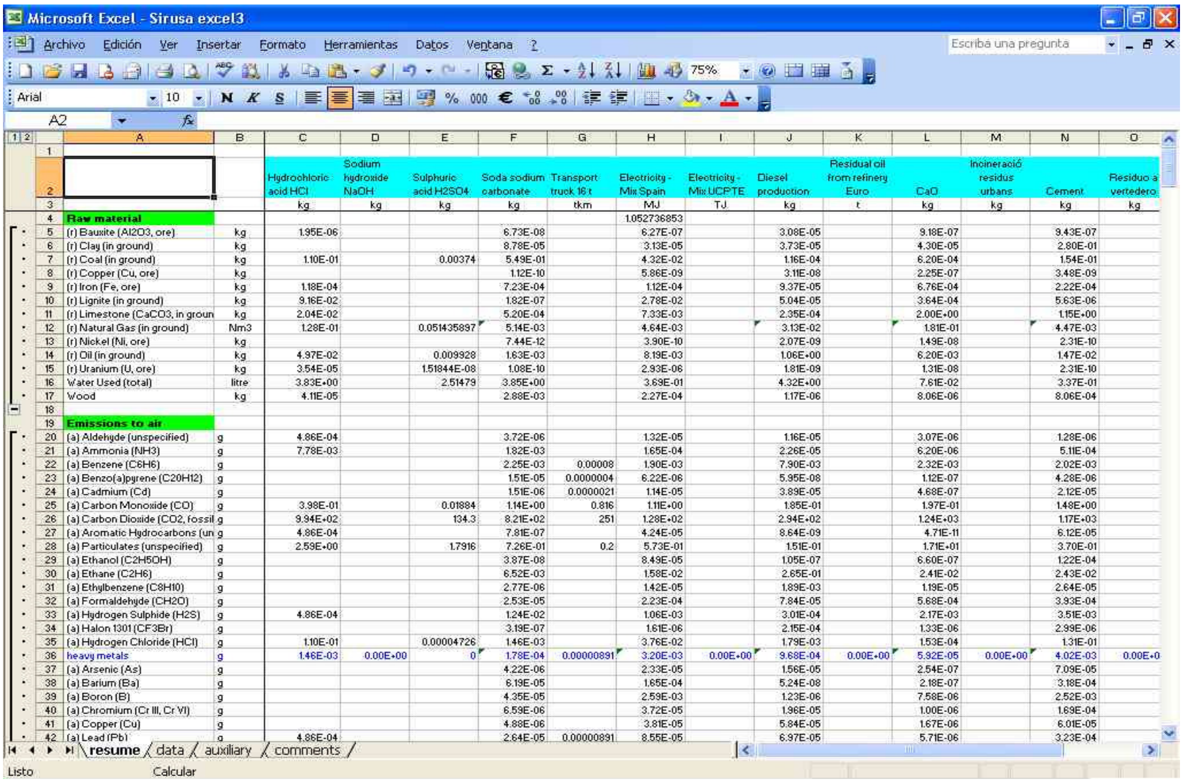
[10] See Chapter 3 in Heijungs and Suh (2002) for solutions to cases when the matrix is not square and invertible.

where *f* is the vector of final demand absorbed or produced by the system; e.g. in our case: 1TJ of electricity co-produced by the incineration of MSW.

Excel-based calculation

Data from Tables A1.1, A1.2 and A1.3 in Annex 1 are fed in an Excel workbook organized in different spreadsheets (see Figure 5). The first one, named "resume" contains all the data imported from ecoinvent 2000 database. This database includes more than 2500 background processes often required in LCA case studies (Frischknecht and Rebitzer, 2005). Each process is documented both with unit process raw data and aggregated LCI data. We selected raw data on consumption and emissions associated with the extraction or production of the raw and ancillary materials used in the system under study. The selected processes are: production of HCl, H_2SO_4, Na_2CO_3, diesel, CaO, cement, salt, and electricity mix Spain at medium voltage as recommended by the Ecoinvent centre (2003).

"Auxiliary" spreadsheet contains data on the production of demineralised water by osmosis, refrigeration of water, purification of water from the incineration, and the treatment of slag and ashes. "Data" is the spreadsheet where the LCI of the system is calculated and "Comments" includes the assumptions considered in the simulation.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1															
2			Hydrochloric acid HCl	Sodium hydroxide NaOH	Sulphuric acid H2SO4	Soda sodium carbonate	Transport truck 16 t	Electricity - Mix Spain	Electricity - Mix UCPTE	Diesel production	Residual oil from refinery Euro	CaO	Incineració residus urbans	Cement	Residuo a vertedero
3			kg	kg	kg	kg	tkm	MJ	TJ	kg	t	kg	kg	kg	kg
4	**Raw material**							1.052736853							
5	(r) Bauxite (Al2O3, ore)	kg	1.95E-06			6.73E-08		6.27E-07		3.08E-05		9.18E-07		9.43E-07	
6	(r) Clay (in ground)	kg				8.78E-05		3.13E-05		3.73E-05		4.30E-05		2.80E-01	
7	(r) Coal (in ground)	kg	1.10E-01		0.00374	5.49E-01		4.32E-02		1.16E-04		6.20E-04		1.54E-01	
8	(r) Copper (Cu, ore)	kg				1.12E-10		5.86E-09		3.11E-08		2.25E-07		3.48E-09	
9	(r) Iron (Fe, ore)	kg	1.18E-04			7.23E-04		1.12E-04		9.37E-05		6.76E-04		2.22E-04	
10	(r) Lignite (in ground)	kg	9.16E-02			1.82E-07		2.78E-02		5.04E-05		3.64E-04		5.63E-06	
11	(r) Limestone (CaCO3, in groun	kg	2.04E-02			5.20E-04		7.33E-03		2.35E-04		2.00E+00		1.15E+00	
12	(r) Natural Gas (in ground)	Nm3	1.28E-01		0.051435897	5.14E-03		4.64E-03		3.13E-02		1.81E-01		4.47E-03	
13	(r) Nickel (Ni, ore)	kg				7.44E-12		3.90E-10		2.07E-09		1.49E-08		2.31E-10	
14	(r) Oil (in ground)	kg	4.97E-02		0.009928	1.63E-03		8.19E-03		1.06E+00		6.20E-03		1.47E-02	
15	(r) Uranium (U, ore)	kg	3.54E-05		1.51844E-08	1.08E-10		2.93E-06		1.81E-09		1.31E-08		2.31E-10	
16	Water Used (total)	litre	3.83E+00		2.51479	3.85E+00		3.69E-01		4.32E+00		7.61E-02		3.37E-01	
17	Wood	kg	4.11E-05			2.88E-03		2.27E-04		1.17E-06		8.06E-06		8.06E-04	
18															
19	**Emissions to air**														
20	(a) Aldehyde (unspecified)	g	4.86E-04			3.72E-06		1.32E-05		1.16E-05		3.07E-06		1.28E-06	
21	(a) Ammonia (NH3)	g	7.78E-03			1.82E-03		1.65E-04		2.26E-05		6.20E-06		5.11E-04	
22	(a) Benzene (C6H6)	g				2.25E-03	0.00008	1.90E-03		7.90E-03		2.32E-03		2.02E-03	
23	(a) Benzo(a)pyrene (C20H12)	g				1.51E-05	0.0000004	6.22E-06		5.95E-08		1.12E-07		4.28E-06	
24	(a) Cadmium (Cd)	g				1.51E-06	0.0000021	1.14E-05		3.89E-05		4.68E-07		2.12E-05	
25	(a) Carbon Monoxide (CO)	g	3.98E-01		0.01884	1.14E+00	0.816	1.11E+00		1.85E-01		1.97E-01		1.48E+00	
26	(a) Carbon Dioxide (CO2, fossil	g	9.94E+02		134.3	8.21E+02	251	1.28E+02		2.94E+02		1.24E+03		1.17E+03	
27	(a) Aromatic Hydrocarbons (un	g	4.86E-04			7.81E-07		4.24E-05		8.64E-09		4.71E-11		6.12E-05	
28	(a) Particulates (unspecified)	g	2.59E+00		1.7916	7.26E-01	0.2	5.73E-01		1.51E-01		1.71E+01		3.70E-01	
29	(a) Ethanol (C2H5OH)	g				3.87E-08		8.49E-05		1.05E-07		6.60E-07		1.22E-04	
30	(a) Ethane (C2H6)	g				6.52E-03		1.58E-02		2.65E-01		2.41E-02		2.43E-02	
31	(a) Ethylbenzene (C8H10)	g				2.77E-06		1.42E-05		1.89E-03		1.19E-05		2.64E-05	
32	(a) Formaldehyde (CH2O)	g				2.53E-05		2.23E-04		7.84E-05		5.68E-04		3.93E-04	
33	(a) Hydrogen Sulphide (H2S)	g	4.86E-04			1.24E-02		1.06E-03		3.01E-04		2.17E-03		3.51E-03	
34	(a) Halon 1301 (CF3Br)	g				3.19E-07		1.61E-06		2.15E-04		1.33E-06		2.99E-06	
35	(a) Hydrogen Chloride (HCl)	g	1.10E-01		0.00004726	1.46E-03		3.76E-02		1.79E-03		1.53E-04		1.31E-01	
36	heavy metals	g	1.46E-03	0.00E+00	0	1.78E-04	0.00000891	3.20E-03	0.00E+00	9.68E-04	0.00E+00	5.92E-05	0.00E+00	4.02E-03	0.00E+0
37	(a) Arsenic (As)	g				4.22E-06		2.33E-05		1.56E-05		2.54E-07		7.09E-05	
38	(a) Barium (Ba)	g				6.19E-05		1.65E-04		5.24E-08		2.18E-07		3.18E-04	
39	(a) Boron (B)	g				4.35E-05		2.59E-03		1.23E-06		7.58E-06		2.52E-03	
40	(a) Chromium (Cr III, Cr VI)	g				6.59E-06		3.72E-05		1.96E-05		1.00E-06		1.69E-04	
41	(a) Copper (Cu)	g				4.88E-06		3.81E-05		5.84E-05		1.67E-06		6.01E-05	
42	(a) Lead (Pb)	g	4.86E-04			2.64E-05	0.00000891	8.55E-05		6.97E-05		5.71E-06		3.23E-04	

Figure 5. Overview of Excel spreadsheets

SimaPro simulation

SimaPro, standing for "System for Integrated Environmental Assessment of Products", is a commercially available LCA-software. We choose this software from various other software (TEAM, Umberto, Regis, PEMS, etc.) as it employs the matrix method described previously to calculate the LCI (Frischknecht and Rebitzer, 2005). All the data it uses is based on Swiss and European demand patterns and correspond to year 2000.

4. Results and discussion

The compilation of LCI of the incineration process implies the calculation of environmental burdens associated to the treatment of waste input of defined composition (see Figure 4) in the municipal waste incinerator SIRUSA described above. As shown in Figure 3, we consider in the analysis six processes for which SIRUSA provided us with data: incineration with electricity co-production, osmosis, water purification, water refrigeration, slag and ash treatment, and nine processes of ancillary materials production, for which we used data from Ecoinvent 2000. To decide which inputs and outputs to consider for each of these processes, we assumed that:

- The composition of MSW entering to incineration (Figure 4) remains unchanged over one year of functioning of the plant;
- Due to the data availability, we do not consider in the analysis the ferric chloride used in the process of water treatment, the additives used in osmosis and active carbon used in gas cleaning advanced system;
- The associated data to the raw materials are extracted from Ecoinvent 2000 data base. There is the possibility of non concordance between the local data and the European averages extracted from the above mentioned data bases.

Considering these limitations, we analysed the incineration system as being composed of fifteen processes and seventeen functional flows: electricity from the national grid, MSW, co-produced electricity, transport, deionised water, H_2SO_4, HCl, NaOH, refrigerated water, purified water, ashes to treatment, slag to treatment, recovered iron, cement, lime, diesel oil and Na_2CO_3. These data lead us to a non-square matrix of 17-by-15 and therefore not invertible.

Table 1. The new technology coefficient matrix after allocation

	1	2	3	4	5	6	7	8	9
1	6.4E+05	-2.3E+05	-2.3E+05	0	-4.4E+04	-1.3E+01	-2.1E+03	-2.3E+02	-4.2E+04
2	0	7.7E+07	-7.7E+07	0	0	0	0	0	0
3	0	0	4.3E+07	0	0	0	0	0	0
4	0	-2.1E+06	-2.1E+06	8.1E+06	0	0	0	0	0
5	0	-2.0E+10	0	0	2.0E+10	0	0	0	0
6	0	0	0	0	-1.5E+03	7.5E+03	0	0	0
7	0	0	0	0	-6.2E+02	0	6.2E+02	0	0
8	0	0	0	0	-1.2E+03	0	0	1.2E+03	0
9	0	0	-5.2E+09	0	0	0	0	0	5.2E+09
10	0	-7.4E+09	0	0	0	0	0	0	0
11	0	-1.7E+06	-1.7E+06	0	0	0	0	0	0
12	0	-1.4E+06	-1.4E+06	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0
15	0	-9.2E+05	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0
17	0	-7.4E+04	-7.4E+04	-6.5E+05	0	0	0	0	0

Table 1. The new technology coefficient matrix after allocation (continuing)

	10	11	12	13	14	15	16	17
1	-4.2E+04	-4.6E+04	-3.0E+02	-3.0E+02	-1.0E+02	-5.5E-01	0	-7.3E+01
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	-1.1E+06	-1.5E+06	-1.5E+06	0	0	0	0
5	0	0	0	0	0	0	0	0
6	-6.0E+03	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	7.4E+09	0	0	0	0	0	0	0
11	0	-3.5E+06	0	0	0	0	0	0
12	0	0	-1.4E+06	-1.4E+06	0	0	0	0
13	0	0	0	2.2E+06	0	0	0	0
14	0	-5.2E+05	0	0	5.2E+05	0	0	0
15	0	0	0	0	0	9.2E+05	0	0
16	-1.2E+04	0	0	0	0	0	1.2E+04	0
17	0	-3.8E+03	-9.6E+02	-9.6E+02	0	0	0	8.0E+05

A closer look to Figure 3 shows that the unit process “incineration and co-electricity production” is a multifunctional process as it has two positive outputs: incinerates MSW and produces electricity. This implies an allocation of resources, inputs and outputs form and to the other processes, and emissions between the two processes “incineration” and “co-electricity production”. Other multifunctional process that needs allocation is the “slag treatment” as it treats the slag resulted from the incineration and recovers steel. The calculations and assumptions implied by the allocation in these multifunctional processes are presented in Annex 2 and the resulting 17-by-17 matrix is given in Table1.

Based on the environmental data by process which SIRUSA and the treatment plants of its residues provided us and the above assumptions, we compiled the matrix LCI of the incineration system by solving equation (2). We compared the results against the “classic” method of mass and energy balances calculated in Excel spreadsheets and a commercial software, SimaPro. Figure 6 shows the comparison between the LCI evaluations of the incineration system by the three methods.

We present the results as percentages of difference in the emissions between the scenario without filters (situation 1) and the scenario which includes the filters (situation 2). These percentages express the reduction or increase of air emissions due to the installation of an advanced flue gas treatment system. Calculating the difference as percentage allows us to represent different pollutants in the same graph. The system of each situation can be described as a sum of sub-processes:

situation 1 = Σ (Incineration 1 (without filters) + Waste Transport + Electricity Production + Diesel Production + ...)

situation 2 = Σ (Incineration 2 (with flue gas treatment) + Waste Transport + Electricity Production + Diesel Production + Lime production + ...)

The differences between the two situations are then calculated as:
situation 1 - situation 2 = Σ(Incineration 1 - Incineration 2 +/- ...)

The sub-processes are the same for the two situations, excepting the production and the transport of lime which only occur in situation 2, with advanced flue gas treatment.

As Figure 6 shows, the introduction of filters implies a reduction in the emissions of As, Cd, HCl, heavy metals, Ni, particulates and SO_x from the incineration plant, as happens in the real emission data reported by SIRUSA. This behaviour is well reflected by the three methods. On the other hand, the simulations show an increase in CO_2, CO and NO_x, emissions, although the real data from the plan show constant emissions. This increase may be explained by additional transports for (treated) ashes, lime, cement and the production of lime and cement, which are considered within the simulation boundaries, meanwhile the real data reflect only the incineration process.

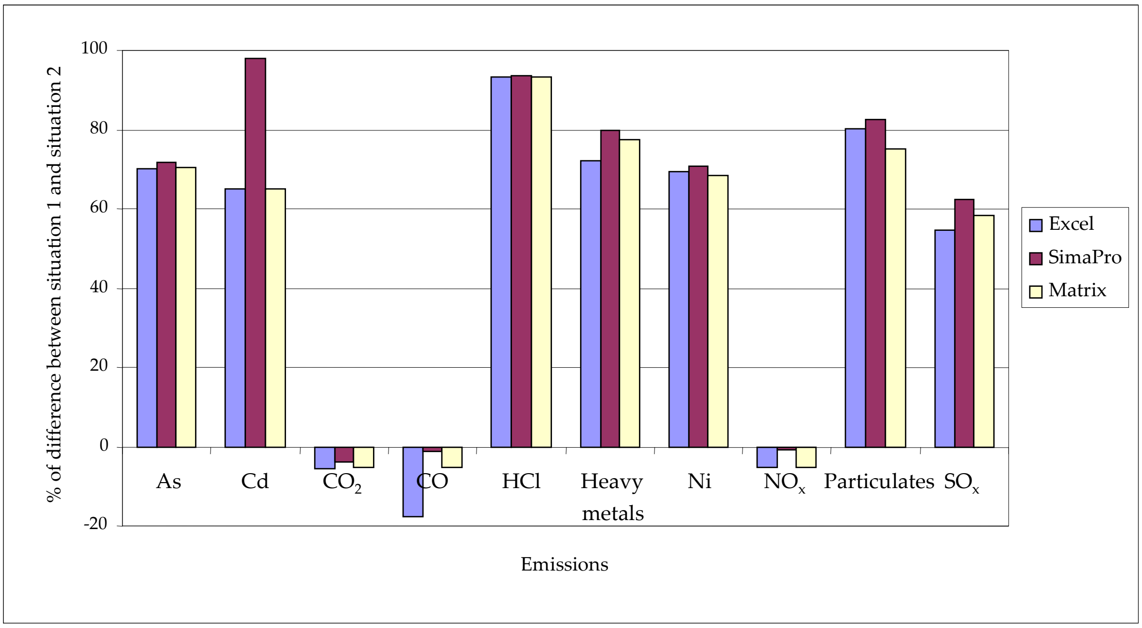


Figure 6. Differences in the emissions between the scenario 1 (without filters) and the scenario 2 (filters)

The results presented in Figure 6 show that the matrix method gives comparable results to the other two methods and always in concordance with them. In our opinion, the matrix method has the advantage of a clearer presentation of data, calculations and results, over the "classic" process-flow diagram formalism. For example, in the case of allocation of "incineration and co-electricity generation" and "slag treatment" processes, the matrix method showed clearly the existence of multifunctionality problem (the initial technology matrix *A* was not invertible as it is a non-square matrix of 15-by-17), meanwhile in Excel we attributed directly all the emissions to the functional unit (1TJ of electricity co-produced) and we do not consider the "avoided" process of steel recovering that would replace the obtaining of steel from raw materials. Besides its elegant and powerful approach to LCI compilation, the matrix method allows an easier connection to IO data or an easier calculation of advanced analysis as uncertainty analysis, perturbation analysis,

key-issue analysis, etc. We do not perform here any of these advanced analyses and neither check the stability of the technology matrix. They are left for future investigation.
One could ask why to bother to perform “by hand” all the calculations in the matrix method presented here, if commercially available software already include it and perform automatically all the calculations; e.g. SimaPro also used here for comparison. Our argument is that in practical analyses, if the calculations are made almost “by hand”, the user observes all the assumptions implied in his or her decisions, meanwhile an automatic software usually perform the calculations in background and do not attention when makes assumptions of allocation of data, or substitution of the missing data.

5. Conclusions

In this chapter we calculated and compared the atmospheric emissions of an incineration system before and after the installation of an advanced gas cleaning system in the incinerator. To perform the calculations we use the methodology of Life Cycle Analysis that considers all the environmental burdens associated to a product, service or activity across all its life cycle; e.g. from raw materials extraction from the environment, going through the production of the inputs in the process, production of the desired product, its use, and finishing with its final disposal or recycling. To compile the inventory phase of the assessment (quantification of all the material and energy flows) we employed three different methods: the “classic” formalism based on process-flow diagram and Excel calculations, the matrix method and a commercially available software SimaPro that also incorporates the matrix calculations. Our goal is to validate the results of the matrix method by their comparison to the other two employed methods of compilation. The results we obtained show that the matrix method gives comparable results to the other two methods and always in concordance with them.

LCA is a very detailed and specific method of accounting for the environmental burdens of a product, service or activity across all its life cycle. Nevertheless it has disadvantage of needing big amounts of data that usually are not available. One way to supply the missing data is to use economic data regularly compiled as part of national statistics, the IO tables. The combination of LCA calculations with IO data and calculations is known as “hybrid approaches to LCI” and is discussed in Chapter V. The use of the matrix method for LCI compilation makes the connection of LCI with IO data and calculations to proceed smoothly. Furthermore, the matrix method allows an easier application of advanced analyses as uncertainty, perturbation, key-issue analysis, etc. to the LCI data and results.

CHAPTER II

ATMOSPHERIC EMISSIONS AND STRUCTURAL PATH ANALYSIS IN THE SPANISH ECONOMY

Abstract

The objective of this chapter is to integrate Spanish atmospheric pollution and macroeconomic data in order to identify the main drivers of atmospheric pollution in Spain. This chapter uses data from the Satellite Atmospheric Emissions Accounts as well as the 2000 input-output tables both published by the Spanish National Statistics Institute. The identification and analysis of the input paths of air pollution in the Spanish production system is performed using Structural Path Analysis (SPA) in a generalised input-output framework. This methodology allows for the detection of "hidden" sectors in the generation of pollution. Our results rank the energetic sectors, food processing industries, other manufacturing industries and transportation as the sectors with the highest emission intensities. Our results also show the production layers contribution in each pollutant, identifying fluorocarbons and ammonia as the substances with higher up-stream sources.

Keywords: Structural Path Analysis, Input-Output Analysis, atmospheric emissions, Spain

1. Introduction

The production and consumption of goods and services cause emissions of pollutants to the atmosphere. It has long been recognised that these substances have major impacts on our health and environment and must therefore be monitored and managed. Air pollution includes the emission of substances of global concern such as greenhouse gases as well as substances which have a more localised effect but are toxic to human health and the environment.

Under the Kyoto Protocol on climate change, the European Union established cuts for most of its members, pledging an overall reduction of 8% of greenhouse gases (GHG) emissions between 1990 and 2012. A "burden-sharing" agreement between EU governments established differentiated emissions limits for each Member State. These limits are expressed in terms of percentages by which Member States must reduce, or in some cases may hold or increase, their emissions compared with 1990, the base year level. Spain was allowed to increase its emissions by 15% above their base-level values. To ensure that this target will not be overpassed, on February 2005 the Spanish National Allocation Plan for Emissions Rights came out, establishing quotas for the country's main industries through 2007. The highest emissions quotas were granted to the electrical energy sector and the cement industry, almost 40% and 16% from the total allowed CO_2 emissions respectively. Other measures to decrease the emission of GHG include promote efficient energy use and clean energy sources, support cleaner technologies, and make the public more sensitive to the problem of global warming. The government plans to encourage train and other public modes of transportation as opposed to individual car use for short distances, as 30% of Spain's GHG direct emissions come from transportation.

In order to assist to air pollution reduction at national level, it is important to identify the polluting industries and to describe and quantify their emissions as detailed as possible. Furthermore, it is important to consider not only the direct or on site emissions, but also the emissions "embodied" or "enclosed" in the products or services that an industry buys for its functioning. This is precisely the aim of this chapter, to determine the direct and indirect emissions associated with the activity of each sector in the Spanish economy in order to detect key sectors and important input paths in air pollution. This information will help decision-making for further emission reduction measures in Spain.

Regarding the methodology, we employ a generalised input-output (IO) model supplemented by a detailed analysis of the "embodied" emissions using an analytical tool, which has not been applied before to the study of the Spanish production factors, namely Structural Path Analysis (SPA). The use of IO techniques to study environmental problems is not new for Spain, the first application dates from 1980 when Pajuelo (1980) proposed an extended Leontief model to study the atmospheric pollution. The extended Leontief model included new rows and columns to account for the atmospheric pollutants as part of the production processes. In the field of water consumption, Duarte *et al.* (2002) and Sánchez-Chóliz and Duarte (2003) used a traditional IO model, but considered the water necessities as inputs in the model. To detect key sectors in the consumption of water, the transfer of water between economic sectors and the relationships between water use and income generation these authors used a particular methodology based on linkages analysis. Combining Structural Decomposition Analysis with the previous method, Sánchez-Chóliz and Duarte (2004) investigated the connection between water use and technical changes in the economy or changes in the final demand. A different approach to the sectoral water consumption estimation was suggested by Velázquez (2006) who proposed a new model by the combination of Leontief model with Proops' energy model. The suggested model permits simulations in order to detect the impact that a new water consumption regulation would have on the regional economy of Andalucia.

Coming to the study of atmospheric pollution and primary energy consumption, an important contribution was made by Alcántara and Roca (1995). They proposed a different input-output model based on the Organisation for Economic Co-operation and Development's (OECD's) energy balance sheets combined with information on energy consumption by type and by economic sector. The model permitted to explain primary energy demands and CO_2 emissions during the decade 1980-1990. Anton Valero *et al.* (1993) constructed the energy input-output tables of the Spanish economy to study the CO_2 emissions under different scenarios of economic development. The calculation of the total atmospheric emissions using IO multipliers was performed recently by various authors. Cadarso and Fernández-Bolaños (2002) computed the emissions multipliers for the Spanish economy for the period 1980-1995 and the total emissions related to each component of the final demand for 11 kinds of pollutants. They analysed the temporal evolution of the emissions and recommended to pay attention to private consumption which, according to their results, was responsible for the main part of the total emissions.

Manresa and Sancho (2004) calculated the energy requirements and CO_2 emissions for the Catalan economy using social accounting matrix (SAM) multipliers. In their work, the simple IO multipliers were discussed as a particular case of SAM multipliers. Although the results obtained using the SAM multipliers were more complete, since they reflected amplified inter-sectoral links, the authors recommended the use of the simple IO multipliers to detect and isolate the effects due only to the productive sectors links. Sánchez-Chóliz *et al.* (2005) used the SAM multipliers calculated for 1999 to estimate seven water pollution and atmospheric emissions footprints of the Spanish population. Associating the estimated footprints with households' income, they found that the *per capita* pollution (an approximation to the ecological footprint) is strongly dependent on the income levels and rise in line with them. Argüelles *et al.* (2006) calculated the direct, indirect and the induced greenhouse gas emissions in Asturias for 1995. They compared the results obtained by considering households exogenous as a whole and respectively by endogenizing part of household consumption and identified the sectors more affected by the Kyoto Protocol implementation in Asturias. Focusing on the six major greenhouse gases (GHG) regulated by the Kyoto Protocol, Butnar and Llop (2007) analysed how exogenous changes in sectorial demand affect the relative contribution of these gases to total Spanish GHG emissions. Their work, based on data from the year 2000, revealed that very few Spanish sectors have a considerable influence on the emission of GHG. In the same field, Llop (2007) analysed the changes in Spanish emission multipliers during the period 1995–2000, revealing a small reduction in multipliers during the period of analysis.

The present work applies Structural Path Analysis (SPA) to the Spanish economy in order to identify the key economic sectors and inter-industry linkages that play a role in given production factors. In particular, to illustrate this methodology, we apply it to the study of atmospheric pollution in Spain, although it can be easily adapted to other production factors such as water consumption and pollution, land-use, natural resource consumption, etc., depending on the availability of data and user interests. Atmospheric emissions by unit of final consumption are estimated using a generalised IO model through the calculation of IO multipliers for 11 kinds of atmospheric pollutants. SPA is applied through a decomposition of the IO multipliers into economic paths along the supply chain. If the previous applications of IO techniques to environmental problems made possible the evaluation of the emissions of each economic sector, our study goes deeper providing also information on the indirect polluting sectors and the paths through which the generation of pollution is propagated. Only knowing both, the direct and the indirect polluting sectors, a good decision-making can be made.

The Spanish National Institute of Statistics provides both the economic and the environmental data used in our calculations, namely the IO tables for the year 2000 (the last year for each are compiled both IO data and data on emissions) and the Satellite Atmospheric Emissions Accounts for the same year (INE, 2001, 2005). The modifications we brought to the original data to fit in the methodology are explained in Section 2.2. The remaining of the chapter is organized as follows. In Section 2.1, we present the generalised IO model and the SPA methodology employed in this study. Section 3.1 contains the results of their application to the Spanish economic sectors as direct and indirect polluters. The results are presented in detailed by emission type. Section 3.2 summarises and discusses the main results and Section 4 draws some conclusions.

2. Methodology

2.1 Generalized Input-Output Model and Structural Path Analysis

Input-output analysis is a top-down economic technique that traces the monetary flows throughout an economic system for a particular period of time, connecting the gross outputs of economic sectors with primary inputs and final demand. In particular, the gross output x_i of an economic sector *i* can be expressed as the sum of the sector's final demand y_i plus all its inter-industry sales:

$$x_i = y_i + \sum_j z_{ij} \tag{1}$$

Here, z_{ij} represents the monetary transaction from industry *i* to industry *j*. In the input-output formalism, a matrix of direct requirements *A* is defined as the inter-industry flows a_{ij} from an industry *i* to an industry *j* per gross output of sector *j*, $a_{ij} = z_{ij}x_j^{-1}$. Using this definition in equation (1), the connection between the gross output (endogenous to the system) and the final demand (exogenous to the system) in a given economy is uniquely determined by the matrix of direct requirements of the system through the relation:

$$x = (I - A)^{-1} y, \tag{2}$$

where *I* is the identity matrix. The matrix $(I - A)^{-1}$, usually named the Leontief inverse or the matrix of total requirements, is also known as "IO multipliers" as it captures the extent to which the total output of a sector is amplified through a change in the final demand. Furthermore, the Leontief inverse can be decomposed into the contributions coming from each layer of the supply chain by using its series expansion:

$$(I - A)^{-1} = I + A + A^2 + A^3 + \ldots \tag{3}$$

Here, each element A^l represents the contribution to the gross output from the layer *l* of production, with the first element (*l*=0) representing the effect on gross output due to direct purchases from final demand.[11]

If the relation between the output of each economic sector and the environmental impact of that sector's activity is known, and assumed linear, a vector of direct impact coefficients *v* is defined, where each element v_i represents the environmental impact (e.g. tones of CO_2 or Mega litres of water used) associated with one euro's worth of industry *i*'s output. These production impacts can then be distributed across final demand using the Leontief model,

$$m' = v'(I - A)^{-1}. \tag{4}$$

The resulting environmental multipliers, *m*, express the total "content" or "embodiment" of environmental factors per monetary unit of final consumption supplied by the production sectors.[12]

In order to analyse in detail the structure of the sectoral contributions to a given multiplier, the total factor multipliers can be decomposed by using the series expansion of the Leontief inverse,

$$m = v + vA + vA^2 + vA^3 + \ldots \tag{5}$$

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[11] For an introduction and further details on the IO theory see Miller and Blair (1985).

[12] The superscript for the vectors *m* and υ denote their transpose.

In particular, following Lenzen (2002), the multiplier associated with the final demand of industry *i* can be written as follows:

$$m_i = v_i + \sum_{j=1}^{n} v_j A_{ij} + \sum_{j=1}^{n}\sum_{k=1}^{n} v_j A_{jk} A_{ki} + \sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n} v_j A_{jk} A_{kl} A_{li} + \dots, \qquad (6)$$

where *n* is the total number of industries of the economic system under consideration. Each element of this series expansion represents a set of paths (each consisting on a sequence of purchases) from the "polluting" industry *j* (the industry directly responsible for the environmental impact) to the final demand of industry *i*. The first term, v_i, is the direct impact coefficient that takes place in industry *i*; the next term contains *n* first order paths $v_i A_{ji}$ between industries *j* and *i*; the n^2 second order paths $v_i A_{jk} A_{ki}$ connect industries *j* and *i* via industry *k* and so on. This analysis is known as structural path analysis. Although the order of these indirect effects is infinite, each term of the series expansion becomes smaller with each round of purchases and the series eventually converges. Here, we analyse only the first 5 layers of suppliers.

2.2 *Data sources*

The economic and atmospheric pollution data used in this chapter come from the Spanish National Institute of Statistics. We have chosen to work with data from 2000 as it is the last year for each the Spanish Institute of Statistics (INE) provides both economic and environmental data.

The economic data comprises the make and use tables (INE, 2005). The use table (matrix *U*) is given as flows of 110 commodities into 72 industries or economic sectors, while the make (or supply) table (matrix *S*) is given as 110 commodities produced by 73 industries. The transactions in both make and use tables are expressed in basic prices. The commodity classification follows the National Classification of Products (CNAP-96). The industry classification follows the National Classification of Economic Activities (CNAE-1993).

The only difference between the classifications in the use and make matrices is the introduction in the use table of a fictitious sector to account for the use of the financial intermediation services, indirectly measured. This fictitious sector, Financial Intermediation Services Indirectly Measured (FISIM), is not considered here. All its inputs are attributed to the financial intermediation sector (FIS). Furthermore, we have aggregated both the make and the modified use matrices into 70 industrial sectors, considering homogenous sectors as reported by INE. The assumption of homogeneity implies that each activity in a homogenous aggregated sector *j* requires the same inputs per unit of output from the aggregate sector *i*. In other words, the homogeneous sectors are considered to produce only primary products, the secondary production being not considered. The list of the 70 economic sectors we considered can be found in Annex III, table A3.1.

The 70-industry-by-70-industry direct requirements matrix *A*, used in our IO model can be computed from the make and use tables following the equation[13]: $A = D^t B$, where D^t stands for the transpose of the share matrix *D*, and *B* is the matrix of technical coefficients in commodity-by-industry terms. Each element of the share matrix d_{ij} represents the fraction of commodity *i* produced by the industry *j* and is derived from the make matrix through: $d_{ij} = s_{ij} \Big/ \sum_i s_{ij}$. Meanwhile, each element of the matrix *B*, b_{ij} is the flow of commodity *i* to industry *j* per unit of industry *j*'s output: $b_{ij} = u_{ij} * (x_j)^{-1}$.

The physical data comes from the Satellite Atmospheric Emissions Accounts (INE, 2001). It consists of emissions of 11 atmospheric pollutants released by 45 domestic economic sectors. The atmospheric pollutants are: sulphur oxides (SO_x), nitrogen oxides (NO_x), no methane volatile organic compounds (NMVOC), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (N_2O), ammonia (NH_3), sulphur hexafluoride (SF_6), hydro-flour carbonates (HFC) and perfluorocarbonates (PFC).

The division of the Spanish economy into 45 sectors in this environmental matrix follows NACE-Rev 1 classification (EUROSTAT, 1993). While this classification is a standard of the European Union, the CNAE-93 industry classification used in the economic tables is a standard national classification that has been elaborated from the NACE-Rev1. Both classifications have, therefore, compatible structures. This similarity allowed us to bring the emissions matrix to the same disaggregation level as the matrix of direct requirements. To further disaggregate the emission data by industry, we used supplementary pollution data published in the Spanish National Inventory of Atmospheric Emissions (EIONET, 2005).

3. Results and discussion

Based on the above determined 70-sectors IO tables and 11 vectors of atmospheric emissions, we determine the main direct and indirect polluting sectors in the Spanish economy and their interdependencies. We perform two types of analyses. First, we analyse each atmospheric pollutant, focusing on the identification of its direct and indirect emitting sectors and the paths through which pollution is transmitted (Section 3.1). Second, we make a global analysis of the economy, showing that few sectors are responsible for the atmospheric pollution in Spain (Section 3.2).

Figure 1 shows the contribution of each layer of suppliers to the total multipliers of the 11 atmospheric pollutants under consideration. The multipliers have been normalized by the values of their respective direct emissions. As expected, indirect effects become increasingly less important as we move up the supply chain and after the fifth layer they become negligible. For some gases, such as HFC and PFC, indirect emissions are very significant, with the first three or four layers of suppliers making an important contribution. For other pollutants, like NMVOC and CH_4 or CO_2, most of the emissions can be attributed to on-site sources.

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[13] See e.g. Miller and Blair (1985).

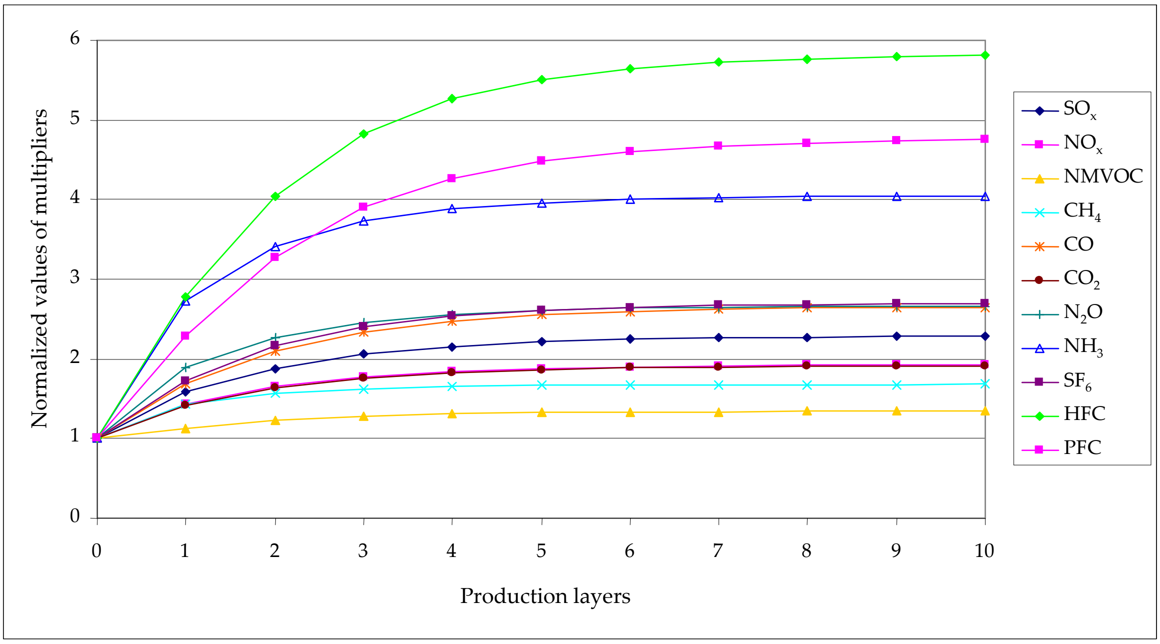

Figure 1. Contribution of production layers to the total multipliers

3.1 *Input paths of atmospheric pollution*

In what follows, we analyse the most important input paths of atmospheric pollution. For simplicity we take into consideration only the first five production layers. The results of this decomposition are shown in tables 1 to 5, where the top 20 input paths appear ranked by their contribution to the total multiplier. Each input path is described by: the path value in its corresponding physical units per euro of final demand (column 2), the path order (column 3), the industries participating in the supply chain (column 4) and the path coverage, that is the contribution in percentages to the total multiplier of the industry supplying the final demand (column 5). For example, the seventh row in Table 1 refers to 4.26 tonnes of SO$_x$ per euro of final demand of industry **11**, standing for Collection, treatment and water distribution, that are embedded in the purchase from industry **9**, Production and distribution of electricity, steam and hot water. The path is of first order and represents 62% of the total SO$_x$ multiplier of sector **11**.

<u>*SOx emissions*</u>

Sulphur oxides emissions, which are the most important contributors to acid rain, result from the combustion of fossil fuels that contain sulphur impurities, gasoline extraction from oil, and metals extraction from ore. Common sources of SO$_x$ include thermal power plants, petroleum refineries, cement manufacturing, and metal processing facilities, as well as locomotives, large ships, and some non-road diesel equipment that burn high sulphur fuel. Because of its petrochemical plants and the traditional use of coal for firing power plants, Spain is one of the main European sulphur oxides emitters. Over the period 1990-2000, the use of alternative fuels for power plants and other pollution prevention actions decreased by 30% the sulphur oxides emissions. In spite of this effort, in 2000 Spanish emissions were of 1.63Mt SO$_x$, representing 25.33% from the total SO$_x$ emissions of the European Union. The major input paths of SO$_x$ emissions (see Table 1) are associated with on-site emissions from the sectors: Production and distribution of electricity, steam and hot water **9**, Manufacture of cement **25**, Production and distribution of gas **10**, and Maritime Transport **47**. Together they are responsible for 70.6% of the national direct SO_x emissions. Most of the important first order paths emerge from sector **9**, due to electricity consumption by other sectors.

Table 1. Top 20 paths for SO_x and NO_x emissions in Spanish economy

Paths for the SO_x emissions					**Paths for the NO_x emissions**				
Rank	Path Value (t/€)	Path order	Sectors	% from the total multiplier	Rank	Path Value (t/€)	Path order	Sectors	% from the total multiplier
1	52.41	0	**9**	89%	1	32.61	0	**25**	91%
2	25.18	0	**25**	83%	2	18.02	0	**47**	90%
3	18.45	0	**10**	92%	3	17.85	0	**9**	83%
4	12.21	0	**47**	87%	4	14.10	0	**3**	89%
5	8.94	0	**8**	77%	5	13.25	0	**6**	87%
6	5.40	0	**27**	52%	6	7.80	0	**16**	67%
7	4.26	1	**9 11**	62%	7	7.72	0	**5**	89%
8	3.85	1	**9 9**	6%	8	6.00	0	**46**	85%
9	3.38	0	**29**	37%	9	5.83	0	**2**	92%
10	2.93	1	**9 45**	66%	10	5.37	0	**1**	68%
11	2.45	1	**9 25**	8%	11	5.27	1	**5 8**	61%
12	2.32	0	**28**	24%	12	4.98	1	**25 28**	55%
13	2.31	0	**26**	40%	13	4.97	1	**5 10**	62%
14	2.27	1	**9 7**	50%	14	4.32	0	**39**	63%
15	2.00	1	**9 27**	19%	15	3.11	0	**4**	65%
16	1.87	1	**9 4**	52%	16	2.87	1	**1 12**	47%
17	1.88	1	**9 29**	20%	17	2.36	0	**48**	56%
18	1.59	0	**21**	26%	18	2.23	0	**10**	28%
19	1.51	0	**23**	25%	19	2.14	1	**1 13**	36%
20	1.48	1	**9 21**	24%	20	1.77	0	**8**	21%

NO_x emissions

Nitrogen oxides, NO_x, is the generic term for a group of highly reactive, acidifying gases, all of which contain nitrogen and oxygen in varying amounts. Nitrogen oxides also contribute to stratospheric ozone layer depletion and global warming. NO_x forms when fuel is burned at high temperatures in a combustion process. Therefore, the primary sources of NO_x are motor vehicles, electric utilities, and other industrial, commercial, and residential equipment that burns fuels. The total amount of NO_x released in Spain in 2000 was 1.35Mt, 6.3% more than in 1990. There are various direct emitters of NO_x (see Table 1), the most important being Manufacture of cement **25**, Maritime Transport **47**, and Production and distribution of electricity, steam and hot water **9**, due to their burning of fuel and oil. Important first order indirect NO_x emissions are embedded in the oil and gas purchased respectively by Coke, refinement and nuclear fuels **8** and Production and distribution of gas **10** from the Petroleum Crude and Natural Gas Extraction sector **5**. The food processing industries, **12** to **16**, due to their inputs from Agriculture **1**, show also important first order indirect emissions. The main contributor to the agricultural NO_x emissions is the combustion of fuel in farm equipment.

NMVOC emissions (No Methane Volatile Organic Compounds)

No Methane Volatile Organic Compounds are organic compounds of anthropogenic nature, other than methane, that are capable of producing photochemical oxidants by reactions with nitrogen oxides in the presence of sunlight. The main VOC of interest are those with eight or less carbon atoms per molecule as these are the most reactive in the atmosphere. They are precursors of ground level ozone formation. In most areas, domestic home heating and motor vehicles are estimated to be the main contributors to VOC emissions. Other sources include housekeeping and maintenance products, and building and furnishing materials, such as solvents, paints, and glues. They also appear in agricultural burns, gasoline pumps, and forestall fires. In Spain, the most important on site polluter is the Forestry sector **2** with a contribution of 42% to the total national NMVOC emissions, that in 2000 totalized 2.02Mt. As Table 2 shows, there are important input paths of NMVOC pollution generated by sector 2; e.g., the most important NMVOC emissions from the Wood and cork industry **20** and Paper industry **21** are due to the use of wood supplied by the Forestry sector **2**. Other important pollution path originating from **2** is Forestry **2** into Wood and cork industry **20** into Furniture and other manufacturing industries **38**.

<u>CH_4 emissions</u>

Methane is a potent greenhouse gas; it traps over 21 times more heat per molecule than carbon dioxide. Anthropogenic sources of CH_4 include landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes. The Spanish emissions of methane increased by 26.3% from the 1990 level, totalizing an amount of 1.8Mt in 2000, manly due to agriculture activities, manure management, landfill sites and mining. The results presented in Table 2 rank the services sectors **61** and **67**, which include activities of waste management, as having the greatest on site intensities, followed by Agriculture **1** and the Mining sector **4**. It is important to note however that in terms of total amounts of emissions Agriculture **1** is the largest CH_4 on-site polluting sector in Spain. However, its high monetary output places its CH_4 intensity in the fifth position in table 2.

Table 2. Top 20 paths for NMVOC and CH_4 emissions in Spanish economy

Paths for the NMVOC emissions					**Paths for the CH_4 emissions**				
Rank	Path Value (t/€)	Path order	Sectors	% from the total multiplier	Rank	Path Value (t/€)	Path order	Sectors	% from the total multiplier
1	1157.48	0	**2**	99%	1	117.60	0	**61**	97%
2	66.30	1	**2 20**	64%	2	115.84	0	**67**	63%
3	31.46	1	**2 21**	67%	3	48.09	1	**61 67**	26%
4	22.52	2	**2 20 20**	22%	4	37.06	0	**4**	98%
5	12.65	0	**1**	69%	5	31.08	0	**1**	84%
6	10.80	2	**2 20 38**	46%	6	16.60	1	**1 12**	70%
7	8.32	2	**2 21 21**	18%	7	12.57	1	**67 67**	7%
8	7.76	2	**2 21 22**	44%	8	12.40	1	**1 13**	71%
9	6.75	1	**1 12**	46%	9	8.90	1	**1 14**	61%
10	6.41	1	**2 24**	54%	10	6.43	1	**1 16**	67%
11	5.24	0	**32**	47%	11	5.70	0	**10**	76%
12	5.04	1	**1 13**	37%	12	5.22	2	**61 67 67**	3%
13	5.00	0	**5**	84%	13	4.33	1	**4 9**	79%
14	4.42	0	**61**	73%	14	2.96	1	**1 1**	8%
15	4.35	0	**67**	49%	15	2.51	1	**1 15**	45%
16	4.14	0	**68**	72%	16	2.36	2	**1 12 12**	10%
17	3.62	1	**1 14**	32%	17	2.35	0	**5**	88%
18	3.41	1	**5 8**	63%	18	1.71	2	**1 14 14**	12%
19	3.21	1	**5 10**	49%	19	1.61	1	**5 8**	69%
20	3.11	0	**16**	27%	20	1.58	2	**1 1 12**	7%

Note as well the significant first and higher order paths emerging from the use of agricultural products (mostly from cattle and sheep farming) in the food manufacturing industries (**12** to **16**). In addition to the polluting effects of the tracks transporting feedstuffs, cattle and meat products, cattle contribute directly to the enhanced greenhouse effect because of the methane they produce. On average, each animal produces 48kg CH_4/year through fermentation in the stomach and gut. Cattle manure also emits greenhouse gases — a further kg CH_4/animal and 0.2kg of nitrous oxide, a persistent greenhouse gas.

CO emissions

CO contributes to the formation of ground-level ozone (smog) and indirectly increases the global warming by being oxidized to carbon dioxide or by reacting with hydroxyl radicals, which otherwise would destroy methane. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Direct sources of CO include industrial processes, transportation activities, biomass burning and biogenic activity (both in soils and oceans). Over the decade 1990-2000, the total Spanish emissions of CO decreased by 24%. The main decrease was registered in the transport sectors (44 to 48) that lowered their CO emissions by 36% from 1990, emitting 208.4kt in 2000. The reduction of CO emissions in spite of the increasing number of vehicles is explained by an increased efficiency of the new cars engines, the improved catalysts these use and by the increasing use of alternative fuels. The biggest contribution to the national direct CO emissions come from Metallurgy **29** and Agriculture **1** that emit respectively 30.7% and 22.7% of the direct CO emissions. As presented in Table 3, Petroleum Crude and Natural Gas Extraction **5** has the highest on-site intensity and induces important indirect emissions in Coke, refinement and nuclear fuels **8** and Production and distribution of gas **10**. Note the important indirect intensities of Manufacture of metallic products **30** and Manufacture of machinery and electrical material **33** because of the embodiment of CO emissions in the products they buy from Metallurgy **29**.

CO_2 emissions

In 2000, the total Spanish CO_2 emissions totalled 383.8Mt, representing an increase of 97.4Mt from 1990. With 82.2% of the total net greenhouse gas emissions coming from CO_2 emissions, CO_2 contributes with the largest share to the anthropogenic greenhouse effect. The 34% increase of CO_2 emissions over the period 1990-2000 represents however 19% more than the Kyoto target established for 2012. Carbon dioxide is released to the atmosphere when fossil fuels (oil, natural gas, and coal), solid waste, and wood and wood products are burned. The main industrial sectors contributing to the release of CO_2 are the manufacturing sectors and the production of electricity sector. Transport intensities are also significant in Spain (see Table 3). The top on-site CO_2 intensities come from the manufacturing industries **25** to **28**, Forestry **2**, Production and distribution of electricity, steam and hot water **9**, and the transport sectors **45** to **49**. The high CO_2 intensity of Manufacture of cement **25** is explained by the high emission factor for clinker in Spain (0.540tCO_2/kt compared to the IPCC[14] default of 0.507tCO_2/kt clinker produced) combined with a relatively low industry output.

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[14] IPCC stands for Intergovernmental Panel on Climate Change, an organization that evaluate the risks of climate change brought on by humans, based mainly on peer reviewed and published scientific/technical literature.

Table 3. Top 20 paths for CO and CO_2 emissions in Spanish economy

Paths for the CO emissions					**Paths for the CO_2 emissions**				
Rank	Path Value (t/€)	Path order	Sectors	% from the total multiplier	Rank	Path Value (kt/€)	Path order	Sectors	% from the total multiplier
1	31.16	0	**5**	94%	1	12.80	0	**25**	94%
2	25.11	0	**29**	70%	2	5.69	0	**2**	98%
3	21.27	1	**5 8**	87%	3	5.24	0	**9**	85%
4	20.11	1	**5 10**	89%	4	1.95	1	**25 28**	73%
5	18.07	0	**25**	83%	5	1.10	0	**5**	83%
6	12.12	0	**68**	94%	6	0.92	0	**47**	71%
7	11.44	0	**6**	71%	7	0.91	0	**8**	46%
8	10.28	0	**1**	71%	8	0.90	0	**3**	71%
9	8.47	0	**16**	59%	9	0.88	0	**6**	64%
10	7.24	0	**2**	89%	10	0.87	0	**26**	61%
11	6.43	1	**29 30**	50%	11	0.86	0	**29**	47%
12	5.48	1	**1 12**	49%	12	0.77	0	**16**	59%
13	4.77	0	**39**	41%	13	0.73	1	**5 8**	37%
14	4.52	1	**29 33**	45%	14	0.69	1	**5 10**	63%
15	4.10	1	**1 13**	45%	15	0.68	0	**48**	62%
16	3.72	1	**29 29**	10%	16	0.65	0	**46**	72%
17	3.48	0	**7**	47%	17	0.61	0	**4**	57%
18	3.28	0	**47**	48%	18	0.47	0	**27**	42%
19	3.04	0	**21**	39%	19	0.46	0	**21**	33%
20	2.94	1	**1 14**	35%	20	0.43	1	**9 11**	48%

N_2O emissions

Nitrous oxide is a persistent greenhouse gas that results from the use of ammonia-fertilizers and from some industrial processes at high temperatures (e.g. nylon and plastic production). In Spain, Agriculture **1** is the largest source of nitrous oxide emissions, primarily from fertilizer application and land conversion to agricultural use (91%) and also from manure management (8%). Emissions of N_2O from agricultural sources in 2000 were estimated at 34kt, representing 38% of the national emissions.

Table 4. Top 20 paths for N_2O and NH_3 emissions in Spanish economy

Paths for the N_2O emissions					**Paths for the NH_3 emissions**				
Rank	Path Value (t/€)	Path order	Sectors	% from the total multiplier	Rank	Path Value (t/€)	Path order	Sectors	% from the total multiplier
1	1.57	0	**1**	83%	1	12.72	0	**1**	84%
2	0.84	1	**1 12**	69%	2	6.79	1	**1 12**	72%
3	0.74	1	**61**	94%	3	5.08	1	**1 13**	75%
4	0.73	1	**67**	61%	4	3.64	1	**1 14**	64%
5	0.63	1	**1 13**	71%	5	2.63	1	**1 16**	75%
6	0.44	0	**1 14**	60%	6	1.21	1	**1 1**	8%
7	0.34	0	**25**	88%	7	1.03	1	**1 15**	53%
8	0.32	0	**1 16**	68%	8	0.97	2	**1 12 12**	10%
9	0.30	0	**61 67**	25%	9	0.70	2	**1 14 14**	12%
10	0.27	0	**23**	64%	10	0.65	2	**1 1 12**	7%
11	0.25	1	**27**	80%	11	0.55	2	**1 14 1**	4%
12	0.15	2	**1 1**	9%	12	0.53	2	**1 1 13**	7%
13	0.14	0	**9**	72%	13	0.49	0	**23**	60%
14	0.13	0	**1 15**	44%	14	0.47	2	**1 13 13**	7%
15	0.12	0	**1 12 12**	10%	15	0.46	2	**1 12 19**	34%
16	0.10	0	**5**	81%	16	0.35	2	**1 1 14**	6%
17	0.09	0	**8**	49%	17	0.34	1	**1 20**	45%
18	0.08	0	**1 14 14**	12%	18	0.30	2	**1 1 16**	7%
19	0.07	0	**5 8**	35%	19	0.25	2	**1 16 16**	7%
20	0.07	0	**1 17**	29%	20	0.22	2	**1 12 44**	19%

The results we present in Table 4 indicate also important direct intensities from the waste processing sectors **61** and **67**, Chemical Industry **23**, and manufacturing sectors **25** to **28**. The food manufacturing sectors **12** to **16** have important indirect intensities because of their purchases from Agriculture **1**, especially meat and milk.

NH_3 emissions

Ammonia, one of the major agents of acid rain, comes mostly from manure, both before mucking out and when the manure is stored or spread. Manure and urine from livestock and pasture also emit ammonia into the atmosphere. Smaller quantities of ammonia are emitted from agricultural land treated with commercial fertilizer. Altogether, agriculture accounts for about 94% of Spanish's direct ammonia emissions that in 2000 totalized 462kt. Note the important indirect intensities expressed by higher order paths deriving from Agriculture, e.g. emissions from the food processing sectors **12** to **16**, (see Table 4). These emissions represent almost 50% of the total Spanish ammonia emissions and are due to the use of agricultural products as raw materials for the food processing industries.

SF_6, HFC and PFC emissions

The total amount of fluorocarbon gases (fluorocarbons (HFC), perfluorocarbon (PFC), and sulphur hexafluoride (SF_6)) emitted by Spain during 2000 summed up 2.85Mt CO_2 equivalents, representing an increase of 1.3Mt from 1995. They are potent industrial greenhouse gases with no natural sources, and deliberately manufactured, mostly for use in refrigeration and air conditioning. The trajectory of the three gases was different over the period 1995-2000: the SF_6 and HFC emissions increased by 109% and 425.4% respectively, meanwhile PFC emissions decreased by 51.5%. The most significant group are the HFCs, widely promoted from the early 1990s by the chemical industry as a substitute for their chlorine-containing gases CFCs and HCFCs. Spain is an important HFC polluter in Europe, in 2000 it emitted 17.54% of the European Union HFC emissions. Our results (see Table 5) point to the Chemical Industry **23** as the industry responsible for most of the HFC input paths. Over 60% of HFC emissions result from routine leaks from refrigeration and air conditioning. Manufacture of machinery and electrical material **33** and Metallurgy **29** are the sectors responsible for most of the SF_6 and PFC pollution paths respectively.

3.2 *Summary and discussion of the results*

In Section 3.1 we analysed each atmospheric pollutant, determining its main direct and indirect sources and the chains through which pollution is transmitted. In this section we resume and reorganize these results, focusing on the sectors which compose the Spanish economy, analysing their emissions distribution and contribution to the national emissions.

Table 6 shows the main contributions by type of pollutant of Spanish economic sectors to the national direct emissions. Each term in Table 6 represents the contribution of each sector, or group of sectors (represented in rows) to the direct Spanish emissions of the pollutants represented in columns. For example, in the row of Chemical Industry **23**, we read that it is the only source of HFC in Spain and it emits 5.33% from the direct emissions of N_2O. A further analysis of Table 6, reveals that the main contributors to the direct Spanish emissions are the group of manufacturing industries **25** to **28**, Agriculture **1** and the transportation sectors **45** to **49**, the energetic sectors **9**, **10**, and the group of services **61-69**.

Table 5. Top 20 paths for polifluoro compounds emissions in the Spanish economy

Paths for SF_6 emissions					**Paths for HFC emissions**				
Rank	Path Value (kg/€)	Path order	Sectors	% from the total multiplier	Rank	Path Value (kg/€)	Path order	Sectors	% from the total multiplier
1	0.73	0	**33**	82%	1	17.21	0	**23**	74%
2	0.12	1	**33 33**	14%	2	4.16	1	**23 23**	18%
3	0.08	1	**33 34**	49%	3	4.13	1	**23 24**	60%
4	0.08	1	**33 35**	56%	4	2.35	1	**23 17**	48%
5	0.07	1	**33 31**	71%	5	1.62	1	**23 26**	60%
6	0.05	1	**33 32**	49%	6	1.25	1	**23 66**	66%
7	0.03	2	**33 34 34**	19%	7	1.20	1	**23 6**	57%
8	0.02	2	**33 33 33**	2%	8	1.01	2	**23 23 23**	4%
9	0.02	1	**33 37**	43%	9	1.00	2	**23 23 24**	15%
10	0.02	1	**33 40**	56%	10	0.98	1	**23 7**	58%
11	0.02	2	**33 34 35**	13%	11	0.95	1	**23 1**	50%
12	0.02	1	**33 36**	36%	12	0.82	2	**23 17 18**	33%
13	0.02	2	**33 32 32**	15%	13	0.77	1	**23 29**	39%
14	0.01	2	**33 33 34**	8%	14	0.74	1	**23 60**	63%
15	0.01	2	**33 33 35**	9%	15	0.73	1	**23 11**	57%
16	0.01	2	**33 33 31**	12%	16	0.68	1	**23 21**	40%
17	0.01	2	**33 33 32**	8%	17	0.62	1	**23 27**	44%
18	0.01	1	**33 9**	55%	18	0.61	1	**23 24 24**	9%
19	0.01	2	**31 33 6**	47%	19	0.54	1	**23 37**	25%
20	0.01	2	**33 36 36**	14%	20	0.51	1	**23 1 12**	29%

Table 5. Top 20 paths for polifluoro compounds emissions in the Spanish economy (continuing)

Paths for SF_6 emissions				
Rank	Path Value (kg/€)	Path order	Sectors	% from the total multiplier
1	3.16	0	**29**	79%
2	0.81	1	**29 30**	67%
3	0.57	1	**29 33**	59%
4	0.47	1	**29 29**	12%
5	0.36	1	**29 37**	50%
6	0.33	1	**29 36**	38%
7	0.30	1	**29 31**	44%
8	0.21	1	**29 38**	54%
9	0.18	2	**29 30 39**	34%
10	0.14	1	**29 39**	32%
11	0.13	1	**29 32**	30%
12	0.12	2	**29 36 36**	15%
13	0.11	2	**29 29 30**	10%
14	0.10	2	**29 30 29**	3%
15	0.10	1	**29 34**	22%
16	0.09	1	**29 28**	41%
17	0.09	2	**29 33 33**	10%
18	0.08	2	**29 30 31**	14%
19	0.08	1	**29 35**	25%
20	0.08	2	**29 29 33**	9%

In terms of total emissions (sum of direct and indirect emissions) the ranking presented in Table 6 changes, other sectors, or group of sectors, occupying top positions because of their important indirect emissions. In Table 7 we represent the contribution of each sector, or group of sectors (represented in rows) to the total Spanish emissions of the pollutants represented in columns. The most important polluting sectors in this classification are the group of other manufacturing industries **30** to **39** and food industries **12** to **16**, followed by the manufacturing industries **25** to **28** and the energetic sectors **9** and **10**.

Table 6. Contribution by type of emission of Spanish sectors to the national direct emissions (% from direct multipliers)

No. sector	**Emission type/ sectors**	**SO_x**	**NO_x**	**NMVOC**	**CH_4**	**CO**	**CO_2**	**N_2O**	**NH_3**	**SF_6**	**HFC**	**PFC**
1	Agriculture	0.28	3.33	1.02	**9.90**	**5.69**	0.72	**31.59**	**93.13**	0.00	0.00	0.00
2	Forestry	0.18	3.61	**93.71**	0.02	4.00	**14.94**	0.46	0.13	0.00	0.00	0.00
8	Coke extraction	0.30	4.78	0.40	0.75	**17.24**	2.82	2.01	0.48	0.00	0.00	0.00
9-10	Energetic sectors	**49.12**	**12.44**	0.22	1.82	1.09	**14.31**	2.90	0.01	0.00	0.00	0.00
12-16	Food Manufacturing industries	0.34	6.01	0.54	0.24	**6.52**	2.55	0.31	0.03	0.00	0.00	0.00
23	Chemical Industry	1.04	0.50	0.21	0.08	0.53	0.95	**5.33**	3.41	0.00	**100**	0.00
25-28	Manufacturing industries	**24.42**	**22.04**	0.09	0.10	**11.99**	**37.25**	**13.82**	0.07	0.00	0.00	0.00
29	Metallurgy	2.34	1.00	0.12	0.08	**13.89**	2.25	1.27	0.10	0.00	0.00	**100**
30-39	Other Manufacturing industries	0.69	3.84	0.91	0.03	**6.45**	1.72	0.97	0.19	**100**	0.00	0.00
45-49	Transport	**8.85**	**16.67**	0.33	0.11	**5.33**	**7.15**	1.88	0.10	0.00	0.00	0.00
61-69	Services	1.03	2.44	1.16	**74.38**	**9.93**	1.93	**31.11**	1.46	0.00	0.00	0.00
Remaining sectors		11.41	23.32	1.27	12.49	17.35	13.40	8.34	0.89	0.00	0.00	0.00
TOTAL		100	100	100	100	100	100	100	100	100	100	100

Comparing the results in Tables 6 and 7, we can see that in the Spanish economy direct emissions are dominant in primary production sectors **1**, **9**, **10** and **25** to **29**, meanwhile indirect emissions are significant in processing sectors **12** to **16** and **30** to **39**, due to their significant intermediate consumption. This type of results is helpful to give information on the polluting sectors in an economy. However, for an efficient decision making at national level, these results are too aggregated and difficult to apply for concrete actions. Therefore, to help policy measures aimed at decreasing pollution in Spain, we suggest complementing these generic results with data as those presented in Tables 1-5, which allow understanding the mechanism of pollution creation and propagation in the Spanish economy. For instance, from the aggregated data in Table 6 it comes out that the group of food industries **12** to **16** has a small contribution to the national direct emissions and only for 1 out of 11 pollutants: CO_2. Nevertheless, in Table 7 we can see they become one of the most polluting groups for 7 out of 11 pollutants in terms of their contribution to the total national emissions. This is explained by the important indirect emissions associated with the activity of food processing industries, that is, due to their significant intermediate consumption.

The question is now: who is providing the food sectors with inputs for their production? In Tables 1 to 5, we can see that Agriculture **1** is a selling sector to the food processing sectors and, therefore, the "hidden" contributor to the high total emissions of the food processing industries.

Table 7. Contribution by type of emission of Spanish sectors to the national total emissions (% from total multipliers)

No. sector	**Emission type/ sectors**	**SO_x**	**NO_x**	**NM VOC**	**CH_4**	**CO**	**CO_2**	**N_2O**	**NH_3**	**SF_6**	**HFC**	**PFC**
1	Agriculture	0.78	2.53	1.1	**7.07**	3.02	0.96	**14.3**	**27.2**	0.26	1.88	0.49
2	Forestry	0.23	2.03	**69.85**	0.12	1.69	**7.93**	0.44	0.4	0.11	0.38	0.17
8	Coke extraction	0.58	2.8	0.36	0.51	**6.9**	1.78	0.93	0.19	0.2	0.41	0.45
9-10	Energetic sectors	**24.1**	**9.48**	0.53	2.46	**5.93**	**9.91**	2.14	0.21	0.89	0.62	0.8
12-16	Food Manufacturing industries	4.21	**10.32**	3.66	**13.4**	**10.1**	**5.44**	**27.2**	**49.6**	1.51	**7.25**	2.63
23	Chemical Industry	1.85	1.19	0.51	0.33	1.21	1.52	3.12	1.4	0.57	**23.3**	0.8
25-28	Manufacturing industries	**17**	**16.71**	0.98	0.74	**8.62**	**25.9**	**7.41**	0.7	2.3	**5.41**	3.91
29	Metallurgy	2.8	1.93	0.31	0.36	**7.44**	2.5	1.15	0.26	0.9	1.96	**26.7**
30-39	Other Manufacturing industries	**10.7**	**9.26**	4.01	1.57	**17.7**	**9.28**	**5.49**	2.43	**77.1**	**15.7**	**43.9**
45-49	Transport	**7.27**	**11.32**	0.88	0.58	**5.13**	**6.37**	2.15	0.81	1.47	2.09	2.24
61-69	Services	4.79	4.04	1.96	**59.3**	**6.5**	4.15	**17.4**	2.35	2.49	**5.72**	2.23
Remaining sectors		25.66	28.39	15.85	13.57	25.77	24.3	18.2	14.3	12.2	35.24	15.68
TOTAL		100	100	100	100	100	100	100	100	100	100	100

When interpreting these results it is important to keep clear in mind that we calculated the amount of pollutants embedded in the Spanish commodities that are delivered to the final demand. In other words, we have not calculated the impacts associated with the production of economic sectors, but with the products or services these sectors sell to the final demand. This means that the sectors with a small final demand will have important intensities of emissions, although they could have small contribution to the total emissions or vice versa: sectors with an important final demand will have small intensities although big contributions to total emissions. To see the difference of using one or the other approach (intensities vs. total embodiments of pollution), let us consider the case of greenhouse gases (GHG), in Figure 2.

To calculate the intensities of emission of key GHG (CO_2, CH_4, N_2O, SF_6, HFC and PFC), we converted the emissions of various gases to carbon dioxide equivalents considering the estimates of global warming potentials of these published in the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC (2001). Analysing Figure 2, we see that the Manufacture of cement, lime and plaster **25** has the biggest intensity of emission of GHG. It is followed by the Anthracite, coal, lignite and peat extraction **4**, Electricity production and distribution **9** and Forestry **2**. As it can be seen, the biggest amount of GHG is released on site.

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INPUT-OUTPUT ANALYSIS FOR USE IN LIFE CYCLE ASSESSMENT: INTRODUCTION TO REGIONAL MODELLING
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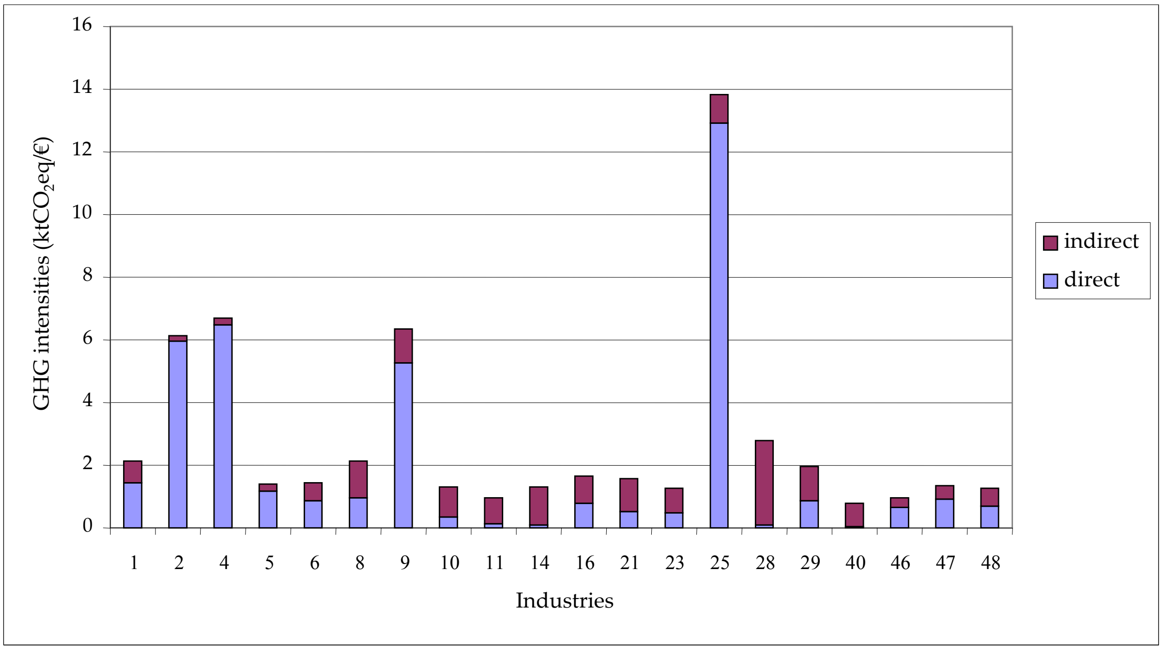

Figure 2. GHG intensities: top 20 polluting sectors

Let us analyse now the case of the total embodiments of GHG represented in Figure 3. Compared to intensities, the ranking changes and the most important polluting sector becomes the Electricity production and distribution **9** followed by Agriculture **1** and the Manufacture of cement, lime and plaster **25**. The explanation of this change is the high final demand of sectors **1** and **9** that implies smaller intensities of emission of these two sectors. At the same time, the small final demand of cement (sector **25**) implies a bigger intensity of GHG emission. Figure 3 also shows bigger indirect emissions. To determine the cause of these indirect GHG emissions, tables similar to Tables 1 to 5 should be constructed.

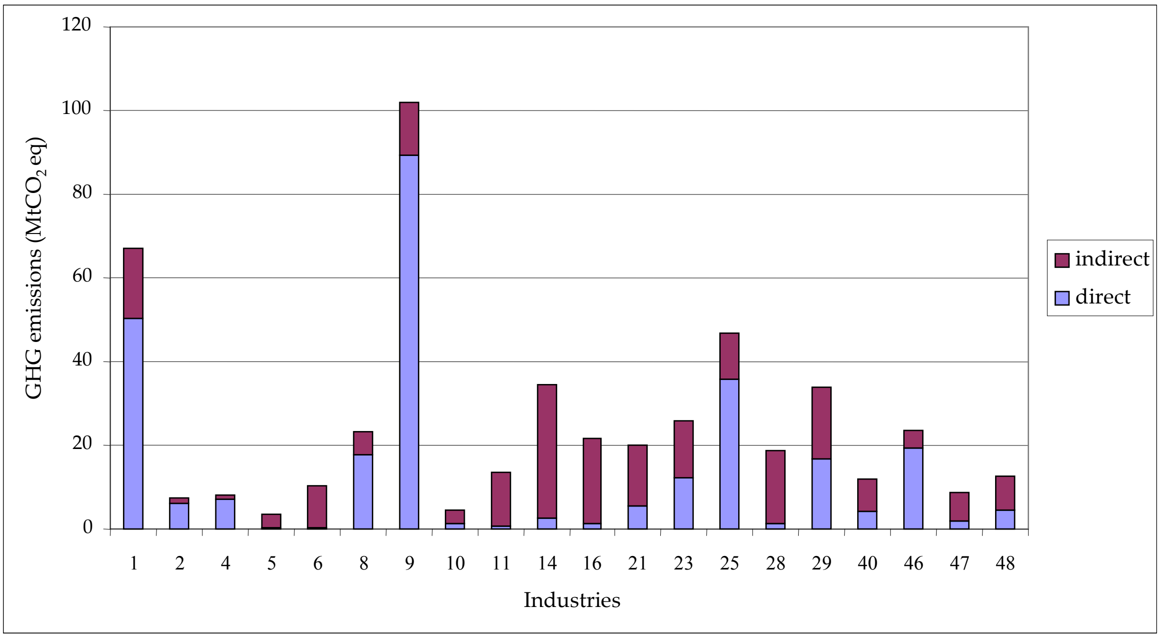

Figure 3. GHG total embodiments: top 20 polluting sectors

Although the method we have presented is easy to use, it has some limitations that should be considered. The linearity of the IO model to calculate the environmental burdens (linear inter-industry interactions, proportionality between the production and the emission of a productive sector), the estimations at national level, data availability and data quality are some of the issues that should be considered when using the results. Some pollutants have effect at local level (CO, NMVOC), suggesting that local policies would be more effective for their reduction. The aggregation of data used for calculations may lead to under/overestimations; e.g. within sector **67** (Other community, social and personal service activities; no market) are considered all the services of waste collection, treatment and disposal indifferently of the waste type. We did not consider the imports in our estimations. For the Spanish economy in which the imports for sectors as Coke, refinement and nuclear fuels **8**, Chemical industry **23**, Manufacture of motor vehicles and trailers **36** or Construction **40** are important, the national GHC balances can be considerably influenced by the inclusion of imports or the exclusion of exports.

Regarding the generalized IO model we used to calculate the sectoral burdens, we improved it compared to the previous Spanish studies by considering the disaggregation of economy in 70 sectors and not only 17 as in the works of Anton Valero *et al.* (1993), Cadarso and Fernández-Bolaños (2002) and Velázquez (2006), or 56 sectors as previously did in Sánchez-Chóliz and Duarte (2004). Although the quantity of results to interpret is bigger in our case, the results are more detailed, permitting to identify the responsible polluting industries and not a generic group containing similar industries. Further improvements may be brought by increasing the number of industries in the national classification and making the analysis at local or regional level, avoiding the aggregation as much as possible.

4. Conclusions

This chapter calculates the direct and indirect atmospheric emissions associated with the activities of the Spanish economy and detects key sectors and important input paths of air pollution in Spain. The incorporation of the embedded emissions associated with the delivery of a good or service is essential to assist pollution abatement policies since it identifies otherwise hidden pollution drivers. This is particularly true when considering the reduction of HFC, PFC and NH_3 emissions, which are driven by the manufacturing sectors. For other pollutants such as NMVOC and CH_4, most of the emissions can be attributed to on-site sources.

The analysis presented in this chapter reallocates pollution emissions from the on-site producer to the sectors delivering to final demand, following a standard Leontief approach. Knowledge of the final demanders' profile, such as household composition and income, can be easily incorporated to this model to analyse the contribution of the various groups of Spanish consumers to the generation of pollution. An analysis of this type for a group of selected environmental burdens can be found in Sánchez-Chóliz *et al.* (2005). It is important to notice that when seeking to describe the effect of producing sectors on production factors, the classical Leontief model is incomplete because it only accounts for the fraction of industrial output that is delivered into final demand. In order to take into account full industrial outputs while conserving the desirable accounting properties of the classical input-output framework, the introduction of shared producer-consumer responsibility is required, see Gallego and Lenzen (2005) and Lenzen *et al.* (2006).

CHAPTER III

COMPOSITION OF GREENHOUSE GAS EMISSIONS IN SPAIN: AN INPUT-OUTPUT ANALYSIS

Butnar, I. and M. Llop. Ecological Economics 61(2-3), 388-395 (2007).

Abstract

Extending the traditional input-output model to account for the environmental impacts of production processes reveals the channels by which environmental burdens are transmitted throughout the economy. In particular, the environmental input-output approach is a useful technique for quantifying the changes in the levels of greenhouse emissions caused by changes in the final demand for production activities. The input-output model can also be used to determine the changes in the relative composition of greenhouse gas emissions due to exogenous inflows. In this chapter we describe a method for evaluating how the exogenous changes in sectorial demand, such as changes in private consumption, public consumption, investment and exports, affect the relative contribution of the six major greenhouse gases regulated by the Kyoto Protocol to total greenhouse emissions. The empirical application is for Spain, and the economic and environmental data are for the year 2000. Our results show that there are significant differences in the effects of different sectors on the composition of greenhouse emissions. Therefore, the final impact on the relative contribution of pollutants will basically depend on the activity that receives the exogenous shock in final demand, because there are considerable differences in the way, and the extent to which, individual activities affect the relative composition of greenhouse gas emissions.

Keywords: Greenhouse emissions, composition of emissions, sectorial demand, exogenous shock.

1. Introduction

In recent decades, environmental pollution has received the attention of both economists and ecologists who have integrated their ideas and concepts. This integration has yielded a consistent framework that accounts for how pollution is generated and provides measures for controlling it. In an economic system, both agents and sectors process materials and energy to produce and consume goods and services. At the same time, production and consumption generate residuals that are disposed of in the environment. In other words, the residuals are the normal outcome of economic activity.

The Kyoto Protocol on climate change specifies targets for emissions of greenhouse gases, which will have to be reached by the signatory countries in the period 2008-2012. The importance of this agreement makes it necessary to accurately analyse the patterns of greenhouse emissions, and also makes it necessary to define and establish the national policy measures and the environmental regulations that will reduce greenhouse emissions.

The input-output model is a framework that analyses environmental impacts by integrating both economic and technical relations that take place within the production system. It is a general tool for calculating such environmental consequences as energy consumption, water use, land disturbance and pollution generation, caused by the activities of production. The Leontief approach, which emphasises the interdependencies among industries and sectors, is the basis for estimating the environmental effects of the changes in the elements that are external determinants of the input-output system. Although the external elements basically depend on the objective of the analysis, the conventional approach exogenously introduces all the components that make up the final demand of production activities (that is, private consumption, public consumption, investment, and exports to foreign markets).

Several recent contributions have used the input-output model to account for the greenhouse emissions and the energy embodiments of production processes. Ostblom (1998) evaluated the Swedish emissions of carbon dioxide, sulphur oxide and nitrogen oxide and analysed the results from the point of view of Sweden's environmental goals and the medium-term economic projections for economic growth. Lenzen (2001) constructed a generalized input-output model in which capital investment and imports were separated from final demand and internalized into intermediate demand, and presented an empirical application of the Australian energy multipliers. In 2002, he went on to decompose the Australian environmental input-output multipliers by using structural path analysis. This decomposition revealed the environmentally important input paths within pollution emissions, energy consumption and resource uses in the Australian production system. Recently, Lenzen et al. (2004) constructed a multi-region input-output model, which was used to calculate pollution generation, and the CO_2 multipliers for five European countries, taking into account the greenhouse gases embodied in international trade operations.

The first application for Spain was in Pajuelo (1980), which studied atmospheric pollution through an extended Leontief model that included atmospheric pollutants as a part of the production processes. Alcántara and Roca (1995) presented an input-output model to analyse the primary energy requirements and CO_2 emissions in Spain, during the period 1980-1990. More recently, Cadarso and Fernández-Bolaños (2002) calculated the total emissions in Spain during the period 1980-1995. They included private consumption emissions in the matrix of emission multipliers, and considered consumption as another category of pollutant commodities. Butnar et al. (2007) proposed a different method for analysing Spanish pollutant emissions. They calculate emissions with a generalized input-output model which determines the key sectors and the input paths of air pollution, and decomposes the global multipliers by structural path analysis. Rodríguez et al. (2007) used a multisectorial model to make an environmental and economic analysis on the basis of a social accounting matrix for Spain, with data for the year 2000. In this chapter, the calculation of the generalised multipliers reveals both the environmental and the economic efficiency of Spanish production activities.

The environmental input-output approach, which has always been used to study the patterns that explain the total emissions in an economy, can also be used to analyse the relative contribution of every type of pollutant to the total amount of emissions. However, the literature on environmental input-output models contains no references to the relative composition of emissions. In this field, the use of the Leontief framework to analyse not only the total emissions but also their relative composition, in terms of types of pollutants, will provide additional knowledge so that greenhouse abatement policies can be designed and the levels of emissions specified by the Kyoto Protocol reached.

The objective of this chapter is to adapt the conventional Leontief model in such a way that it will be able to calculate the changes in the composition of greenhouse emissions under exogenous shocks in sectorial demand. Specifically, we provide a method that measures the relative composition of greenhouse pollution and analyses how the exogenous inflows in final demand of activities (consumption, government expenditure, investment and exports) modify the relative importance of every pollutant within the total greenhouse emissions. With this approach, therefore, we further analyse pollution generation and provide valuable information about the processes of greenhouse gas emissions. We apply this analytical context to Spain, using both economic and environmental information for the year 2000. The greenhouse emissions we consider are the six major greenhouse gases regulated by the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6).

This chapter helps to understand the factors that underlie the generation of pollution within the production system. How changes in private consumption, public expenditure, investment, and exports affect the emission of greenhouse gases and their relative composition is an interesting question for environmental analysis. The approach we present here extends our knowledge of the economic-ecologic relationships that take place within the production sphere, and this may help to define and implement successful environmental policies.

Our results show that the emission multipliers for the six major greenhouse gases in Spain are very different in terms of quantities, and depend on such factors as the sector of activity and the type of gas analysed. The results also show different sectorial effects of exogenous shocks on the composition of emissions, depending on the activity that receives the inflow in demand. The changes in sectorial demand have opposite effects on the relative contribution of gases, and this suggests that the impacts on the components of emissions under modifications to sectorial demand are substitutive.

The rest of the chapter is organised as follows. Section 2 describes the environmental input-output model and presents the measurements of the composition of greenhouse emissions. Section 3 describes the databases used in the application to Spain and section 4 contains the empirical results. At the end of the chapter we provide some concluding remarks.

2. Modelling the composition of greenhouse emissions

The analytical framework that accounts for the composition of emissions is based on the input-output approach. The standard representation of the input-output model, in matrix notation, can be defined as follows:

$$X = AX + Y = (I - A)^{-1} Y, \qquad (1)$$

where X is the vector of final production in every sector, Y is the vector of final demand (and includes private consumption, public consumption, investment and exports to foreign markets), A is a matrix of technical coefficients (calculated by dividing the industry-by-industry direct requirements of sectorial inputs by the sectorial production) and, finally, I is the identity matrix. The multiplier analysis assumes that the technical input-output coefficients are constant, so matrix A does not vary. In expression (1), $(I - A)^{-1}$ is the matrix of input-output multipliers and shows the overall effects (direct and indirect) on sectorial production caused by unitary and exogenous changes in the final demand of sectors.

The input-output model can be extended to account for the environmental pollution associated with activities of production. Let B be the matrix of sectorial greenhouse emissions per unit of output, in which each element is the amount of gas type i (in physical units) per monetary unit of final production in activity j. The sectorial greenhouse emissions associated with a given level of final demand can then be calculated as follows:

$$F = B(I - A)^{-1} Y, \tag{2}$$

where F is the vector of i greenhouse emissions. As the different gases are measured in different units, to allow for comparisons and global estimations, we rescale matrix B to express all the emissions in common units, which are *carbon dioxide equivalents* (CO_2 eq.). This is determined by multiplying the amount of a particular gas emitted by the global warming potential of the gas (that is, its ability to absorb heat in the atmosphere). We considered that methane has a warming potential of 21 and nitrous oxide of 310. For the group of fluorocarbon gases, we used the 2002 averages: for PFC 7182, for HFC 1732 and for SF_6 23900. So, vector F will contain the total emissions of the different types of greenhouse gases measured in the common units of carbon dioxide equivalents.

Following expression (2), the changes in the amount of sectorial emissions (dF) caused by exogenous changes in the final demand of activities (dY) can be calculated as:

$$dF = B(I - A)^{-1} dY, \tag{3}$$

Expression (3) captures the entire sequence between the exogenous shocks in sectorial demand and the resulting impacts on total pollutant emissions. Following the logic of the input-output model, new demand increases the sectorial production and, at the same time, increases the level of emissions. The elements in matrix $B(I - A)^{-1}$ are the *emission multipliers* that measure the amount of type i emissions caused by exogenous and unitary inflows to the final demand of sector j. Therefore, this approach makes it possible to analyse how changes in the demand of activities, for instance an increase or decrease in consumption, investment and exports, affect the amount of greenhouse emissions. This is valuable information for decision-making in environmental protection, as it shows the environmental impacts associated with production activities.

The input-output model can explain the process of pollutant emissions in greater depth. In particular, this model makes it possible to analyse how changes in the final demand of activities modify the composition of greenhouse emissions, in terms of the percentages of different types of gases in total air pollution. To study the changes in the components of emissions, we can define the relative composition of greenhouse gases (vector *g*) by normalizing expression (2):

$$g = \frac{B(I-A)^{-1}Y}{e'B(I-A)^{-1}Y} = \frac{F}{e'F}, \tag{4}$$

where *e′* is a unitary row vector and *g* is a column vector that contains the relative contribution of every gas to total greenhouse emissions. So, *g* is the vector of the *relative composition of total greenhouse emissions*, which is calculated by dividing the vector *F* of *i* greenhouse emissions by the total emissions ($e'F$). Notice that the only restriction for calculating vector *g* is that we need to know the amount of emissions per type of greenhouse gas for each sector (matrix *B*) in the same physical units, which are carbon dioxide equivalents.

Following expression (4), we can quantify the changes in the relative composition of emissions (*dg*) caused by an exogenous and unitary change in the final demand of production activities (*dY*) as follows:

$$\begin{aligned}
dg &= \frac{e'B(I-A)^{-1}YB(I-A)^{-1} - B(I-A)^{-1}Ye'B(I-A)^{-1}}{\left[e'B(I-A)^{-1}Y\right]^{2}}dY = \\
&= \frac{B(I-A)^{-1}}{\left[e'B(I-A)^{-1}Y\right]} - \frac{B(I-A)^{-1}Ye'B(I-A)^{-1}}{\left[e'B(I-A)^{-1}Y\right]^{2}}dY = \\
&= \frac{1}{e'B(I-A)^{-1}Y}\left[B - \frac{B(I-A)^{-1}Ye'B}{\left[e'B(I-A)^{-1}Y\right]}\right](I-A)^{-1}dY = \\
&= \frac{1}{e'F}\left[B - \frac{Fe'B}{e'F}\right](I-A)^{-1}dY = GdY.
\end{aligned} \tag{5}$$

In expression (5), *G* is the matrix of the *changes in the relative composition of greenhouse emissions*, and has *i* rows of the different types of pollutants and *j* columns of the production activities. This matrix shows the effects of exogenous inflows in the final demand of activities on the relative contribution of the different pollutants to the amount of greenhouse emissions. The elements of this matrix can be either positive or negative (that is to say, they show a rise or a decrease, respectively, in the relative contribution of a pollutant to the total emissions). So, one individual element of this matrix, G_{ij}, determines the magnitude (positive or negative) of the change in the relative significance of pollutant *i* on the total emissions caused by a unitary inflow in the final demand of activity *j*. Notice that this way of representing the greenhouse pollution process involves a set of bilateral connections between activities and emissions and tells us how one activity influences the relative significance of the pollutants. In particular, the analytical context in expression (5) reflects the changes in the composition of greenhouse gases caused by one monetary unit of change (increase or decrease) in private consumption, public consumption, investment and exports, which are the elements that are considered to be exogenous by the input-output framework.

It should be pointed out that, irrespective of the dimension of matrix *G*, the sum of the columns is zero. This can be easily checked by applying the following calculation:

$$e'G = e'\frac{1}{e'F}\left[B - \frac{Fe'B}{e'F}\right](I-A)^{-1} =$$

$$= \frac{1}{e'F}\left[e'B - \frac{e'Fe'B}{e'F}\right](I-A)^{-1} =$$

$$= \frac{1}{e'F}[e'B - e'B](I-A)^{-1} = 0.$$

This mathematical operation means that, through matrix G of changes in the composition of greenhouse gases, the context of relative emissions can be interpreted as a process of winners and losers. In other words, the modifications in the relative contribution of the components of greenhouse emissions compensate for each other.

The analytical method described above evaluates the changes in the composition of greenhouse gases under exogenous changes in sectorial demand. If the multipliers quantify the increase in emissions due to exogenous changes in sectorial demand, the relative emissions' context shows how the relative importance of each pollutant is modified by exogenous changes in sectorial demand. The analysis of relative emissions, therefore, extends our knowledge of how changes in the economic activity of production sectors can affect greenhouse emissions within the context of air pollution.

3. Databases

In this section we use the latest economic and atmospheric information for Spain, which is for the year 2000. Specifically, this information comprises the Satellite Atmospheric Emissions Account (INE, 2001) for pollution emissions, and the Supply Table and Use Table corresponding to the input-output accounts (INE, 2005) for the production system.

The Supply Matrix and the Use Matrix are given in terms of industry by product classification, following the National Classification of Economic Activities (CNAE93) for activities, and the National Classification of Products (CNAP96) for products, respectively. We aggregated both matrices for as many as 17 homogeneous activities of production. Both matrices contain information expressed in basic prices.

The direct structural coefficients or input-output coefficients matrix A is derived from the Use Matrix in two steps. First, the elements of the Use Matrix are divided by the domestic output of the absorbing industry. Second, the resulting matrix C is pre-multiplied by the transpose of the share matrix D by calculating $A = D'C$ (Miller and Blair, 1985). Matrix D is derived from the Supply Matrix and its elements are calculated by dividing each commodity by the total commodity output.

The data on atmospheric emissions are organized in matrix B, whose rows contain the amount of pollutants i generated by domestic industries j (in the columns). In our empirical application, matrix F distinguishes the six major greenhouse gases regulated by the Kyoto Protocol. Like the input-output coefficients matrix, the columns in B contain 17 different activities of production. The original units of emissions have been rescaled so that they are all expressed in the same units, which are carbon dioxide equivalents (CO_2 eq.). We show both the production sectors and the greenhouse gases in Table 1.

Table 1. Sectors of Production and Greenhouse Gases

j	**Sectors**	*i*	**Gases**
1	Agriculture	1	Methane (CH_4)
2	Energy	2	Carbon Dioxide (CO_2)
3	Metals	3	Nitrous Oxide (N_2O)
4	Minerals	4	Sulphur Hexafluoride (SF_6)
5	Chemistry	5	Hydrofluorocarbons (HFC)
6	Machinery	6	Perfluorocarbons (PFC)
7	Automobiles		
8	Food		
9	Textiles		
10	Paper		
11	Other Industry		
12	Construction		
13	Commerce		
14	Transportation		
15	Finance		
16	Private Services		
17	Public Services		

4. Empirical Application to the Spanish Greenhouse Emissions

The analytical context discussed in section 2 shows how exogenous and unitary inflows to final demand of production activities affect the relative composition of greenhouse emissions. Specifically, by calculating matrix *G* we provide a general representation of the ecologic-economic channels taking place in the production system. This tells us how the shocks in sectorial production, as changes in consumption, investment and exports, modify the relative importance of every greenhouse gas within total air pollution.

The information reported by the model shows different aspects of greenhouse emissions. First, we focus on the emission multipliers that quantify the changes in the levels of emissions in response to changes in final demand. Second, we show the relative composition of greenhouse emissions. Finally, we analyse the patterns that explain the changes in the relative contribution of pollutants to the total emissions.

4.1 *Emission Multipliers*

Following the logic behind the input-output representation of pollution processes, an exogenous increase in the final demand of activities will lead to an increase in sectorial production to cover the new demand and, as the levels of pollution have a direct and fixed relationship with the levels of production, this will also lead to an increase in the levels of emissions.

In this section, we quantify the changes in the amount of greenhouse gas emissions when there are exogenous and unitary changes in the final demand of activities. From this perspective, we can identify which production activities are responsible for the greatest

increases in the levels of pollution after an increase in their exogenous demand. These results are very valuable for designing abatement measures of industrial pollution.
Table 2 contains the elements of matrix $B(I - A)^{-1}$ corresponding to the emission multipliers. The elements in this table show the changes in the Spanish emissions when there is an exogenous and unitary inflow to the activities of production. Specifically, Table 2 should be read as follows. The element of the first row and first column indicates that when agriculture (sector 1) receives an exogenous and unitary increase in its final demand, CH_4 emissions will increase by 586.23tonnes of CO_2 eq.

The sum of the columns in Table 2 shows the increase in the levels of greenhouse emissions when the activity corresponding to the column receives a unitary and exogenous injection in demand. Likewise, these total values quantify the effects of pollution, in terms of carbon dioxide equivalents, generated by the exogenous inflows to each activity. As we can see from Table 2, the greatest column sum corresponds to energy (sector 2), which generates 2584.01 tonnes of CO_2 eq. per exogenous and unitary inflow received. This effect is followed by minerals (sector 4), which generates 2232.91 tonnes of CO_2 eq. and agriculture (sector 1) with 1654.33 tonnes of CO_2 eq. These three activities show a considerable ability to generate greenhouse emissions in Spain, and jointly amount to about 52% of the total emissions reflected in Table 2.

Table 2. Emission Multipliers ($B(I - A)^{-1}$). Tons of Carbon Dioxide Equivalents

	1	2	3	4	5	6	7	8	9	10
CH_4	586.23	41.64	1.42	9.72	13.16	5.46	4.48	200.81	20.3	35.59
CO_2	623.83	2508.46	166.03	2167.68	574.19	336.59	174.53	478.88	262.13	526.52
N_2O	442.37	33.21	2.59	53.19	70.79	10.11	7.37	153.37	22.59	22.62
SF_6	0.09	0.06	0.06	0.2	0.11	1.99	0.34	0.09	0.07	0.08
HFC	1.62	0.52	0.35	1.7	23.46	1.05	1.09	1.61	2.11	1.69
PFC	0.18	0.12	0.13	0.42	0.23	4.15	0.72	0.19	0.14	0.18
Total	1654.33	2584.01	170.58	2232.91	681.94	359.34	188.54	834.95	307.34	586.69

Table 2. Emission Multipliers ($B(I - A)^{-1}$). Tons of Carbon Dioxide Equivalents (continuing)

	11	12	13	14	15	16	17	Total
CH_4	19.78	9.7	29.14	8.05	6.69	9.06	125.3	1126.53
CO_2	292.99	499.86	228.28	591.68	236.75	456.66	190.37	10315.42
N_2O	24.81	17.46	24.61	12.21	7.52	15.72	23,41	943.96
SF_6	0.18	0.29	0.05	0.06	0.05	0.05	0.06	3.83
HFC	3	1.39	1.02	0.78	1.55	7.66	1.24	51.84
PFC	0.37	0.6	0.1	0.13	0.1	0.11	0.13	8
Total	341.13	529.29	283.2	612.91	252.65	489.27	340.5	12449.57

On the other hand, new demand in metals (sector 3) and automobiles (sector 7) causes the smallest increases in emissions (170.58 and 188.54 tonnes of CO_2 eq., respectively). It is interesting to point out that most service activities (from sector 13 to sector 17) have less impact on the levels of emissions. The exception is transportation (sector 14) which, with 612.91 tonnes of CO_2 eq., generates 5% of the total emission multipliers.

The sum of rows in Table 2 shows the increase in the emissions of the pollutant gas in the row when there is one unitary injection in the final demand of all the activities simultaneously. These total values reflect, therefore, the pollution effects on every type of emission caused by the joint inflows to all the sectors of production. From this table, the greatest effect is on CO_2 emissions, which is quantified as 10315.42 tonnes of CO_2 eq. (82.8% of the total). This is followed by the effect on CH_4 emissions, which is quantified as 1126.53 tonnes of CO_2 eq. (9.05% of the total). Therefore, these two gases together make up about 92% of Spanish emission multipliers. On the other hand, the SF_6 and PFC multipliers show the smallest values, which amount to 3.83 and 8.00 tonnes of CO_2 eq., respectively.

Another important aspect that Table 2 makes clear is that some bilateral effects are very significant in terms of pollution generation, and this means that some activities have a strong influence on Spanish greenhouse emissions. For example, an inflow to energy (sector 2) generates 2508.46 tonnes CO_2 eq. of CO_2, which is 20% of the total emission multipliers. Additionally, an inflow to minerals (sector 4) generates 2167.68 tonnes CO_2 eq. of CO_2 (17.41% of the total effects), and an inflow to agriculture (sector 1) generates 586.23 tonnes CO_2 eq. of CH_4 (4.7% of the total effects). These results suggest that the inflows received by a small number of activities concentrate most of the pollution generation in the Spanish production system. This concentration of total emissions in just a few sectors of production may make it easier to apply the policy measures aimed at reducing the levels of industrial greenhouse pollution.

To sum up, Table 2 indicates that Spanish emissions have important asymmetries at the sectorial level, and the effects of production activities on air pollution are very heterogeneous. Our results show that the increase in the greenhouse emissions caused by the Spanish production system will essentially depend on the activity that receives the exogenous inflow in final demand. The results also show that there are considerable differences in the quantitative significance of the different gases analysed.

4.2 *Composition of greenhouse emissions*

This section presents the empirical results of the relative greenhouse emissions. Table 3 shows the composition of sectorial emissions, which were calculated by dividing the emission multipliers' matrix ($B(I-A)^{-1}$) by the transposed matrix of the total emission multipliers in each activity: that is, the transposed matrix of the column sum in the emission multipliers' matrix ($(e' B(I-A)^{-1})^T$). The elements in Table 3 show, therefore, the relative contribution of each pollutant to the total emissions of each activity of production.

The relative significance of gases is very different, and depends basically on the sector and the type of gas analysed. The highest CH_4 relative emissions are in agriculture (sector 1), and in public services (sector 17), and they represent 35.44% and 36.80% of the total emissions of agriculture and public services, respectively. For CO_2 emissions, the highest relative significance is in energy (sector 2), metals (sector 3) and minerals (sector 4), with values of 97.08%, 97.33% and 97.08%, respectively. For N_2O emissions, the highest values are in agriculture (sector 1) and food (sector 8), with values of 26.74% and 18.37%, respectively. On the other hand, Table 3 shows that in all the activities the relative importance of SF_6, HFC and PFC is much smaller than that of the other pollutants.

Table 3. Composition of Sectorial Emissions in Spain (%)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
CH_4	35.44	1.61	0.83	0.44	1.93	1.52	2.38	24.05	6.60	6.07	5.80
CO_2	37.71	97.08	97.33	97.08	84.20	93.67	92.57	57.35	85.29	89.74	85.89
N_2O	26.74	1.29	1.52	2.38	10.38	2.81	3.91	18.37	7.35	3.86	7.27
SF_6	0.01	0.00	0.04	0.01	0.02	0.55	0.18	0.01	0.02	0.01	0.05
HFC	0.10	0.02	0.20	0.08	3.44	0.29	0.58	0.19	0.69	0.29	0.88
PFC	0.01	0.00	0.08	0.02	0.03	1.16	0.38	0.02	0.04	0.03	0.11
Total	100	100	100	100	100	100	100	100	100	100	100

Table 3. Composition of Sectorial Emissions in Spain (%) (continuing)

	12	**13**	**14**	**15**	**16**	**17**
CH_4	1.83	10.29	1.31	2.65	1.85	36.80
CO_2	94.44	80.61	96.54	93.71	93.34	55.91
N_2O	3.30	8.69	1.99	2.98	3.21	6.87
SF_6	0.05	0.02	0.01	0.02	0.01	0.02
HFC	0.26	0.36	0.13	0.61	1.57	0.36
PFC	0.11	0.04	0.02	0.04	0.02	0.04
Total	100	100	100	100	100	100

To sum up, Table 3 shows that agriculture (sector 1) and food (sector 8) have relatively high emissions of CH_4 and N_2O, while energy (sector 2), metals (sector 3) and minerals (sector 4) have relatively high emissions of CO_2. Table 3 also shows that chemistry (sector 5) has relatively high emissions of HFC and machinery (sector 6) has relatively high emissions of PFC and SF_6.

Table 4. Composition of Total Greenhouse Emissions in Spain (g)

Gases	g_i
Methane (CH_4)	10.01%
Carbon Dioxide (CO_2)	82.21%
Nitrous Oxide (N_2O)	7.03%
Sulphur Hexafluoride (SF_6)	0.05%
Hydrofluorocarbons (HFC)	0.58%
Perfluorocarbons (PFC)	0.12%
Total	**100.00%**

Table 4 shows the relative contribution of every gas to the total greenhouse emissions in Spain. This information corresponds to vector g, which has been defined in expression (4) above. CO_2 is the most important component in Spanish emissions, totalling 82.21% of the greenhouse pollution. This is followed by the relative contribution of CH_4, which is 10.01% of the emissions in the year 2000. On the other hand, the SF_6 emissions and the PFC emissions contributed little to Spanish emissions and together made up 0.17% of all greenhouse pollution.

4.3 Changes in the composition of greenhouse emissions

This section shows the changes in the relative composition of pollutants within the amount of greenhouse emissions. Specifically, Table 5 modifies the original changes in relative emissions, as it contains the non-normalized elements for the matrix $(e'F)G$. So, the values in Table 5 show how many tonnes of CO_2 eq. are reassigned among pollutants when the total emissions are held constant at the initial level. In other words, it shows the tonnes of emissions that change from one gas type to another because of the changes in their relative contribution. For example, the first element in Table 5 shows that when agriculture (sector 1) receives an exogenous inflow, the relative CH_4 emissions increase by 420.62 tonnes of CO_2 eq. On the other hand, this same inflow reduces the relative CO_2 emissions by 736.24 tonnes of CO_2 eq. Notice that the columns in this table add up to zero as do those in matrix G, and this means that we can also interpret this table as a process of winners and losers in which the effects on the gases compensate for each other.

Reading down the columns in Table 5 shows how much pollution is reassigned among the types of pollutants under an exogenous and unitary increase in the demand of the sector in the column. Of the different activities, agriculture (sector 1), energy (sector 2) and minerals (sector 4) have the largest column values and this means that these activities are more able to modify the relative importance of pollutants under exogenous changes in their demand. On the other hand, automobiles (sector 7), textiles (sector 9) and some services, such as commerce (sector 13) and finance (sector 15), are not so able to modify the relative emissions.

Reading across the rows in Table 5 shows the changes in the relative emissions of the gas in the row when there is an exogenous and unitary increase in the final demand of all the activities simultaneously. As we can see, CH_4 emissions show the largest adjustment: its relative emissions are reduced by 119.80 tonnes of CO_2 eq. when all the activities raise their demand by one monetary unit. The row sums of SF_6 and PFC are the smallest, and their relative emissions are reduced by 2.94 and 6.15 tonnes of CO_2 eq., respectively.

It should be pointed out that, while the relative emissions of CO_2 and N_2O increase under a new and exogenous demand to all the activities of production, the relative emissions of CH_4 decrease. Furthermore, if we compare the row sum for CO_2 and N_2O in Table 5 with those of the other gases, we can conclude that these two pollutants have substitutive effects with respect to the other greenhouse gases under exogenous inflows to the productive system. Table 5 also shows that the changes in the relative greenhouse emissions have no direct relation with the relative distribution in activities (Table 3). Moreover, if we compare Tables 2 and 5, we can see how important it is to understand the pollution generation process and how it is related to production activities. Our results show that the changes in the emissions levels (Table 2) are very different from the changes in the relative emissions (Table 5). In fact, while the largest adjustment to the levels of Spanish pollution was in CO_2 emissions, the largest adjustment to Spanish relative emissions was in CH_4 emissions.

Table 5. Changes in Relative Greenhouse Emissions (e'FG). Tons of Carbon Dioxide Equivalents

	1	2	3	4	5	6	7	8	9	10	11
CH4	420.62	-217.05	-15.65	-213.82	-55.11	-30.52	-14.39	117.22	-10.47	-23.14	-14.37
CO2	-736.24	384.07	25.79	331.94	13.55	41.16	19.52	-207.55	9.46	44.18	12.54
N2O	326.02	-148.54	-9.41	-103.86	22.83	-15.16	-5.89	94.64	0.98	-18.64	0.82
SF6	-0.81	-1.35	-0.03	-1.01	-0.26	1.80	0.24	-0.36	-0.10	-0.23	-0.01
HFC	-7.89	-14.33	-0.63	-11.14	19.54	-1.02	0.01	-3.19	0.35	-1.68	1.04
PFC	-1.70	-2.81	-0.07	-2.12	-0.55	3.74	0.50	-0.76	-0.21	-0.49	-0.02
Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 5. Changes in Relative Greenhouse Emissions (e'FG). Tons of Carbon Dioxide Equivalents (continuing)

	12	13	14	15	16	17	Total
CH4	-43.28	0.79	-53.31	-18.61	-39.92	91.22	-119.8
CO2	64.71	-4.54	87.79	29.04	54.42	-89.57	80.29
N2O	-19.77	4.69	-30.9	-10.25	-18.69	-0.54	68.33
SF6	0.00	-0.11	-0.27	-0.09	-0.22	-0.12	-2.94
HFC	-1.66	-0.61	-2.74	0.1	4.85	-0.72	-19.74
PFC	0.00	-0.22	-0.57	-0.19	-0.45	-0.26	-6.15
Total	0.00	0.00	0.00	0.00	0.00	0.00	0.00

In summary, the analysis of changes to relative emissions completes our knowledge of greenhouse gas emissions and clarifies the underlying effects that generate environmental consequences within the production system. This information is very important if environmental policy is to be successful at improving the environmental efficiency of an economy.

5. Conclusions

This chapter has analysed the relative composition of greenhouse gas emissions in Spain, using both economic and atmospheric emissions data for the year 2000. Specifically, we have extended the traditional environmental input-output model to account for the relative composition of total emissions and how this composition is modified by changes in the exogenous components of the input-output approach. This provides additional information about the complex process of pollution generation and how it is related to production activities. In particular, the extension of the environmental input-output model has revealed that the modifications in the relative status of the six major greenhouse gases regulated by the Kyoto Protocol are a set of bilateral connections, which tell us how the inflows to activities affect the relative contribution of every pollutant to the amount of emissions.

Our application to Spanish emissions reveals important asymmetries in the effects of sectors on the levels of greenhouse pollution. One important finding is, therefore, that there are significant differences in the way some activities affect greenhouse emissions. This suggests that even if the pollution abatement policies in the production sphere focus on only a few activities the effects on the environment could be extremely beneficial. Our results also show that very few activities have a considerable influence on the process of relative emissions.

In the context of environmental preservation and pollution control, the underlying effects that contribute to the processes of environmental burdens and pollution generation must be understood. To explain the environmental consequences of the productive system, we require flexible analyses that capture the economic and ecologic relationships that take place within pollution generation processes. The analytical context we present in this chapter identifies several aspects that can clarify the generation and the transmission of environmental impacts.

CHAPTER IV

ENVIRONMENTAL ASSESSMENT OF PLANTS USING INPUT-OUTPUT TECHNIQUES AND ITS APPLICATION TO LCIs

Abstract

Life Cycle Inventory (LCI) attempts to quantify environmental interventions over the entire life cycle of a product or activity from raw material acquisition, manufacture and use, to ultimate disposal. However, current methods for LCI suffer from problems of subjective boundary definition, high-cost, data confidentiality and incompleteness. In this chapter we investigate the use of Input-Output (IO) techniques in LCI, especially for system boundary definition. We describe five different IO methods to calculate the emissions emitted directly and indirectly by a plant. We apply these methods to the case of an incineration plant and compare the results with those of process analysis (LCI). The method which gives the closest results to LCI is the one considering the concept of shared producer-consumer responsibility and the disaggregation of the economy to include as new sector the plant under study. Based on the results given by this method, we perform a Structural Path Analysis (SPA) to decide which processes to include or leave out of analysis in a detailed LCI.

Keywords: Life cycle inventory (LCI), Input-Output (IO) techniques, shared consumer-producer responsibility, Structural Path Analysis (SPA), plant environmental assessment.

1. Introduction

Due to the high aggregation of data, Input-Output (IO) techniques are generally used to perform macroeconomic analyses at regional or national levels, depending on the availability of IO tables. Much more detailed and specific, Life Cycle Inventory (LCI) is concerned with the compilation and quantification of inputs and outputs of a given product system throughout its life-cycle, from raw materials extraction through its production and use to its final disposal (ISO 14040). Theoretically, all processes in an economy are interconnected directly or indirectly. Therefore the compilation of a complete LCI is practically impossible, as it would imply collecting process specific data for all the economy. This problem has led to the use of IO techniques in LCI. IO analysis can help LCI in two ways. Firstly, it can offer a solution to the selection of boundaries in LCI, and secondly, it can be used for the estimation of environmental flows of the processes left out from the LCI evaluation. In this chapter we discuss only the first option, while the second one is the objective of the next chapter.

The decision on which processes to include in a detailed LCI is made normally based on data availability, more than on objective cut-off criteria. Processes never assessed by the LCI practitioner can be left out of the analysis because of the missing data, without proving their negligibility. IO techniques, particularly Structural Path Analysis (SPA), can help to decide objectively which processes to include or leave out of analysis. SPA allows identifying key sectors in environmental interventions (air pollution, land-use, water-use, water-pollution, etc.) and describes the chains through which pollution is transmitted in an economy. Due to the aggregation of data, SPA suits well analyses at national level (see Chapter II). It is possible to apply SPA at more disaggregated level, company or producing activity level, if detailed monetary and environmental data are available, allowing to model the company's or activity's emissions by using IO techniques. To this end, we apply IO techniques for estimating the emissions of an incineration plant and describing the chains through which the pollution is propagated to the plant. We use IO tables and Satellite Atmospheric Emissions Accounts for Spain, and emissions and economic data from the plant.

The Municipal Solid Waste (MSW) Incinerator of Tarragona (SIRUSA) is a public plant, operated and maintained by the public funds of the surrounding cities: Tarragona, Reus, Valls, Salou, Cambrils, Vila-Seca and Constantí. SIRUSA is located in an industrial polygon area, approximately three kilometres outside of Tarragona. It has an incineration capacity of 430t waste per day and receives wastes from all surrounding municipalities. In addition to reducing the volume of waste, the plant also generates electricity. Despite its positive aspects, waste incineration also creates problems through the release of air pollutants and generation of secondary waste streams (slag and fly ash). In the first part of this chapter we are concerned with the calculation of direct and indirect air emissions associated with the activity of the plant by using IO techniques. We test four IO methods. The first one is tedious assuming the plant is only a final consumer, demanding goods and services from the economy, but does not produce. As the on site emissions of the plant are important, the second IO method adds the on-site emissions of the plant to those generated to produce the inputs necessary to the plant for its production, but the plant is still out of the IO tables. The last two consider the disaggregation of the Spanish economy to include a new sector represented by the plant. In this way we can model the interactions of the plant with the rest of the economy and the final demand. We describe the four methods and compare their results to those obtained by using a process analysis technique, namely LCI. Furthermore, we introduce the concept of shared producer-consumer responsibility and compare its results with those of the last two above mentioned methods. The method considering the plant as a new sector in the Spanish economy and the shared producer-consumer responsibility gives results closer to the LCI results presented in Chapter I. In the second part of the chapter, we apply SPA to the multipliers calculated above to determine the most polluting input paths to the plant and therefore a method to establish the boundaries of a more complete LCI.

The first applications of IO in LCI assumed a plant or activity as having the same emissions intensities (emissions per monetary unit of output) as the sector to which it belongs (Moriguchi *et al.* (1993), Lave *et al.* (1998), Hendrikson *et al.* (1998)). This approach is later improved by Joshi (2000) who proposes considering the plant or activity as individual sector in the economy. This is obtained by selective disaggregation of input-output data or creation of hypothetical new commodity sectors. In Joshi's approach, the emissions intensities of the plant are calculated using on-site data on the emissions and economic transactions of the plant. The emissions generated by the production of input requirements of the plant are estimated considering every input as "typical" output of a sector. The emissions generated downstream the plant are not estimated. Although they cover only the pre-consumer stages of an LCI of the plant, all the above described approaches are known as "IO-based LCI models" (Suh and Huppes, 2005). As far we are concerned, there are no contributions comparing LCI results with the results of IO-based LCI models. In this chapter we provide a comparison between the results of LCI and different IO calculations applied to LCI.[15] We also apply the concept of shared responsibility quantitatively conceptualised by Gallego and Lenzen (2005). It implies the share of the emissions of the plant both with its suppliers and its consumers. In this approximation, the plant is made responsible for only a part of its final demand and part of its intermediate demand and intermediate outputs, the remaining parts being attributed to its suppliers and consumers. In the second part of the chapter, we identify the most polluting suppliers to the plant until the sixth layer and the paths through which the pollution is transmitted to the plant. This exercise guides the data collection and boundary selection in a detailed LCI (see Lenzen (2002) for the use of SPA in LCI).[16]

The chapter is organized as follows. In Section "Conventions" we present the assumptions and simplifications of this work. Section 2 describes the four IO methods to calculate the direct and indirect atmospheric emissions of a plant and the shared responsibility calculations, and presents the results of their application to the case of SIRUSA incineration plant. In Section 3 we present the SPA method and apply it to the case of SIRUSA to describe the chains through which the pollution is propagated to the plant. Finally, we conclude by highlighting the utility and the limitations of using IO data for LCI.

Conventions

The methods described in this work permit the calculation of eleven types of atmospheric emissions "embodied" in a particular good or service provided by a plant or activity. In our particular application to an incineration facility, one calculation determines one type of emission (e.g. SO_x) emitted directly and indirectly to produce one euro of electricity from waste. The incineration of MSW is considered as having two positive outputs: reduces the volume of the MSW at appreciatively one third from the initial one and produces electricity. As wastes do not have a monetary value or have a negative one, we assume here the only useful output of the incineration plant is the electricity produced by using the vapour generated in the incineration process. This is an important simplification as the incinerator is primarily designed to reduce the volume of wastes and not to produce electricity. Nevertheless, an important monetary input of the plant (26%) comes from selling electricity.

2. IO methodology and application to the calculation of environmental burdens of a company

IO analysis is a linear modelling technique widely used in economic research since its introduction by Leontief (1941). Because of data aggregation, it suits well macroeconomic analyses at national or regional scales. Initially, the economy is disaggregated into *n* sectors, each of them producing a unique and distinct good or service. The structure of the

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[15] We prefer not to call them "IO based LCI models", as they do not imply all the life cycle of the activity or plant they model. That is, they capture the on site emissions of the plant.

[16] See Lenzen (2002) for the use of SPA in LCI.

model, a linear network, assumes that each sector consumes goods or services from the other sectors in fixed proportions in order to produce its unique (or typical) output. Let us define the matrix of technical coefficients *A*, as the *n x n* matrix of intermediate monetary transactions between sectors divided by the sectoral total outputs. An element a_{ij} of this matrix represents the inputs from industry *i* needed by industry *j* to produce one unit of its monetary output. If *x* is the vector of the sectorial total outputs and *y* is the total final demand of sectors[17] (industries), then we can write:

$$x = Ax + y\,. \tag{1}$$

In other words, equation (1) states that the total output of an industry is the summation of sales to intermediate industries and sales to final demand. Following equation (1), the total output *x* required to satisfy a given final demand *y* is calculated as:

$$x = (I - A)^{-1} y\,, \tag{2}$$

where *I* is an *n x n* identity matrix.

Less aggregation of the economy is obtained when commodities are distinguished from industry outputs. If we consider the disaggregation of economy into *m* commodities, equation (2) can be rewritten as:

$$x = D(I - A_c)^{-1} y_c\,, \tag{3}$$

where y_c is the vector of commodities delivered to final demand and A_c is an *m x m* matrix of direct requirements expressed in commodity-by-commodity terms. Matrix A_c is calculated from the make, *S*, and use, *U*, matrices following the equation: $A_c = BD$, where *D* stands for the share matrix and *B* is the matrix of technical coefficients in commodity-by-industry terms.[18] Each element of the share matrix d_{ij} represents the fraction of commodity *i* produced by the industry *j* and is derived from the make matrix through: $d_{ij} = s_{ij} / \sum_i s_{ij}$. Each element of the matrix *B*, b_{ij}, is the flow of commodity *i* to industry *j* per unit of industry *j*'s output: $b_{ij} = u_{ij} * (x_j)^{-1}$.

The IO framework can be extended to account for environmental pollution. This implies two assumptions: the environmental interventions generated by an industry are proportional to its output, and they remain constant over one year. Let us define a *k x n* matrix *F*, each of its elements f_{kj} representing the environmental burden of type *k* generated by industry *j* in order to produce one unit of its monetary output. Then, the total direct and indirect environmental interventions generated by the productive economic system to satisfy a given final demand are calculated by:

$$g = F(I - A)^{-1} y\text{, in industry terms;} \tag{4}$$

$$g_c = FD(I - A_c)^{-1} y_c\text{, in commodities terms.} \tag{5}$$

Although IO is a simple technique, it would hardly be useful without large amounts of data. The Spanish Institute of Statistics (INE) reported for 2000 both economic and environmental data. The make and use tables for 2000 (INE, 2005) are given disaggregated into 110 commodities and 72 economic sectors, following CNAE-93 classification. We

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[17] The terms "sector" or "industry" are used interchangeable throughout this work.

[18] See Miller and Blair (1985), p. 167.

aggregated them into 70 sectors considering homogenous sectors.[19] The list of the 70 economic sectors used in this work can be found in Annex 3. The emission data coming from the Spanish Satellite Atmospheric Emissions Accounts[20] (INE, 2001) consist of emissions of 11 atmospheric pollutants released by 45 domestic economic sectors, following NACE Rev.1. As both classifications CNAE-93 and NACE Rev.1 have compatible structures, we disaggregated the emissions matrix F into 70 sectors as the use and make matrices. For this task we used supplementary pollution data published in the Spanish National Inventory of Atmospheric Emissions (EIONET, 2005). The atmospheric pollutants are: sulphur oxides (SO_x), nitrogen oxides (NO_x), non methane volatile organic compounds (NMVOC), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (N_2O), ammonia (NH_3), sulphur hexafluoride (SF_6), hydro-flour carbonates (HFC) and perfluorocarbons (PFC). Using these data, equations (4) and (5) can be solved for a vector g of 11 atmospheric emissions for the year 2000.

The easiest way to determine the environmental interventions of a plant by using IO analysis is to consider it a final demander. We assume as a first approximation that the plant does not produce, but it demands goods and services from the economy. Using equations (4) and (5), we calculate the atmospheric emissions induced by producing the plant requirements or inputs from the economy. Let us call these calculations approximations A1a (in commodity terms) and A1b (in industry terms).[21] For the application we use the data of SIRUSA incineration plant. The vectors y and y_c in equations (4) and (5) are substituted in this case by the vector of expenditures of the plant, in terms of industries and commodities respectively. To perform these calculations we need the vector of expenditures of the plant to be expressed in basic prices for year 2000. Annex 4 contains the calculations implied in the conversion of the original data from the plant into the vector of expenditures we need. The results are presented in Figure 1 and Table 1.

Figure 1 presents the total emissions values for the 11 pollutants presented on the x axe. They are expressed in physical units as follows: SF_6, PFC and HFC emissions are valued in kg, CO_2 in thousands of tones and the rest of pollutants emissions are expressed in tones. On the same graph we represented also the LCI results, calculated in Chapter 1. The calculated LCI emissions of N_2O, NH_3, SF_6 and PFC are zero as the product system considered in the LCI evaluation does not release these pollutants.[22] For a better understanding of the results pictured in Figure 1, we give also the values of emissions in Table 1 and present the direct emissions of the sectors from which SIRUSA buys (from the Spanish NAMEA, after the disaggregation into 70 sectors) in Table A3.

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[19] The homogeneous sectors are considered to produce only primary products, the secondary production being not considered.

[20] The matrix formed by the emissions of each sector by type of pollutant is called also NAMEA, acronym of National Accounting Matrix including Environmental Accounts.

[21] These approximations are also known as "IO-based LCI models" (see Suh and Huppes (2005) for a review of these applications).

[22] The plant of incineration SIRUSA generates several types of atmospheric emissions including particles, dioxins, heavy metals, nitrous and sulphur oxides, volatile organic compounds, CO and CO_2, etc. In this study we only consider the 11 pollutants included in the NAMEA of Spain for the year 2000.

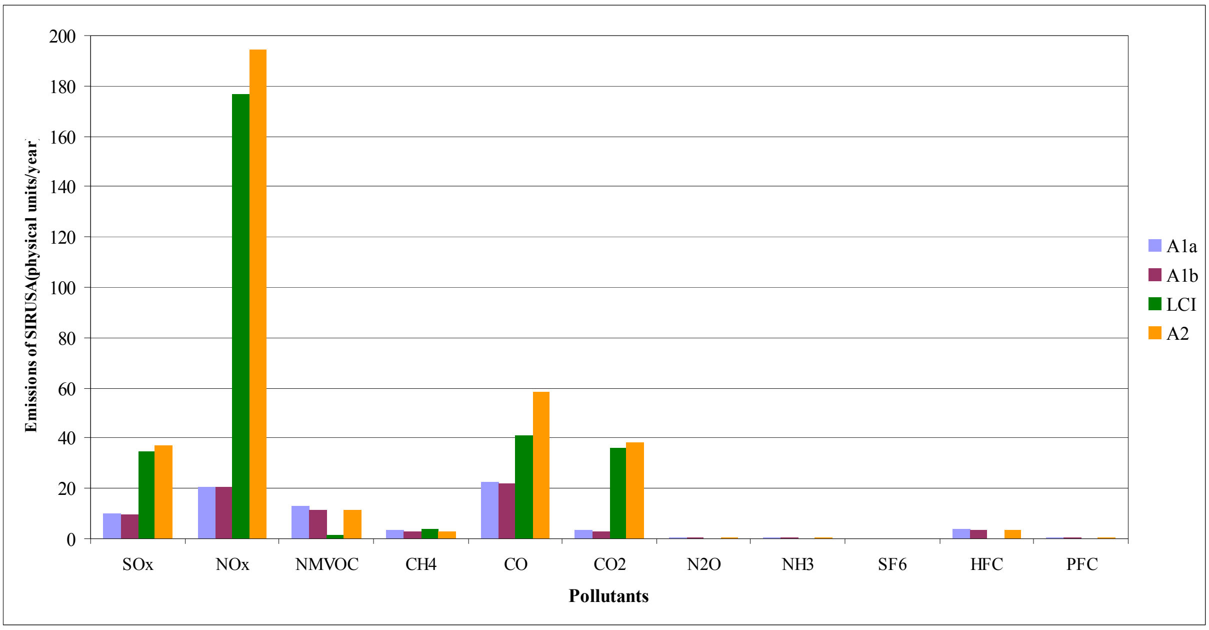

Figure 1. Emissions of SIRUSA, approximations A1a and A1b in comparison with LCI results and A2.

The difference between the two approximations A1a and A1b is quite insignificant. As the boundaries of the assessment in this case are national, we would expect bigger IO emissions compared to LCI results (see Chapter 1 for a description of LCI method and results). However, the results of A1a and A1b are smaller for 5 out of 11 pollutants. This is reasonable, considering that LCI calculations include not only the emissions embodied in the direct purchases of the plant but also the emissions resulted from the incineration itself and from the treatment of the wastes generated in the process of incineration, all of them highly polluting processes. The difference between IO results (A1a and A1b) and LCI results is especially important in the case of four pollutants: SO_x, NO_x, CO and CO_2, for which LCI results multiply several times IO results (see Table 1). This is due to the important on site emissions of these pollutants, which are not considered in these approaches.

Table 1. Total emissions of SIRUSA calculated by A1a and A1b in comparison with LCI and A2.

Emissions	Units	A1a	A1b	LCI	A2
SO_x	t	10.15	9.51	34.58	37.01
NO_x	t	20.68	20.37	176.73	194.37
NMVOC	t	12.99	11.77	1.62	11.77
CH_4	t	3.33	2.81	3.82	2.81
CO	t	22.86	21.86	41.38	58.26
CO_2	.000 t	3.31	3.21	36.32	38.11
N_2O	t	0.30	0.26	0.01	0.26
NH_3	t	0.62	0.43	0.02	0.43
SF_6	kg	0.04	0.03	0.00	0.03
HFC	kg	4.17	3.39	0.00	3.39
PFC	kg	0.66	0.60	0.00	0.60

SIRUSA is a waste treatment plant by incineration and the emissions generated by its functioning are important and cannot be neglected. It is obvious that any method of assessment that does not include these emissions, would lead to an underestimation of the environmental impact of the plant. We can consider that producing the output of SIRUSA implies exogenous increases in the demand for its input requirements in the economy, e.g. the changes in the exogenous demand vector y are equal to changes in the input requirement vector for producing the output of SIRUSA. Then, the total environmental burdens associated with the plant are a sum of environmental burdens associated with the production of its input requirements and the direct environmental burden associated with its production, E_{os} (this is the "final demand approach" outlined by Miller and Blair (1985) and Joshi (2000)).[23]

$$g = F(I-A)^{-1}y + E_{os}\,. \tag{6}$$

The results are presented by orange bars in Figure 1 (approximation A2). In this case, the results are bigger than LCI results for all the pollutants because of the important emissions generated by SIRUSA on site. We are aware that this approximation suffers form inconsistency as we have considered the plant both as final demander and producer and this implies a double-counting.

To include in calculations its direct emissions without implying a double-counting, SIRUSA has to be considered as an individual sector in the economy. As it was possible to obtain both economic and environmental data from the plant, we have all the data necessary for the further disaggregation of the economy to include SIRUSA as separate sector from the sector "Other community, social and personal service activities, market" **61** to which it belongs. This approach is sometimes called "IO-based hybrid analysis" as it combines economic data from the IO tables and information on the purchases and sales of the process plant (Suh and Huppes, 2005). Regarding the disaggregation procedure, Joshi (2000) recommends to use detailed process information on input requirements, sales structure and environmental interventions. See Annex 4 for the disaggregation of IO tables and NAMEA to include SIRUSA as a new sector. The environmental burdens associated with the production of final demand of SIRUSA are calculated in this case as:

$$g_{71} = F_{71}(I-A_{71})^{-1}y_{SIRUSA}\,, \tag{7}$$

where A_{71} is the new direct requirements matrix with dimension 71x71, F_{71} is the new matrix of emissions intensities that includes the on site emissions of SIRUSA[24] and y_{SIRUSA} the vector of SIRUSA's final demand (is a column vector, with 0 in all positions, excepting 61 which contains the monetary value of electricity sold to the final consumers). The results of this new approach (approximation A3) are presented in Figure 2 and Table 2. For an easier comparison, we left in the same figure the results of LCI and approximation A2.

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[23] This approach is similar to what is lately known as "tiered hybrid analysis" (Suh and Huppes, 2005) with the difference on the considered environmental interventions of the plant. Here we consider only the emissions resulted from the activity of the plant, meanwhile the tiered hybrid analysis include also the emissions associated with the downstream interactions of the plant (use and end-of-life phases of its product).

[24] Note the difference between the terms "emissions on site" or "direct emissions" used in LCI and "direct emissions" used within IO. In LCI terminology, direct or on site emissions refer to the emissions generated by a specific process of production or activity. In IO, "direct emissions of a sector" is a much more aggregated and general term, referring to a statistical result of the aggregation of all the emissions reported for similar products produced by the sector in question.

As Figure 2 shows, the results of approximation A3 (dark red bars) are slightly smaller than the results of A2 (orange bars) and bigger than LCI results for all the pollutants. Approximation A3 calculates the total emissions emitted directly and indirectly by SIRUSA in order to produce its final demand (electricity from waste). Compared to A2, the results of A3 eliminate the double counting. In this particular case of the incinerator, the double counting was not important, as it overestimated the total emissions (A3) by appreciatively only 3%. Compared to LCI results, as expected A3's results are bigger as they include into analysis all the economy and not only few processes as LCI.

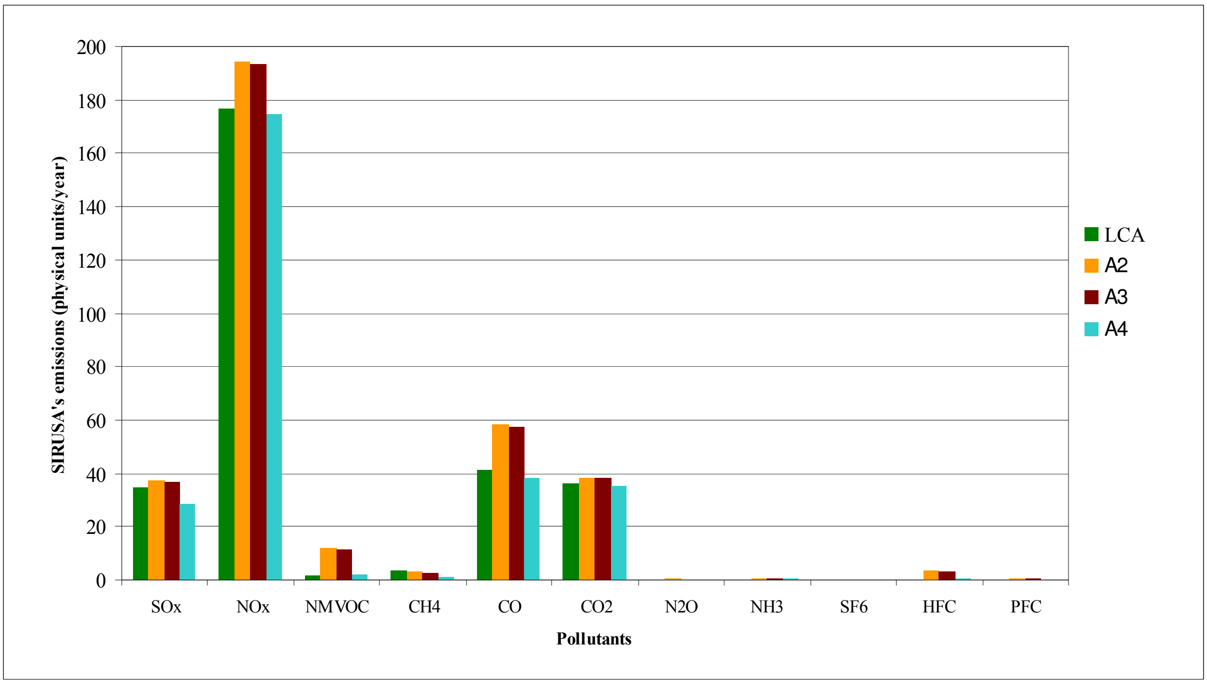

Figure 2. Emissions of SIRUSA, approximations A2, A3, and A4 in comparison with LCI results.

Now that SIRUSA is a sector within the IO tables, we can calculate also its share of emissions as due to its production, both intermediate demand and final demand. For that we use the following equation:

$$g = F_{71}(y_{SIRUSA} + Z_{71} * u) = F_{71}x_{SIRUSA}, \tag{8}$$

where Z_{71} is the inter-industries transactions matrix, including SIRUSA in position 61 and u is a column unit vector of adequate size. The product $Z_{71}*u$ gives the intermediate outputs of the plant (summation by rows of the inter-industries matrix). The results of this approximation, A4, are represented by light blue bars in Figure 2. In this case, the total emissions attributed to SIRUSA as a producer are smaller than LCI results and approximation A3. These results are consistent, as for calculating eq. (8) we did not considered the production of inputs to the plant, but only the outputs of the plant (recovered iron and other metals, and production of electricity).

Table 2. Total emissions of SIRUSA calculated by A2, A3 and A4 in comparison with LCI.

Emissions	Units	LCI	A2	A3	A4
SOx	t	34.58	37.01	36.63	28.55
NOx	t	176.73	194.37	193.43	174.84
NMVOC	t	1.62	11.77	11.48	1.90
CH4	t	3.82	2.81	2.79	1.26
CO	t	41.38	58.26	57.36	38.09
CO2	.000 t	36.32	38.11	38.01	35.13
N2O	t	0.01	0.26	0.25	0.06
NH3	t	0.02	0.43	0.42	0.35
SF6	kg	0.00	0.03	0.03	0.01
HFC	kg	0.00	3.39	3.31	0.49
PFC	kg	0.00	0.60	0.58	0.07

In the approximations analysed above, we considered the incineration plant first as final demander (A1a, A1b, and A2) and then as a producer (A3 and A4). The last two approximations give results closer to the reality, as SIRUSA is a producer of electricity from waste (not considering the reduction of wastes' volume). If these results are to be used for making the incinerator responsible for the pollution it produces, the question which arise is which share of these emissions should be attributed to the plant and which share to its final demand or its inputs providers? Clearly the existence of the plant is a necessity driven by the amount of generated MSW, wastes which need to be handled to not end up in landfill sites. The production of electricity in this case is a valorisation of the heat resulted from the incineration of wastes. Would it be fare then to allocate all the environmental impacts due to the incineration to the final consumers of electricity from waste (approximation A3) or to the plant (approximation A4)?

A possible answer to this question can be given by using the concept of shared consumer - producer responsibility. It recognizes that in every transaction there are always involved two groups: the producer and the consumer and therefore, the responsibility for the impacts of production has to be shared between them. Although not new, the idea of shared responsibility was consistently and quantitatively conceptualised only recently by Gallego and Lenzen (2005). These authors describe the way to divide the impacts between the supplier (producer) and the recipient (consumer) in an IO-type impact model. Following the concept of shared responsibility, the total impacts of the plant should be computed as:

$$g = F_{71}(I - \alpha \neq A_{71})^{-1}(\underbrace{\beta \neq y_{SIRUSA}}_{consumers} + \underbrace{(1-\beta) \neq y_{SIRUSA} + [(1-\alpha) \neq Z_{71}]u}_{plant(producer)}) \quad , \qquad (9)$$

where α and β are the shared responsibility parameters among industries and respectively between industries and final consumers. The symbol ≠ refers to element by element multiplication, so that the matrix $\alpha \neq A_{71}$ has the elements $\alpha_{ij} * A_{ij}$. Equation (9) says that from all the pollution the sector *i* receives with its inputs and/or emits on site, a fraction α_{ij} is passed to the producers *j* of its inputs and a fraction β_i goes to its consumers. The responsibility of the sector *i* is given by fractions $1-\alpha_{ij}$ and $1-\beta_i$.

The shared responsibility parameters are numbers between 0 and 1 (Gallego and Lenzen, 2005). At the limit, $\alpha_{ij} = 0 \quad \forall i, j$, we recover the full producer responsibility formulation, $g = F_{71}(y_{SIRUSA} + Z_{71} * u') = F_{71} x_{SIRUSA}$, given in equation (8). At the other extreme, $\alpha_{ij} = 1 \quad \forall i, j$, we recover the full consumer formulation, $g_{71} = F_{71}(I - A_{71})^{-1} y_{Sirusa}$, given in equation (7). To calculate the value of shared responsibility parameters, Lenzen *et. al* (2006) propose to use:

$$1 - \alpha_{ij} = 1 - \beta_i = \frac{v_i}{X_i - Z_{ii}}, \tag{10}$$

where v_i is the value added of sector *i*, and ($x_i - Z_{ii}$) is net output of industry *i* (output of *i* minus intra-industry transactions).

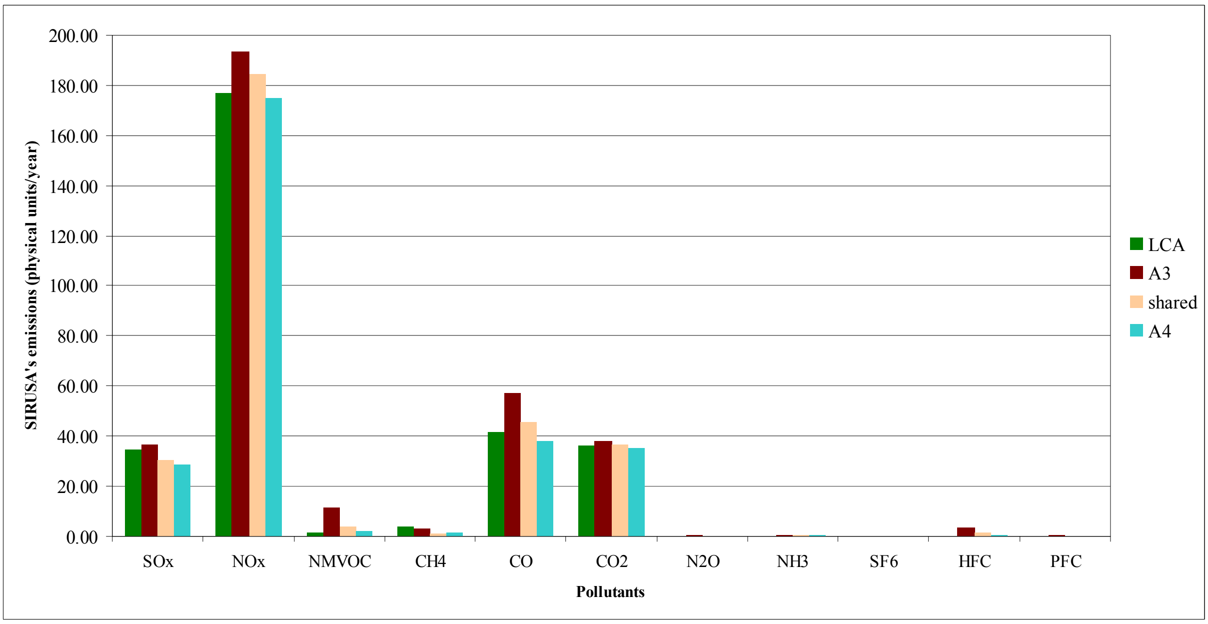

Figure 3. Emissions of SIRUSA by approximations A3 and A4 in comparison with shared responsibility and LCI.

The environmental impact attributed to SIRUSA by using shared responsibility is given in Table 3 and is represented by light pink bars in Figure 3. The total emissions generated by the plant are the emissions produced downstream the plant and on site so that SIRUSA is able to produce its final demand and its intermediate output (sold to other industries).

The emissions of SIRUSA in shared responsibility are values between the full-consumer approximation (A3) and full-producer approximation (A4). At the same time, they are closer to the LCI calculated results.

Table 3. Emissions of SIRUSA calculated by A3 and A4 in comparison with shared responsibility.

Emissions	Units	LCI	A3	shared	A4
SO_x	t	34.58	36.63	30.56	28.55
NO_x	t	176.73	193.43	184.48	174.84
NMVOC	t	1.62	11.48	4.22	1.90
CH_4	t	3.82	2.79	1.23	1.26
CO	t	41.38	57.36	45.48	38.09
CO_2	.000 t	36.32	38.01	36.43	35.13
N_2O	t	0.01	0.25	0.13	0.06
NH_3	t	0.02	0.42	0.27	0.35
SF_6	kg	0.00	0.03	0.01	0.01
HFC	kg	0.00	3.31	1.36	0.49
PFC	kg	0.00	0.58	0.17	0.07

If we share this total pollution between consumers and the plant:

$$g = F_{71}(I - \alpha \neq A_{71})^{-1}(\underbrace{\beta \neq y_{SIRUSA}}_{cons})$$

and

$$g = F_{71}(I - \alpha \neq A_{71})^{-1}(\underbrace{(1-\beta) \neq y_{SIRUSA} + [(1-\alpha) \neq Z_{71}]u'}_{plant(producer)})$$

, we obtain the results presented in Figure 4.

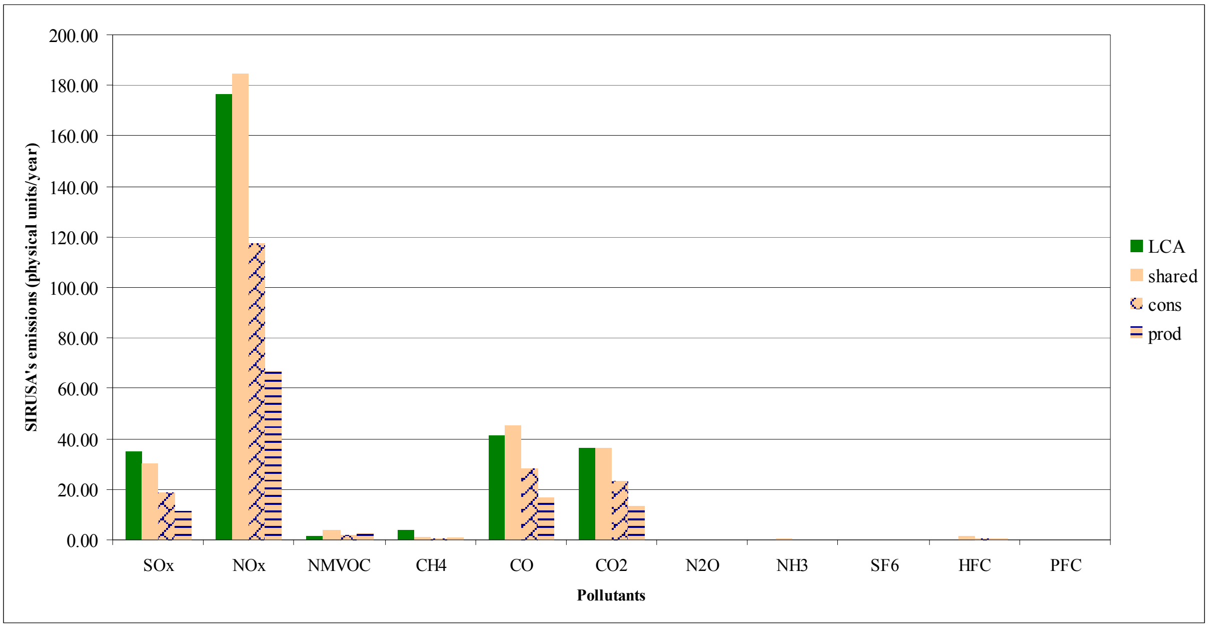

Figure 4. Emissions of SIRUSA by total responsibility, compared to consumer (cons) and producer (prod) responsibility, and LCI.

In this case, SIRUSA is made responsible only for the fractions $1-\alpha_{ij}$ and $1-\beta_i$ of its output, the remaining ones being attributed to its consumers or inputs providers. As it can be seen in Figure 4, the consumers of electricity (output of the plant) are made responsible for a bigger part of pollution, compared to the share of the plant. Even so, the emissions which the plant would be made responsible of are smaller than the LCI calculated.

The mechanisms through which the consumers should be made responsible for their share of pollution does not make the object of this work, so we will focus only on the plant and its responsibility for the emissions it produces. On our view, the plant has two options to reduce its emissions. First, it can work on improving its technology, e.g. improving the heat recovery, making a better selection of wastes before incineration, installing better filters, etc. the second option is to identify the most polluting providers of its inputs and ask them to improve their environmental profile. Therefore, in the next section we will apply Structural Path Analysis (SPA) in order to identify the most polluting input paths to the plants and also the processes left out of the LCI evaluation.

3. SPA methodology and application to the selection of boundaries in LCI

IO analysis can help LCI in two ways. Firstly, it can offer a solution to the selection of boundaries in LCI and secondly, it can be used for the estimation of environmental flows of the processes left out from the LCI evaluation. In what follows we discuss only the first option, while the second one is the objective of the next chapter "hybrid IO-LCI methods".

The current LCI methodologies and standards by the International Standards Organisation (ISO 14000 Series) impose practical difficulties in setting the system boundaries for an LCI study. The decision on which processes to be left out of the analysis is made on a subjective base, many times based on the data availability than on objective cut-off criteria. IO techniques, particularly Structural Path Analysis (SPA) can help to decide which processes to include or leave out of analysis. SPA allows identifying key sectors in air pollution (or other environmental interventions) and describes how the pollution is transmitted through out an economy.

Let us begin by particularising equation (4) for one atmospheric emission:

$$g = f(I - A)^{-1} y, \tag{11}$$

where f is the vector of emission intensities of type k (e.g. t CO/€ output of industries from **1** to **71**). The term $m = f(I - A)^{-1}$ is called vector of emission multipliers and expresses the total "embodiment" of atmospheric emission per monetary unit of final consumption supplied by the production sectors. Given a final demand y, the product my can be decomposed according to equation (12) to show the contribution by layers of suppliers:

$$my = f(I - A)^{-1} y = fy + fAy + fA^2 y + fA^3 y + \dots, \tag{12}$$

where the first term represents the contribution of the direct emissions, the second is the contribution of the first layer of suppliers, etc. Particularized for the final demand of industry i, y_i, the decomposition of its associated emissions can be written as follows (Lenzen and Treloar, 2003):

$$m_i y_i = f_i y_i + \sum_{j=1}^{n} f_j A_{ji} y_i + \sum_{k=1}^{n} f_k \sum_{l=1}^{n} A_{kj} A_{ji} y_i + \sum_{l=1}^{n} f_l \sum_{k=1}^{n} A_{lk} \sum_{j=1}^{n} A_{kj} A_{ji} y_i + \dots, \tag{13}$$

where n is the number of industries in which the economy is disaggregated. Each element of this decomposition represents a set of paths (each consisting on a sequence of purchases) from the "polluting" industry j (the industry directly responsible for the environmental impact) to the final demand of industry i. The first term, $f_i y_i$, is the direct pollution generated by the industry i; the next term contains n first order paths $f_j A_{ji} y_i$

between industries *j* and *i* and sums the emissions of the first layer of suppliers of industry *i* to produce the inputs needed by industry *i* to satisfy its final demand y_i; the n^2 second order paths $f_k A_{kj} A_{ji} y_i$ connect industries *j* and *i* via industry *k* and so on. Although the order of these indirect effects is infinite, each term of the series expansion becomes smaller with each round of purchases and the series eventually converges.

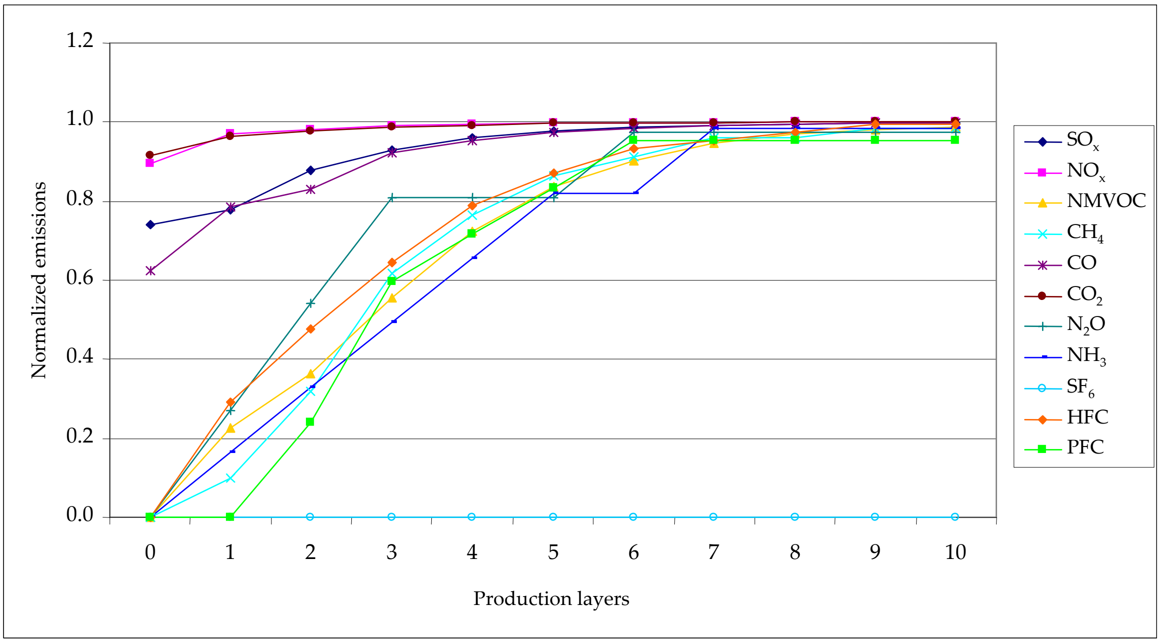

Figure 5. Normalized emissions as a function of the order of production layer

The evaluation of equation (13) for the first ten layers of suppliers of SIRUSA leads us to the results presented in Figure 5. All the values of emissions are normalized by the total emissions (sum of direct and indirect emissions) generated in the economy to deliver 1€ of electricity from waste to the final demand. Emissions listed under the zeroth order represent the emissions generated by the plant to deliver 1€ of output (electricity from waste) to the final demand. First order emissions originate from the suppliers of materials and services for the incineration of MSW at SIRUSA, e.g. transport of residues, lime, etc. As here we consider the plant generates only SO_x, NO_x, CO and CO_2, we have on site emissions different of zero only for these emissions. Especially for CO_2 and NO_x the direct emissions of SIRUSA make the most of the total emissions, meanwhile for SO_x and CO the contribution of the first and higher order layers of suppliers become important. For the rest of emissions, the only emissions contributing to the total are the indirect emissions and therefore the first and higher orders layers of suppliers are important. Anyway, Figure 5 evidences that after the sixth layer of suppliers the contributions of higher order layers to the total are insignificant and the series converge. Therefore, the decomposition described by equation (13) was performed only for the first six layers of suppliers. The only exception from this is SF_6 that does not converge. As the only source of SF_6 in the Spanish economy is sector **33** Manufacture of machinery and electrical material that does not appear in the upstream suppliers of SIRUSA, the contribution to the total SF_6 emissions of the first ten layers of suppliers of SIRUSA is small (approximatively 15%) and the serie does not converge.

Equation (13) was solved for 11 different vectors of emissions f_j corresponding to the emissions reported by INE in the Spanish NAMEA. The vector y contains the final demand of SIRUSA considered as the sector **61** (y_{SIRUSA} in the previous section) for the year 2000. The inputs paths calculated for the 11 pollutants are presented in Table 4 in descending order of their contribution to the total emissions of the respective pollutant. They are assigned a code consisting of (1) the path value in physical units, (2) the path description (industries implied in the supply chain), (3) the path order and (4) the path coverage, or the contribution in percentages to the total emissions of the given emission. The physical units are as follows: kg for SF_6, PFC and HFC, thousands of tones for CO_2 and the rest of pollutants are evaluated in tones. For example, the path: 0.09-**8 46 61** (2;0.24%) corresponding to CO_2, position 5, describes the generation of 0.09 thousands tones of CO_2 by the industry **8** Coke, refinement and nuclear fuels supplying oils to Other land transport; transport via pipelines **46** supplying SIRUSA **61**. The path is of second order and represents 0.24% from the total CO_2 emissions generated by SIRUSA in order to produce its output for the final demand in 2000.

The decomposition presented in Table 4 presents the important contribution of on site generation of SIRUSA (**61**) of SO_x, NO_x, CO and CO_2 to the total emissions of these pollutants. The most polluting direct suppliers of SIRUSA (**61**) are sectors "Other land transport; transport via pipelines" (**46**), "Manufacture of cement, lime and plaster" (**25)**, "Recycling" (**39**), and "Chemical Industry" (**23**). Important first order paths originate in sector **46** for NMVOC (11.67% from the total NMVOC emissions), CH_4 (7.18%), CO (6.74%), and N_2O (23.20%). Second and higher order paths involve sectors **8** "Coke, refinement and nuclear fuels", **9** "Electricity production and distribution", and **29** "Metallurgy" due to the consumption of oils, electricity and respectively metallic products by the suppliers of SIRUSA.

A LCI of a plant normally includes all the emissions generated on site and by the first order suppliers to the plant, besides those generated downstream the plant. As the production of electricity in coal-fired power plants is an important source of air pollution, almost every LCI includes also within its boundaries the process of electricity production although the process/activity under study may produce enough electricity for its functioning (the case of SIRUSA). As seen in Chapter I, the LCI of SIRUSA includes the production of electricity, but not the refining of fuels, neither the production of metallic pieces of machinery (sectors **8** and **29**). Although they are suppliers of second layer, both of these sectors induce important indirect emissions to the plant. Important second order paths originate also in sector **1** "Agriculture, livestock and hunting", representing purchases of vegetal oils or food for catering by the suppliers of **61**. These indirect inputs are not intuitively associated with the incineration of MSW and therefore they would be probably left out of analysis in a process-based estimation of emissions associated with the incineration of MSW (LCI).

Table 4. Top 10 paths for the pollution generated by MSW incineration

	SO_x		NO_x		NMVOC
1	27.42-**61** (0;74.86%)	1	173.90-**61** (0;89.90%)	1	1.34-**46 61** (1;11.67%)
2	0.91-**8 46 61** (2;2.49%)	2	9.22-**46 61** (1;4.77%)	2	0.81-**39 61** (1;7.03%)
3	0.88-**25 61** (1;2.40%)	3	3.17-**39 61** (1;1.64%)	3	0.31-**41 46 61** (2;2.71%)
4	0.60-**9 39 61** (2;1.64%)	4	1.14-**25 61** (1;0.59%)	4	0.20-**32 61** (1;1.69%)
5	0.35-**9 58 61** (2;0.95%)	5	0.311-**42 61** (1;0.16%)	5	0.15-**23 61** (1;1.29%)
6	0.32-**9 42 61** (2;0.87%)	6	0.214-**46 39 61** (2;0.11%)	6	0.13-**49 46 61** (2;1.14%)
7	0.23-**9 65 61** (2;0.63%)	7	0.21-**46 42 61** (2;0.11%)	7	0.11-**42 61** (1;1.00%)
8	0.22-**46 61** (1;0.60%)	8	0.20-**9 39 61** (2;0.11%)	8	0.09-**22 58 61** (2;0.77%)
9	0.14-**29 39 61** (2;0.37%)	9	0.18-**8 46 61** (2;0.09%)	9	0.08-**8 46 61** (2;0.69%)
10	0.13-**9 46 61** (2;0.35%)	10	0.12-**9 58 61** (2;0.06%)	10	0.06-**29 39 61** (2;0.51%)
	CH_4		CO		CO_2
1	0.20-**46 61** (1;7.18%)	1	36.32-**61** (0;63.33%)	1	34.92-**61** (0;91.87%)
2	0.08-**1 14 61** (2;3.01%)	2	3.86-**46 61** (1;6.74%)	2	1.01-**46 61** (1;2.65%)
3	0.08-**62 58 61** (2;2.82%)	3	3.50-**39 61** (1;6.10%)	3	0.45-**25 61** (1;1.18%)
4	0.08-**1 42 61** (2;2.80%)	4	1.02-**29 39 61** (2;1.77%)	4	0.23-**39 61** (1;0.60%)
5	0.07-**62 42 61** (2;2.58%)	5	0.78-**42 61** (1;1.36%)	5	0.09-**8 46 61** (2;0.24%)
6	0.04-**39 61** (1;1.47%)	6	0.63-**25 61** (1;1.10%)	6	0.06-**9 39 61** (2;0.16%)
7	0.03-**62 46 61** (2;1.39%)	7	0.30-**41 46 61** (2;0.51%)	7	0.04-**9 58 61** (2;0.09%)
8	0.02-**68 58 61** (2;0.73%)	8	0.15-**30 39 61** (2;0.26%)	8	0.03-**29 39 61** (2;0.09%)
9	0.02-**10 39 61** (2;0.72%)	9	0.13-**49 46 61** (2;0.23%)	9	0.03-**42 61** (1;0.09%)
10	0.02-**68 42 61** (2;0.67%)	10	0.09-**46 39 61** (2;0.16%)	10	0.03-**9 42 61** (2;0.08%)
	N_2O		NH_3		SF_6
1	0.064-**46 61** (1;23.20%)	1	0.034-**1 14 61** (2;8.19%)	1	0.002-**33 32 61** (2;6.97%)
2	0.022-**23 61** (1;5.95%)	2	0.032-**1 42 61** (2;7.61%)	2	0.0006-**33 39 61** (2;2.51%)
3	0.010-**25 61** (1;4.70%)	3	0.027-**23 61** (1;6.34%)	3	0.0003-**33 42 61** (2;1.00%)
4	0.010-**8 46 61** (2;3.86%)	4	0.006-**23 23 61** (2;1.53%)	4	0.0002-**33 31 61** (2;0.80%)
5	0.009-**39 61** (1;3.43%)	5	0.006-**1 65 61** (2;1.49%)	5	0.0002-**33 58 61** (2;0.74%)
6	0.005-**42 61** (1;1.77%)	6	0.005-**46 61** (1;1.31%)	6	0.0001-**33 46 61** (2;0.63%)
7	0.004-**1 14 61** (2;1.67%)	7	0.004-**1 39 61** (2;1.06%)	7	0.0001-**33 65 61** (2;0.45%)
8	0.004-**1 42 61** (2;1.55%)	8	0.004-**39 61** (1;0.96%)	8	0.000-**33 23 61** (2;0.33%)
9	0.003-**23 23 61** (2;1.44%)	9	0.003-**1 17 61** (2;0.90%)	9	0.000-**33 25 61** (2;0.16%)
10	0.002-**30 46 8 61** (3;1.05%)	10	0.002-**23 39 61** (2;0.66%)	10	0.000-**33 14 61** (2;0.02%)
	HFC		PFC		
1	0.98-**23 61** (1;29.67%)	1	0.12-**29 39 61** (2;22.18%)		
2	0.24-**23 23 61** (2;7.18%)	2	0.005-**29 32 61** (2;0.87%)		
3	0.10-**23 39 61** (2;3.10%)	3	0.001-**29 25 61** (2;0.18%)		
4	0.09-**23 58 61** (2;2.96%)	4	0.001-**29 31 61** (2;0.16%)		
5	0.06-**50 23 23 61** (3;1.74%)	5	0.001-**29 23 61** (2;0.10%)		
6	0.05-**23 42 61** (2;1.47%)	6	0.001-**29 58 61** (2;0.08%)		
7	0.03-**23 65 61** (2;0.80%)	7	0.000-**29 42 61** (2;0.03%)		
8	0.02-**23 46 61** (2;0.60%)	8	0.000-**29 46 61** (2;0.03%)		
9	0.02-**23 17 61** (2;0.49%)	9	0.000-**29 65 61** (2;0.02%)		
10	0.01-**23 32 61** (2;0.40%)	10	0.000-**29 57 61** (2;0.01%)		

In Figures 6 and 7 we tried to give an easier visualisation of the results presented in Table 4. For reasons of brevity, we present only the results for SO_x and CH_4, but similar diagrams can be traced for all the others pollutants. The first order paths are represented by continuos lines, the second level by dotted lines. To keep the diagrams as clear as possible, we give only some top values of emissions (numbers and units associated to some paths). In both cases, in the first layer of suppliers we present all the direct suppliers of SIRUSA, although not all of them contribute to the SO_x or CH_4 emissions. In the second layer of suppliers we present only the top contributors to each emission.

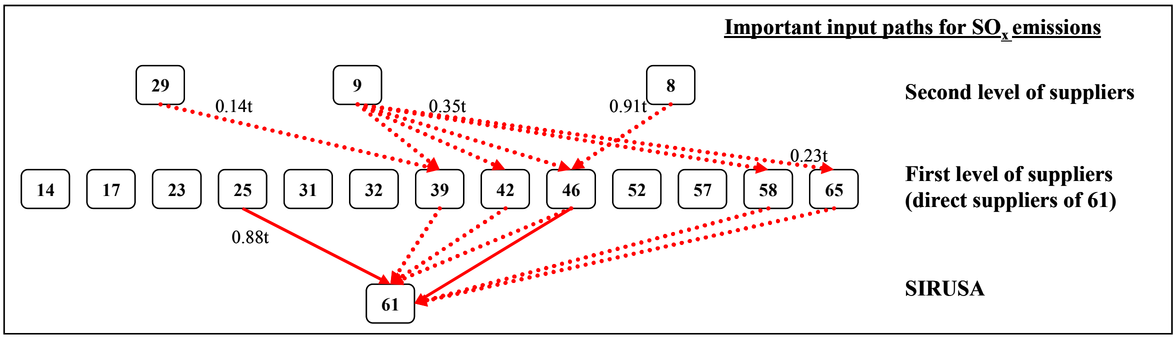

Figure 6. Top 10 paths for the SO_x emissions generated by SIRUSA

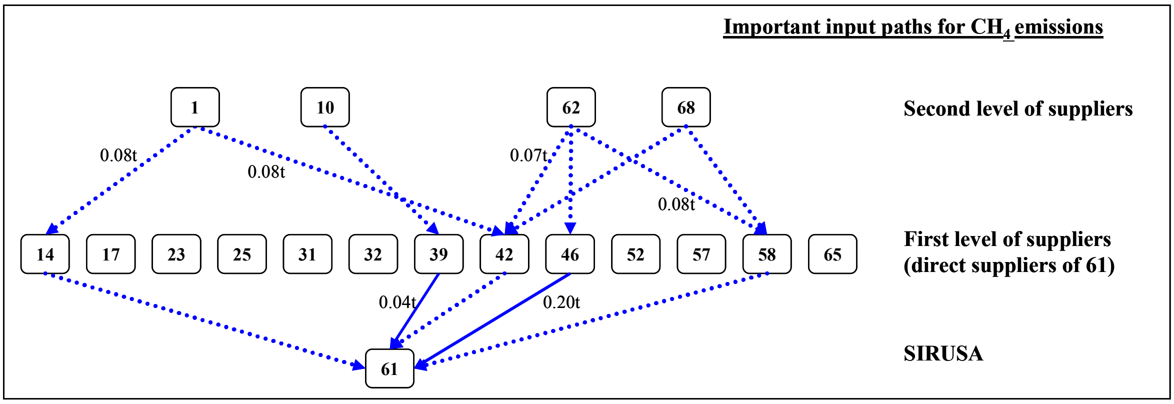

Figure 7. Top 10 paths for the CH_4 emissions generated by SIRUSA

In Figure 7 we read the "Agriculture", or sector **1**, is an important CH_4 releaser and although it is not a direct supplier of SIRUSA, it induces important indirect emissions of methane by selling to sector **14** "Manufacture of other food products" the necessary materials to extract the oils and fats needed by SIRUSA to function (second order paths). The services sectors **62** and **68** have also important indirect contributions to the emissions of methane. These are valuable data for an LCI, where all the emissions implied in a production of a good or service should be considered in order to evaluate properly if the respective good or service is "green". Because the limitations of LCI databases, the processes included in these second order transactions would not be introduced in the total inventory implying an underestimation of CH_4 emissions.

4. Conclusions

Considering the case-study of a municipal solid waste incineration plant, we compare different IO techniques for evaluating the total emissions (sum of direct and indirect emissions) generated by a process plant. We present four IO techniques; one of them uses the IO tables in their original form and the other three proceed to the disaggregation of one sector into two sub-sectors: one containing the sales and purchases of the plant to and from the other sectors and the other one being the difference between the disaggregated sector and the new one. We obtain better results when we disaggregate the original IO tables to include the plant as an individual sector in the economy. In this case, real data from the plant were used in the calculations instead of average data on the sectors the economy is divided and the results come closer to other types of analyses; i.e. process-based analysis (LCI).

Considering the plant as an individual sector in the IO table, we consider that the best estimation of its emissions has to consider the concept of shared responsibility. If there is to perform a LCA of incineration and then others of the transport of wastes or ulterior treatment of wastes resulted from incineration, etc., the results of these LCAs will count again and again all the emissions from transport, treatment of ashes and slags, etc and each individual company that provide these services will be made responsible for much more that it actually emits. Therefore, in the chain of MSW incineration the responsibilities each company would have to assume are not clear. By dividing these emissions between all the actors implied in the chain, we avoid double counting; furthermore, each company (actor) would know exactly which its share of emissions is and also which are those of its providers and it can choose easier the providers with less environmental impact, this implying also a decrease of its emissions.

Performing a structural path analysis (SPA) to the results obtained by considering the plant as individual sector, we demonstrate the utility of IO techniques to decide the processes to be included or excluded from a detailed LCI. Applied to the same case of an incinerator, SPA highlighted the important “hidden” contributions of “Agriculture”, “Metallurgy” and “Coke, refinement and nuclear fuels” to the upstream induced emissions of the plant. These contributions would not be evaluated in a conventional LCI because of the limited data availability, but they would be better estimated in a hybrid IO-LCI approach.

Compared to LCI, IO techniques can be used only for the evaluation of few environmental interventions (e.g. atmospheric emissions, land-use or water-use) for which national inventories are available; i.e. for the applications in this chapter we estimated only the emissions of 11 pollutants for which emissions per sectorial output are available at national level, compared with over 1000 emissions that can be estimated using LCI databases. Also, IO techniques can provide LCI only for the pre-consumer stages of the product or activity life cycle, while the rest of the life cycle stages are outside the system boundaries of IO analysis (Joshi (2000), Suh *et al.* (2004), Suh and Huppes (2005)). Furthermore, IO data suffer from aggregation; i.e. the Spanish economy is disaggregated into 70 sectors and 110 commodities. Under the same generic commodity there are various similar products and in all the calculations these products are considered as having the same input structures. In a LCI this is quite a coarse approximation and it can lead to under or overestimations of the impact a product can have on the environment. All of these arguments make that the IO results cannot be used in LCI as stand-alone results (summed up to the LCI results), but rather as supplementary information, guiding an LCI study on the boundary selection or covering the processes an LCI would be impossible to cover.

CHAPTER V

HYBRID LIFE CYCLE INVENTORIES OF MUNICIPAL SOLID WASTE INCINERATION

Abstract

Life Cycle Assessment (LCA) evaluates the environmental impact of a production activity using material and energy flows. Environmental Input-Output (IO) does the same but with monetary flows. Although very specific and detailed, LCA has the main disadvantage of little availability of data that reduces the boundaries of the analysis to few more processes than the production process itself. On the other side, IO allows estimations at national or regional levels, but its results are aggregated and unspecific. To improve their strength and reduce their weakness, recent approaches have tried to bring IO and LCA in a common framework known as "hybrid IO-LCA models". In this chapter we adapt and apply two hybrid models, specifically the tiered-hybrid and the integrated hybrid methods, to the case of a Spanish incinerator. Our results show that applied to end-of-life processes, the two methods give the same results meanwhile the tiered hybrid model is easier to apply in practice. Using together IO and LCA in hybrid models allows making trade-off analyses between the economy and environment.

Keywords: Life Cycle Inventory (LCI); hybrid IO-LCI models; municipal solid waste incineration (MSW).

1. Introduction

ISO 14040 defines LCA as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle". The life cycle of a product begins with the extraction of the raw materials used for its production, and follows through processing, transport, use, reuse, recycling or/and final disposal. To cover all these stages, LCA needs specific and very detailed information at process level, and can thus be extremely resource intensive. A complete LCA study can be performed at the level of small organizations or technologic entities (e.g. a process plant), but at higher scale it would imply high costs and quite a long time for gathering the necessary data.

On the other side, IO analysis is a technique that shows how industries are linked together through supplying inputs for the output of an economy. It uses data compiled mainly at national level in the IO tables. In these tables are compiled all the monetary transactions between the sectors an economy is considered to be disaggregated. Because of data aggregation, IO techniques can be used for analyses at national level, but they are not adequate for comparisons between similar products considered within the same economic sector or for the assessment of new technologies. On this aspect, LCA is much more accurate and specific but lacks of completeness. It is quite complicated to draw the borders of a process-specific assessment: as the system under study increases (the boundaries are enlarged to include the production of inputs to the LCA system), the LCA practitioner find himself faced with the availability of data. From a point on, he/she has to stop compiling data and draw a border (this is known as truncation in LCA) or to use more aggregated data, thus losing specificity. The use of IO data to overcome the problem of completeness of the assessment is generally known as hybrid analysis.

The first combination of process-specific data with IO average data was suggested by Bullard *et al.* (1978) in the field of energy analysis. They calculated the energy cost of an atypical product that cannot be represented by an aggregated industrial sector (e.g. a power plant) by using a process-flow diagram and process-specific data supplemented by IO average data. Given an atypical product, the first step in their approach is to determine the materials and energy required for its production (draw the process-flow diagram). Some of these inputs may be typical outputs of industrial sectors and IO equations can be used to calculate their total energy costs. For the rest of them, the chain of inputs has to be traced back to the point where the input is sufficiently "typical" output of an industrial sector (see Figure 1). The IO-based results that cover processes far upstream from the process that deliver the product under study are then summed up to the process-analysis results that cover the processes near the studied production process. This type of approach is referred to as a "tiered hybrid method".[25]

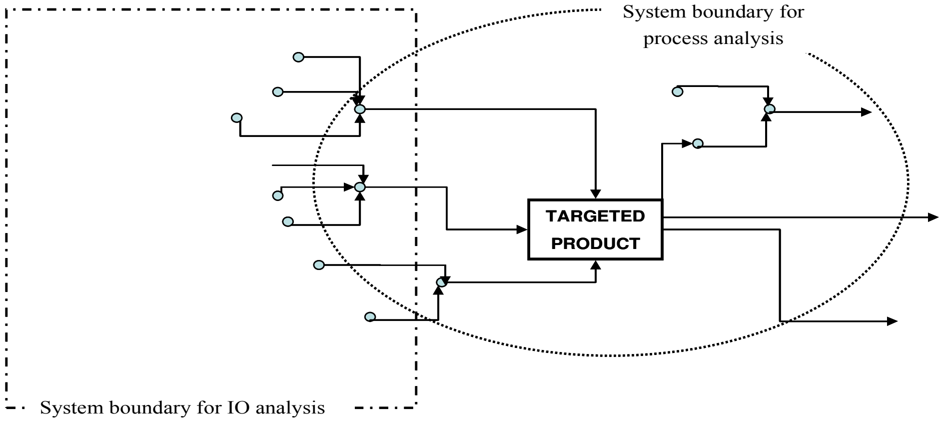

Figure 1. System boundaries for process and IO analyses

Using this approach, Moriguchi *et al.* (1993) analyse the CO_2 emissions of a car. Their application uses IO for the pre-consumer stages and LCA for the use and end-of-life stages of a car. Then, the total emissions are obtained by summing up the results of the IO part with those of LCA. Model II by Joshi (2000) uses the same approach, but starting from the IO side. He considers the disaggregation of the IO tables to improve process specificity but the results cover only the pre-consumer stages of a product or activity. To cover the use and end-of-life, a process-analysis method is still necessary.

By using together IO and LCA, the boundaries of the analysis are wider, but the upstream system boundary could not yet be reached specially for economies that strongly rely upon imports. To overcome this problem, Hondo *et al.* (1996) used process-modelling for far upstream processes not covered by the Japanese IO tables (e.g. coal mining) and IO for the remaining sectors.

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[25] See Rebitzer et al. (2004) and Suh and Huppes (2005) for the classification of hybrid models.

There appear several problems when using together LCA and IO results:

- The different computational structures of IO and LCA imply separated analyses. IO is computed in a matrix form and LCA uses the graphical representation of the processes within the boundaries of the assessment. This problem is overcome by computing LCA in a matrix form;[26]
- IO can only account for the pre-consumer stages of a product life-cycle;
- The type of data used in IO is different of those used in LCA: monetary vs. physical units, environmental loads per unit of sectoral output vs. environmental loads per unit of product (kg, kWh, hours of washing, etc.);
- The flows accounted in process-analysis are already included in the data in IO tables used in the IO-part; hence a summation of LCA and IO results implies a double-counting;
- If the analyst applies other analytical tools (e.g. uncertainty and sensitivity analyses) to the results of assessment, the calculations are to be performed separately.

All these problems make difficult the modelling of interactions between LCA and IO. A change in the process-analysis is not reflected in the results of the IO part, unless the later is reformulated and adapted to the change. Therefore, Suh (2004) proposed a hybrid model which integrates not only the results of LCA and IO, but also their computational structures within a consistent framework. This approach is known as "integrated hybrid analysis".

The objective of this chapter is to adapt and apply the tiered-hybrid and the integrated hybrid methods to the practical case of an incinerator in Spain. The results of these methods are compared to those obtained by applying LCA to the same case-study. The chapter is structured as follows: in Section 2 we briefly explain the computational structures of LCA and IO but pay special attention to the integrated hybrid analysis equations. We follow by giving a procedure to compile step-by-step a hybrid model and apply it to the case of SIRUSA waste incinerator. The chapter concludes with some remarks on the use of hybrid models and the differences on results compared with pure process-specific models (LCA) or pure economic models (IO).

2. Computational structure of LCA, IOA and hybrid models

LCA is a method to quantify and evaluate the potential impacts of goods and services. The analysis is conducted in a life-cycle perspective, from "cradle to grave", covering every stage of a product life cycle, from raw materials acquisition, through manufacture, distribution, use, possible recycling and final disposal (ISO 14040 (1998), Guinée *et al.* (2002)). As it requires large amounts of data, in the first phase of the analysis (goal and scope definition) is necessary to define the boundaries of the study, in other words, define which processes are to be included in the analysis. The compilation and quantification of all material and energy flows within the boundaries of the product system is made in the inventory phase (see Chapter I for a detailed description of LCA phases). In matrix formulation, the inventory of a product-system is calculated by:

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[26] See Heijungs (1994), Heijung and Suh (2002) and Chapter I of this book for the description of the matrix method for computing LCA.

$$g_{LCI} = B * A^{-1} * f, \tag{1}$$

where g_{LCI} is the vector of the total amounts of natural resources consumed and emissions released directly and indirectly by the product-system under analysis in order to deliver a certain amount of product outside the system[27] (Heijungs (1994) and Heijungs and Suh (2002)). B is the matrix of environmental loads; each of its elements b_{ij} shows the amount of natural resources or emissions i consumed or released by unit process j. A is the technology matrix, its elements a_{ij} show the inflow or outflow of product i to or from the unit process j; and f is a vector that shows the functional unit of the system.

The main problem of LCI is the large amounts of data it requires. In principle, all processes in an economy are directly or indirectly connected with each other and the compilation of a complete LCI is practically impossible, as it would imply collecting process specific data for all the economy. This problem has led to the use of IO techniques in LCI. In IO the analysis is made at national or regional scale and unit processes considered in LCI are equivalent to economic sectors, each of them producing a unique and distinct good or service. The structure of IO model, a linear network, assumes that each sector consumes goods or services from the other sectors in fixed proportions in order to produce its unique (or typical) output. Given a final demand y, the total output x required to satisfy it is calculated as:

$$x = (I - \tilde{A})^{-1} y, \tag{2}$$

where I is an $n \ x \ n$ identity matrix, x is the vector of the sectorial total outputs and $\tilde{A}$ is the matrix of technical coefficients (Miller and Blair, 1985). An element $\tilde{a}_{ij}$ of this matrix represents the inputs from industry i needed by industry j to produce one monetary unit of its output. If $\tilde{B}$ is a matrix which elements $\tilde{b}_{kj}$ represent the environmental burden of type k generated by industry j in order to produce one monetary unit of its output, then the total direct and indirect environmental loads generated by the economy to satisfy a given final demand are calculated by:

$$g_{IO} = \tilde{B}(I - \tilde{A})^{-1} y. \tag{3}$$

Due to the aggregation of information by sectors, the results of IO analysis are less specific than those of process-analysis. IO accounts for "commodities" instead specific "goods", "services" of "products" in LCI nomenclature. Under the same commodity are grouped various similar products, e.g. all the drinks as lemonade, cola, wine, beer, etc. are classified as "beverages" in the IO tables. Therefore LCA practitioners generally consider the results of IO analysis as less reliable due to aggregation, temporal differences between the IO data and current process operation, their dependence on prices, import assumptions, etc. If IO results are to be used to supplement LCI data, LCA practitioners prefer to use them only for upstream and downstream cut-offs for which better data are not available. This is the idea behind the tiered hybrid models introduced in Section 1. These models use process-analysis for the production, use and disposal phases as well as for several important upstream flows and for the remaining flows that have to be cut-off from the analysis, due to the missing information, the data are imported from IO analysis.

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[27] The index *LCI* in g_{LCI} is used here to differentiate the result of LCI analysis from the ulterior IO result.

The result of a tiered hybrid model g_{th}[28] is obtained by the simple summation of LCI results, obtained by applying equation (1), to the IO results, obtained by equation (3):

$$g_{th} = g_{LCI} + g_{IO}. \tag{4}$$

Compared to LCI, the results of the tiered hybrid model are more complete, as they include all the economy in the analysis. One of its weak points is the unclear boundaries definition between the IO and LCI part. Significant errors can be introduced if important processes are modelled using aggregated IO data. For a better selection of LCI boundaries, IO techniques, such as Structural Path Analysis (SPA) described in Chapter IV, can be applied. Another weak point of the tiered hybrid model is the independent compilation of the two models IO and LCI. The flows accounted in process-analysis are already included in the data in IO tables used in the IO-part; hence a summation of LCA and IO results implies a double-counting. Furthermore, because of the independence between the two parts, important changes in LCI cannot be properly reflected in the IO part; e.g. the modelling by LCI of a new technology that would imply a change in the flows between different sectors in the IO would not have any effect in the IO part. A solution to these problems is to use the integrated hybrid model described by Suh (2004). In his approach, both LCI and IO models are merged into one matrix and the solution to the inventory problem is given by solving:

$$g_{ih} = \overline{B} * \overline{A}^{-1} * \overline{y}\ . \tag{5}$$

Equation (5) has the same form as equations (1) and (3), but $\overline{B}$ is a matrix containing information from both LCA and IO, and is given by:

$$\overline{B} = \begin{bmatrix} B & \tilde{B}_* \end{bmatrix}, \tag{6}$$

where B is the matrix of environmental loads per functional unit of each process assessed in the LCI part, and $\tilde{B}_*$ is the matrix of environmental loads per monetary output of sectors considered in the IO part from which were subtracted the environmental burdens accounted in the LCI part.

Matrix $\overline{A}$ in the integrated hybrid approach contains information from the process-based analysis, the IO part and also additional information describing the two-sided interaction of LCI with the IOA-system (upstream and downstream cut-offs from LCI). It is given by:

$$\overline{A} = \begin{bmatrix} A_* & -C^d \\ -C^u & I - \tilde{A}_* \end{bmatrix}, \tag{7}$$

where A_* is the technology matrix by LCI (A in equation (1)) modified for the integration with the IO part, C^u and C^d represent the upstream cut-off by process and the downstream cut-off by functional flow matrices respectively. C^u contains all the upstream cut-off flows from the LCI analysis and is calculated by dividing the total bill of products not covered by LCI by the total monetary output of the product system under analysis. C^d contains the downstream flows cut-off from the LCI analysis and is calculated by dividing the annual sales of functional flow (in physical units) by the production of each total commodity. $\tilde{A}_*$ is the matrix of technical coefficients from which were subtracted all the commodity

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[28] The index *th* is used to make the difference between the result of tiered hybrid and integrated hybrid models.

flows covered by the LCI part. All the operations of subtraction of commodity flows accounted in the LCI part are made at the level of make and use matrices (Suh, 2004).

Finally, if $\overline{y}$ is the vector of final demand for functional flow considered in LCI (its value shows the functional unit of the LCI part), then equation (5) gives the total amount of environmental loads resulting from the interactions between the functional-flow based part (LCI) and the commodity based part (IO) in both directions.

3. Application of the tiered hybrid and integrated hybrid models to the case of a MSW incinerator. Results and discussion.

In this section we apply the tiered hybrid and integrated hybrid models described in the previous section to the real case of the municipal solid waste (MSW) incinerator of Tarragona, Spain. The main activity of the incinerator is to treat by incineration the MSW coming from the surrounding cities Tarragona, Reus, Valls, Salou, Cambrils, Vila-Seca and Constantí. As result, the amount of MSW is reduced to one third, but incineration is a highly polluting and expensive process. Therefore, to increase the efficiency of the process, the heat resulted from incineration is recovered and electricity is co-produced. As electricity is the only output with positive monetary value, in our LCI study we consider the functional unit 1 TJ of electricity co-produced and not 1000t of incinerated MSW as considered in previous studies realized by the research group from the University Rovira i Virgili (Alonso 1998; Nadal 1999; Sonnemann 2002). Besides the data on environmental loads generated by the incinerator, SIRUSA provided us the economic data on the purchases and sales of the plant. This information allows us to calculate the LCI of the plant and also to derive the economic data for the cut-off flows from LCI and apply the tiered hybrid and integrated hybrid models. For a detailed description and application of matrix LCI to the data of SIRUSA and results, see Chapter I. Also, the application of IO techniques to the data of the plant and results are presented in Chapter IV. In this section we focus only on the application of the two hybrid models described in Section 2.

To perform the calculations described by equations (1) to (7), we use data from SIRUSA and from the Spanish Institute of Statistics. The plant provided us with environmental data on the emissions generated by its functioning and also by the treatment of its residues during the year 2000. The economic data provided by SIRUSA for the same year consist on the purchases and sales of the plant. The Spanish Institute of Statistics (INE) reported for 2000 both economic and environmental data. The make and use tables for 2000 (INE, 2005) are given disaggregated into 110 commodities and 72 economic sectors, following CNAE-93 classification. We aggregated them into 70 homogenous sectors. The emission data coming from the Spanish Satellite Atmospheric Emissions Accounts (INE, 2001) consist of emissions of 11 atmospheric pollutants released by 45 domestic economic sectors, following NACE Rev.1. As both classifications CNAE-93 and NACE Rev.1 have compatible structures, we disaggregated the emissions matrix into 70 sectors as the use and make matrices. For this task we used supplementary pollution data published in the Spanish National Inventory of Atmospheric Emissions (EIONET, 2005). The atmospheric pollutants are: sulphur oxides (SO_x), nitrogen oxides (NO_x), no methane volatile organic compounds (NMVOC), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), nitrous oxide (N_2O), ammonia (NH_3), sulphur hexafluoride (SF_6), hydro-flour carbonates

(HFC) and perfluorocarbons (PFC). SIRUSA provided us with environmental data on 20 atmospheric pollutants including particles, dioxins, heavy metals, nitrous and sulphur oxides, volatile organic compounds, CO and CO_2, etc. In this study we only consider the 11 pollutants included in the Spanish Satellite Atmospheric Emissions Accounts of Spain for the year 2000.

As described in Chapter I, the matrix LCI includes in analysis only few processes: the process of incineration, the production of the utilities necessary in this process, the treatment of ashes and slag resulted from incineration, and the transport of wastes to an from the incinerator. Nevertheless, there are materials necessary for the functioning of the plant that are cut-off from the system. These are: fungible material for the office supply, writing paper, informatics, cleaning material, chemicals for the purification of water in the water plant next to the incinerator, auxiliary materials used in the plant, lubricating oils and fats. There are also important expenditures of the plant for protocol actions, external specific analysis of resulted wastes that cannot be performed in the laboratories of the plant, security personal and other expenditures for the maintenance of the plant. All of these flows are cut-off from the LCI analysis as they are considered very low of no polluting. However, they can be quickly assessed by using the tiered hybrid model described by equation (4). If we list all the purchases of the plant and identify each expense with its appropriate sector in the IO classification, we obtain the upstream interaction of LCI analysis with the IO system:

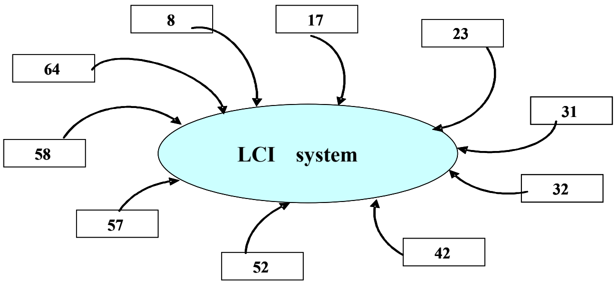

Figure 2. Upstream cut-off flows from LCI

In Figure 2, sectors from which SIRUSA buys are represented by number codes. The correlation of the cut-off flows from LCI with these code numbers and with the name of the sectors in IO classification is given in Table 1.

If we apply equation (3) to calculate the environmental loads associated with the production of products and services that SIRUSA purchases from the rest of the economy, we obtain the results represented in by white bars in Figure 3. In the same graph we represent the results of the matrix LCI and of the tiered hybrid model calculated using equation (4).

Table 1. Sectors of production in Spanish IO classification

Upstream cut-off flows	Sector code number	Name of sector
lubricating oils and fats	8	Coke, refinement and nuclear fuels
security and cleaning material	17	Textile industry
chemicals for water purification and laboratory	23	Chemical industry
auxiliary materials and spare machinery	31	Machinery and mechanical equipment
informatics	32	Office machines and computers
fungible materials, cleaning products	42	Wholesale trade and commission trade, except of motor vehicles and motorcycles
pension funding	52	Insurance and pension funding, except compulsory social security
analysis and research	57	Research and development
administrative services	58	Other business activities
social insurances	64	Public Administration

As Figure 3 and data in Table 3 show, the contribution of upstream cut-off flows to the total amounts of emissions is small for the pollutants emitted on site by the plant; e.g. for CO_2 it is 1.36%, NO_x 1.25%, SO_x 8.81% and for CO is of 8.77%. Nevertheless, for the pollutants not emitted on site by the plant, the contribution of the upstream cut-offs is around 99%.

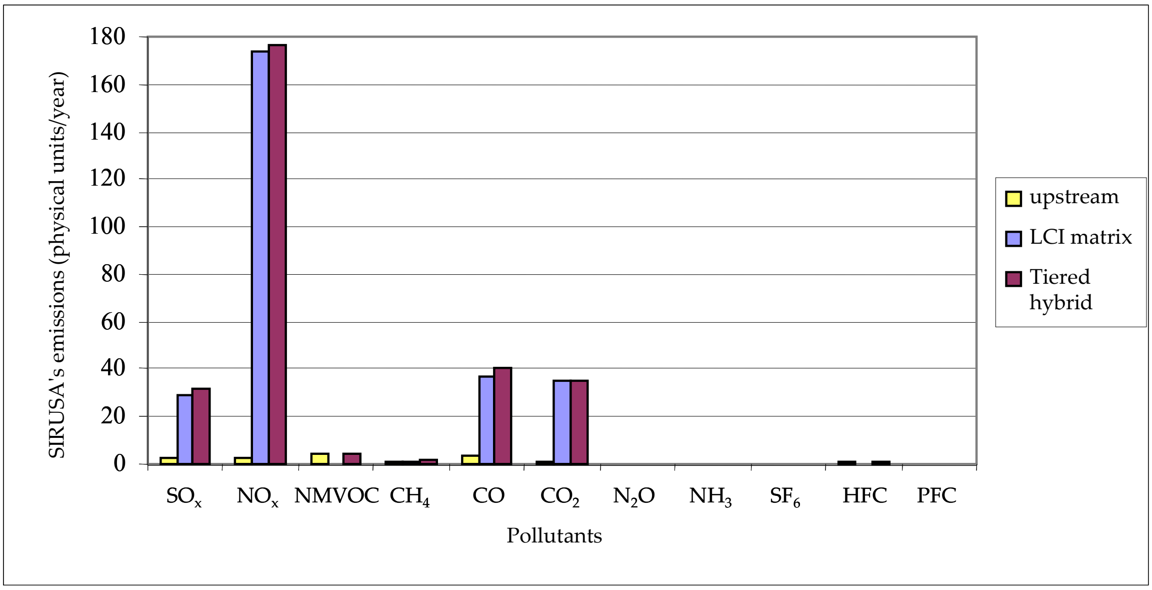

Figure 3. Emissions from the production of inputs to SIRUSA in comparison with LCI of the plant

Let us see now how change the results of the assessment if we apply the integrated hybrid model described by equation (5). First of all, the LCI matrix of the incineration process cannot be used in its original form (as presented in Figure 6, Chapter I). To be integrated with the IO tables, the inventory matrix has to be redefined in order to reflect the relations between processes based on supply-demand interaction (Suh, 2004) and not on production-consumption as in its initial form. The new inventory matrix is given in Table 2. If we compare it with the inventory matrix given in Table 1, Chapter I, we note there are few changes. In the new representation, the flows of ashes and slag for treatment changed their signs in the process of incineration and ash and slag treatments. In the process of incineration, the resulting flows of ash and slag for treatment are not considered as outputs of incineration, with positive sign, but as consumption of "kg waste treatment service" and therefore with negative sign. Processes of ash and slag treatment have now as output "kg of waste treatment service" and therefore, the flows of ash and respectively slag have positive signs.

The economic system in which the new inventory matrix is to be integrated is composed by 70 sectors. The original IO tables provided by INE have to be modified in order to subtract the flows already covered by LCI analysis. The operation of subtraction is made at the level of make and use tables. For a detailed description of the subtraction procedure, see Appendix A in Suh (2004). To construct the upstream cut-off matrix, we use the list of purchases of SIRUSA. Each element c_{ij}^{u} of the cut-off matrix represents the amount of cut-off commodity *i* to process *j* in monetary terms. To construct this matrix, first we identify each expense with its appropriate sector in the IO classification, resulting the cut-off commodity *i* and second, each entry in the table is divided by the total production in monetary units of process *j*. As for the downstream cut-off matrix, as LCI covers all the end-of life of incinerated wastes, we consider it as having all entries equal to 0; $\forall i,j \quad c_{ij}^{d}=0$.

Table 2. The new technology coefficient matrix for integration with IO tables

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	6.4E+05	-2.3E+05	-2.3E+05	0	-4.4E+04	-1.3E+01	-2.1E+03	-2.3E+02	-4.2E+04
2	0	7.7E+07	-7.7E+07	0	0	0	0	0	0
3	0	0	4.3E+07	0	0	0	0	0	0
4	0	-2.1E+06	-2.1E+06	8.1E+06	0	0	0	0	0
5	0	-2.0E+10	0	0	2.0E+10	0	0	0	0
6	0	0	0	0	-1.5E+03	7.5E+03	0	0	0
7	0	0	0	0	-6.2E+02	0	6.2E+02	0	0
8	0	0	0	0	-1.2E+03	0	0	1.2E+03	0
9	0	0	-5.2E+09	0	0	0	0	0	5.2E+09
10	0	-7.4E+09	0	0	0	0	0	0	0
11	0	-1.7E+06	-1.7E+06	0	0	0	0	0	0
12	0	-1.4E+06	-1.4E+06	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0
15	0	-9.2E+05	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0
17	0	-7.4E+04	-7.4E+04	-6.5E+05	0	0	0	0	0

Table 2. The new technology coefficient matrix for integration with IO tables (continuing)

	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	-4.2E+04	-4.6E+04	-3.0E+02	-3.0E+02	-1.0E+02	-5.5E-01	0	-7.3E+01
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	-1.1E+06	-1.5E+06	-1.5E+06	0	0	0	0
5	0	0	0	0	0	0	0	0
6	-6.0E+03	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	7.4E+09	0	0	0	0	0	0	0
11	0	3.5E+06	0	0	0	0	0	0
12	0	0	1.4E+06	-1.4E+06	0	0	0	0
13	0	0	0	2.2E+06	0	0	0	0
14	0	-5.2E+05	0	0	5.2E+05	0	0	0
15	0	0	0	0	0	9.2E+05	0	0
16	-1.2E+04	0	0	0	0	0	1.2E+04	0
17	0	-3.8E+03	-9.6E+02	-9.6E+02	0	0	0	8.0E+05

The results obtained by applying the integrated hybrid model are represented in Figure 4 and Table 3.

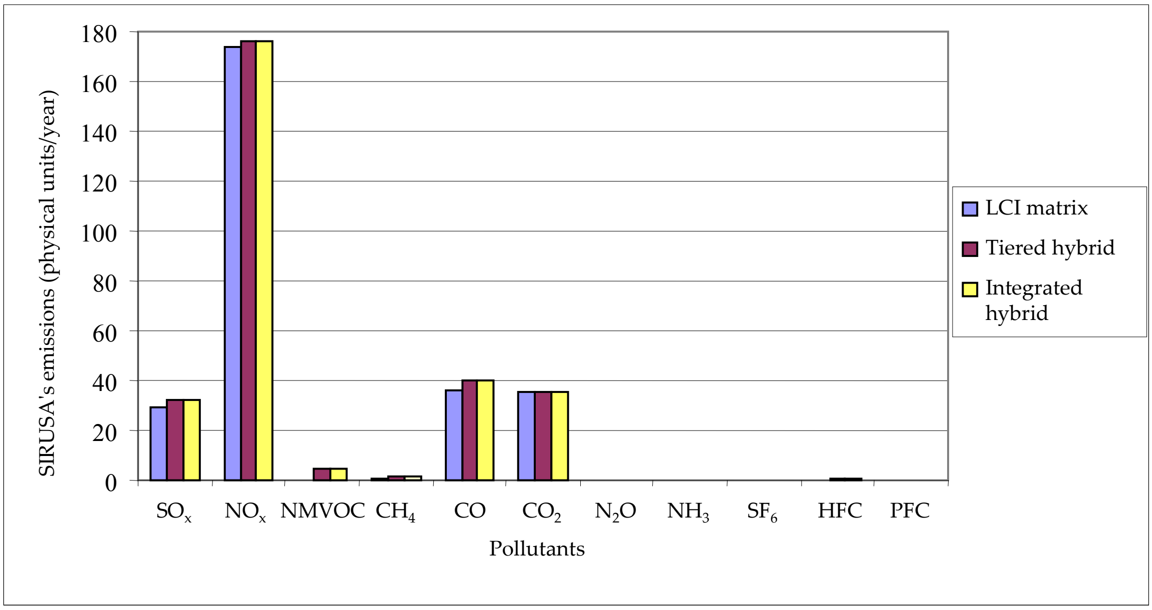

Figure 4. Emissions of the incineration system calculated by integrated hybrid model in comparison with LCI matrix and tiered hybrid model results.

The differences between the tiered hybrid and integrated hybrid methods are very small in the case of the analysed system (they differ only at the 4th decimal) and are due probably to computation round-offs. It is expected to be in this way, because for the studied system, the integrated hybrid model does not consider any downstream connection of LCI with the IO system. In this specific case, the integrated hybrid model is composed by a pure-LCI part and additional upstream requirements calculated by IO, identical to the tiered hybrid method.

Table 3. Values of emissions calculated by LCI, IO upstream and hybrid methods.

Emissions	Units	LCI matrix	Upstream	Tiered hybrid	Integrated hybrid
SO_x	**t**	29.18	2.82	32.00	32.00
NO_x	**t**	174.21	2.20	176.41	176.41
NMVOC	**t**	0.12	4.18	4.30	4.30
CH_4	**t**	0.56	1.15	1.71	1.71
CO	**t**	36.48	3.51	39.99	39.99
CO_2	**kt**	35.04	0.48	35.53	35.53
N_2O	**t**	0.00	0.06	0.06	0.06
NH_3	**t**	0.00	0.18	0.18	0.18
SF_6	**kg**	0.00	0.01	0.01	0.01
HFC	**kg**	0.00	0.82	0.82	0.82
PFC	**kg**	0.00	0.08	0.08	0.08

Figure 6 presents the contribution of LCI processes and IO sectors to the total emissions of SO_x, NO_x, CO_2 and CO calculated by the hybrid method. The contributions of the incineration process to the total emissions of these pollutants are presented in Table 4. As they are very high compared to the remaining processes and sectors, they are not represented in Figure 5.

Table 4. Contributions to the total emissions calculated by integrated hybrid model

Emissions	Contribution in % to the total emissions	
	incineration process	LCI system
SO_x	85.81	91.22
NO_x	98.46	98.75
CO	91.08	91.26
CO_2	98.27	98.74

It is interesting to note in Figure 5 the contributions of petroleum and natural gas extraction, paper industry and metallurgy to the total emissions of the four pollutants, which indicates the direction for further data collection. In fact, Table 4 indicates that the incineration system is quite complete, for NO_x and CO_2 emissions they are estimated by around 99% only by performing LCI. If the analyst is more interested in the calculation of SO_x or CO emissions, it would be interesting to check the connections of the LCI system with sectors as agriculture, petroleum and natural gas extraction, paper industry, or metallurgy. As a rule of thumb, for further collection of data for a detailed LCI, Guinée *et al.* (2002) appreciate that if a single flow, for which data are missing and is estimated by using IO data, contributes with more than 5% to the results of the hybrid approach, then specific process data should be collected for that flow. Here, the most important contribution of a cut-off flow is below 1% and therefore the system analysed in LCI part can be considered as complete.

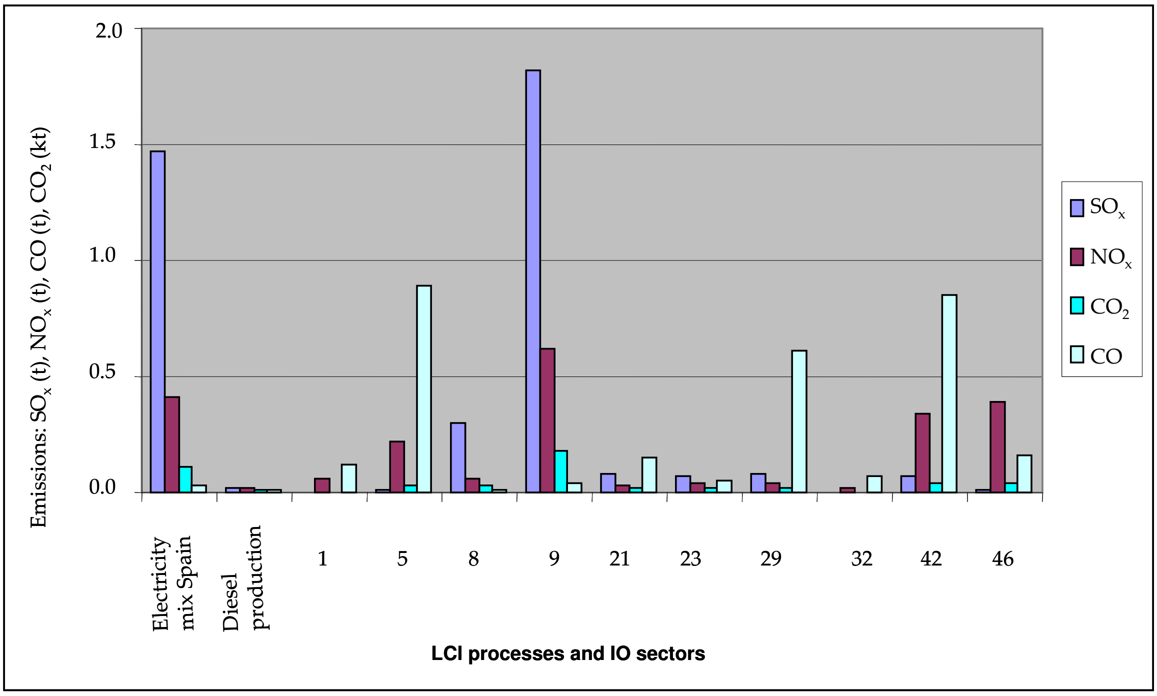

Figure 5. Results of integrated hybrid model: contributions by LCI processes and IO sectors

The results we obtained could be further improved by using the commodity-by-commodity instead of industry-by-industry accounts.[29] For Spain this is not possible yet, as detailed atmospheric emissions accounts by commodity are not available. The integrated hybrid model described by Suh (2004) also makes the difference between domestic and imported goods, and between current and capital goods. This would imply an important amount of work and is beyond our interest here.

Comparing the results of the integrated hybrid model with those of tiered hybrid and of LCI matrix, it is obvious that the hybrid models provide a more complete system definition (national boundaries) while preserving process specificity. The differences between the two hybrid methods are very small in the analyzed case-study, but the amount of work in the two cases is very different. We would recommend that if a process-LCI has been done already and the LCI analyst wants to check the definition of boundaries, it is better to use the tiered hybrid method as it is easier to perform and needs fewer additional data (data on purchases and sales of the plant). Its results would indicate if a further expansion of the boundaries is necessary in order to include the processes of production of those inputs that are identified as important in the results of the model. In the case the expansion is needed, the analyst can collect process-specific data and perform again the tiered hybrid model with the new system. By this iterative method, the analyst can efficiently direct efforts to achieve a more complete system and more accurate results. If a very detailed and complete LCI is required, then other analytical tools as uncertainty and sensitivity analyses have to be applied to the results of the study. For these tasks, the integrated hybrid method is a better choice, as LCI and IO are merged together and the analysis needs to be applied only once (in the tiered hybrid method, as LCI and IO parts are independent, uncertainty and sensitivity analysis are performed separately).

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[29] The original integrated hybrid model described by Suh (2004) considers the commodity-by-commodity approach.

4. Conclusions

This chapter calculates the direct and indirect atmospheric emissions associated with the activity of municipal incinerator of Tarragona (SIRUSA). Specifically, we applied the tiered-hybrid and the integrated-hybrid models using specific data provided by the incinerator and more aggregated data compiled in the Spanish IO tables. All the calculations are performed for the year 2000. The results show that the LCI of the incineration is complete, LCI contributing around 99% to the results of the hybrid models. It means that all the important processes are modeled in the LCI part and that there is no need for further process-specific data collection for the particular process analyzed here.

Both hybrid models analyzed here conserve the specificity of the analyzed system, meanwhile being more complete than the LCI study. The boundaries of the system are expanded to include in the analysis all the economy. The tiered-hybrid model, although suffering from double-counting, gives similar results to the integrated hybrid model that needs a much more laborious work. Therefore, for further studies, if LCI is already calculated, we recommend the use of the tiered-hybrid method as a first approach for boundaries expansion, and then iterative calculations until the LCI system is complete. If advanced analyses of the system are to be performed, as sensitivity and uncertainty estimations, then it is better to construct the integrated-hybrid model.

If real improvements are to be made, it is important to analyze LCI within the broader economic system that includes it. Therefore, it is important to know not only the specific analyzed product-system, but also its interactions with the economy. For this task, the integrated-hybrid model is of much help, as it defines clearly the upstream and downstream connections of the LCI study with the broader surrounding economic system.

CONCLUSIONS, DISCUSSION AND FUTURE WORK

1. Conclusions

Each chapter of this thesis ends with the discussion of results and conclusions of the respective chapter, so here we give only a summary of the main conclusions:

- The revised versions of the ISO standards on LCA (ISO/FDIS 14040:2006(E) and ISO/FDIS 14044:2006(E)) mention the possible application of LCA methodology for sustainability assessments, but they do not specify how to apply it for regional or higher level analyses. The same standards admit "limitations of the LCI phase, such as setting the system boundary, that do not encompass all possible unit processes for a product system or do not include all inputs and outputs of every unit process, since there are cut-offs and data gaps" (ISO/FDIS 14040:2006(E), section 5.4.3), but they do not offer guidance on how to overpass these limitations. Hybrid techniques using IO analysis can and should be used to solve theses issues in an ISO-compatible way (Chapters IV and V).
- The main limitation of LCA for use at regional or higher scales is the availability of data on the flows of materials and energy within a region or a country and their associated environmental loads. However, compiling a matrix LCA allows a further connection of LCA system with regional or national models, such as IO. The matrix method of LCA compilation offers a clearer representation of the system under study and gives results in good agreement with other "traditional" ways of LCA computation, as process-flow diagram (Chapter I).
- Environmental IO suits well analyses at regional or national levels, providing valuable information on the emissions associated with the activities of a given economy (Chapters II and III). However, it only accounts for the fraction of industrial output that is delivered to the final demand. In order to take into account the full industrial account (the inter-industries flows) it is necessary to consider shared producer-consumer responsibility (Chapter IV).
- The materials and energy flow analysis in LCA and IO analysis can share a common computational structure without loosing specificity for any of the two investigated methods (in Chapters I and V).
- The integrated hybrid approach of IO-LCA allows a full connection of the two methods and expands the boundaries of the system while preserving process-level detailed information. However, at practical level, the integrated approach is more laborious and needs more data than other hybrid approaches, e.g. tiered-hybrid approach, while conducting to similar results (Chapter V).

2. Further research

During the years I have worked on this thesis, I had to choose one direction from the several possible at that moment. For example, I have chosen to enter more in the details of the hybrid IO-LCA modeling instead of evaluating the sensibility of data I used, or the uncertainties associated with these data. Nevertheless, in the future, I would like to address some important points that I could not treat in this thesis. They are related to:

- Implementation of a regional model based on hybrid LCA;
- Quantitative uncertainty analysis of the hybrid model;
- Incorporation of information from other disciplines into hybrid LCA; e.g. indicators to assess social sustainability, Geographic Information Systems (GIS);
- Development of a user-friendly software for hybrid LCA.

Of course, these are only few from the possible directions opened by this thesis, but I consider them as very important for an appropriate use of the work done in this thesis.

On the following I would like to address some assumptions and simplifications I made during writing this thesis.

3. Discussion

A model is a schematic description of a system that accounts for its known properties and allows the scientists to understand the system's behavior. It can be used for investigation of the properties of the system and prediction of future outcomes. In general, a model consists of the description of system's components, the flows between components and the flows which cross the system's boundaries from and to the given system. These flows can be materials, energy, services or money interchanged between the components of the system. A linear model assumes that the input-output ratios of flows in a component of a system are fixed. Basically, all the equations used in this work are linear. Both LCA and IO systems can be well described by linear systems of equations. By sharing the same computational structure, LCA and IO can be used conjointly, functioning together and complementing each other in a common framework. Of course, the results of linear models do not reflect exactly the reality, but they are simple to understand and implement by researchers in different fields. When the reality is too complex to be modeled by linear equations, more complex models can be introduced to supplement the basic structure in its weak points; e.g. by incorporating a Geographic Information System (GIS) to an LCA of biofuels, biomass feedstock data can be analyzed both statistically and graphically, helping decision-making on the placement of a biodiesel production plant. Caution has to be taken when interpreting the results of linear LCA and IO as they are valid only under the assumption of fixed input-output ratios. If there is a technological change, neither LCA nor IO can reflect the new situation without modifying the initial models.

Besides the assumption of fixed input-output ratios, IO analysis based on the Leontief model considers the market economy as driven by the final demand. Under this assumption, a demand-driven model calculates the amount of industrial output required to meet a given final demand; e.g. how much electricity should be produced in order to meet the electrical requirements of a given district. Due to this assumption, the IO based on the Leontief model can provide LCA only for the pre-consumer stages of a product life-cycle. To cover the end of life stages of an LCA study, a supply-driven IO model should be used. Such a model calculates the amount of outputs enabled by given system inputs. For this type of calculations, the economists use the Ghosh model. Dietzenbacher (1997) reinterpreted this model as a price model: by increasing or decreasing the amount of inputs, in monetary terms, the Ghosh model calculates how increases or decreases the production, in monetary terms, and these changes can be done by changing prices without involving changes in actual quantities. However, in physical quantity terms is difficult to imagine a situation when an increase in the amount of inputs induces a proportional increase of outputs, while the other inputs remain unchanged; e.g. the production of electricity in a coal-fired power plant: if the price of coal increases, it will be reflected in higher energy prices; if the amount of coal increases, the production of electricity will also increase, not necessarily proportionally. The problem comes when considering the downstream processes which receive electricity from the power plant, the surplus of electricity inputs will hardly ever increase their outputs proportionally. Therefore the supply-model becomes invalid as soon as in the chain of production appears a process that requires outputs from others as inputs for its functioning. It implies the Ghosh model can not be used for the prediction of emissions induced by a change in production due to changes in its inputs. Nevertheless, it can be used descriptively as it indicates how the inputs to production have been used or absorbed further downstream. This property of the Ghosh model is used to assign downstream shared responsibility between producers and consumers.

The concept of sharing responsibilities amongst producers, between producers and consumers, and between producers and providers of primary inputs, opens a new interesting question area. Gallego and Lenzen (2005) provide the mathematical formulation of shared responsibility and Lenzen *et al.* (2007) discuss on the values these shares of responsibilities should have. The last authors propose the use of a quantity which is independent of the sector classification, such as value added:

$$1-\alpha_{ij}=1-\beta_i=\frac{h_i}{x_i-Z_{ij}}, \qquad (1)$$

where h_i is the value added of sector *i*, and the denominator represents the net output of sector *i*, that is its sectoral output x_i minus its intra-industry transactions. Parameters α and β represent the shares of responsibility amongst industries and between industries and consumers, respectively. Equation (1) assumes that the share of value added captured by agents at each stage of supply chain reflect their power over the supply chain and also over its environmental impacts. As the same authors comment, this assumption can be criticized as "the economic value added reflects both the consumer preferences (demand) and resource or service scarcity (supply)", and therefore it cannot be used as a base to assign producer responsibility (Lenzen *et. al* (2007), p. 37). The gross operating surplus could be considered as a better proxy, but it presents the disadvantage of depending on the sectorial classification. One interesting idea would be to assign values to these parameters of shared responsibility based on a physical, rather than on economic, base. We will return later to this point.

The calculation of environmental loads (such as air emissions, water and soil pollution, land-use, water-use, resource consumption, etc.) either by LCA, generalized IO or hybrid IOLCA, adopts the principle of consumer responsibility. All the environmental loads generated along the life cycle, respectively along the supply chain, of the product are added up at the end of life cycle, or production chain, and assigned to the product sold to the final consumer. This principle is in contrast to the producer responsibility principle, on which is based the Kyoto Protocol. Countries that adopt this protocol are engaged to reduce their emissions of greenhouse gases (GHG), or agree emissions trading if they maintain or increase emissions of these gases. National emissions are reported in form of emissions statistics at the level of specific industries. As a consequence, an extensive discussion on the allocation of GHG is conducted in literature (Alcántara (1995), Kondo *et al.* (1998), Munksgaard and Pedersen (2001), Sánchez-Chóliz and Duarte (2004), Mongelli *et. al* (2006), etc.). Using generalized IO models, these authors analyze pollution not only at national level, identifying the most polluting sectors, but they also analyze GHG embodied in international trades, considering that technical improvements at local level can have negative impacts at global level. However, their analyses adopt both consumer responsibility, calculating embodiments of GHG in final demand, and producer responsibility, evaluating GHG emissions due to production processes in the economy.

At company level, the producers have started to calculate their environmental impact based on the standardized LCA methodology. Adding all the producer's environmental loads in a region or a country implies a double-counting, as their life-cycle assessments overlap; e.g. the producers of electricity have to report their environmental emissions per kWh of electricity produced. As they sell electricity to various other industries and final consumers, the life-cycle assessments of these latter will account again for the emissions associated with the electricity they use, etc. The result of this operation is that the sum of all the environmental loads attributed to producers and consumers in a region overpass the regional environmental accounts. Therefore, methods to share the environmental burdens responsibility along the life-cycle of a product or activity are desired. The idea of shared producer-consumer responsibility described by Gallego and Lenzen (2005) is interesting and it could be also applied in LCA reporting. But probably the values of shared responsibility parameters would be calculated based on physical values, rather than monetary, as in Lenzen *et al.* (2007).

At the end, all the sustainability indicators and indices, environmental models and other tools produced nowadays in the field of environmental assessment, have the same purpose: to understand and describe the functioning of the actual society in order to minimize its impacts on the surrounding environment. Based on this knowledge, population is aware and educated on the "right action" to take. Probably it is not so much about who is responsible and which is its share of responsibility, but about being aware of what happens, which are the consequences of our behavior and assuming responsibility for our choices.

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ANNEXES

Annex 1: Technical data of the incineration system

Table A1.1. Technical data of SIRUSA (adapted from Sonnemann (2002))

Situation	**Without filters**	**With filters**
Alternative no.	1	2
Production data		
Produced electricity (TJ)	162.91	155.25
Electricity sent out (MW)	130.3	124.2
Working hours per year (h)	8,280	8,280
Emission data		
Gas volume (Nm^3/h)	90,000	
CO$_2$[30] (g/Nm3)	186	186
CO (mg/Nm^3)	40	40
HCl (mg/Nm^3)	516	32.8
HF (mg/Nm^3)	1.75	0.45
NO$_x$ (mg/Nm^3)	191	191
Particles (mg/Nm^3)	27.4	4.8
SO$_2$ (mg/Nm^3)	80.9	30.2
As (◎g/Nm^3)	20	5.6
Cd (◎g/Nm^3)	20	6.6
Heavy metals[31] (◎g/Nm^3)	450	91
Ni (◎g/Nm^3)	30	8.4
PCDD/Fs (ng/Nm^3) as toxicity equivalent (TEQ)	2	0.002
Materials		
IN		
CaO (t/a)	0	921
Diesel	148.8	148.8
OUT		
Slag (t/a)	42,208	42,208
Scrap for treatment (t/a)	2,740	2,740
Ashes for treatment (t/a)	590	3,450
Ashes for disposal (t/a)	767	4,485

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[30] Corresponds to the measured value, not to the adjusted one used in the LCA study.

[31] "Heavy metals" is a sum parameter in form of Pb equivalents of the following heavy metals (As, B, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb). Cd is considered apart for its toxicity, and As and Ni for their carcinogenic relevance.

Table A1.2. Technical data of TRISA (ash treatment)

Situation	**Without filters**	**With filters**
Alternative no.	1	2
Emission data		
Volume of gas (Nm^3)	366390	2142450
Solid particles (kg/m^3)	186	186
HCl (kg/m^3)	186	186
NH_3 (kg/m^3)	40	40
TOC (kg/m^3)	516	32.8
Mercaptanes (kg/m^3)	1.75	0.45
SO_2 (mg/Nm^3)	80.9	30.2
Materials		
IN		
Electricity (TJ)	0.028	0.164
Transport (tkm)	183800	1073260
Ashes (t)	590	3450
Gasoil (t)	0.65	3.78
Cement (t)	89	518
OUT		
Wastes to landfill (t/a)	767	4485

Table A1.3. Technical data from LYRSA (recuperation of iron)

Situation	**Without filters**	**With filters**
Alternative no.	1	2
Emission data		
Air	-	-
Water	-	-
Materials		
IN		
Electricity (TJ)	0.00216	0.00216
Transport (tkm)	2926320	2926320
Scrap (t)	2740	2740
Gasoil (t)	1.913	1.913
Water (m^3)	90	90
OUT		
Iron (road construction) (t)	2192	2192
Wastes to landfill (t/a)	548	548

Annex 2: Allocation in the incineration system

By definition,[32] a functional flow is any of the flows of a unit process that constitutes its goal; e.g. the product or service resulted from a production process, the waste inflows of a waste treatment process. A multifunctional process is a unit process yielding more than one functional flow, e.g. co-production, combined waste processing and recycling, etc. The methodological problem that arises in LCI when a multifunctional process occurs is to decide what share of environmental burdens of the multifunctional process should be allocated to product investigated or the chosen functional unit. The occurrence of a multifunctional process is a necessary condition for the existence of allocation problem, but not a sufficient one, as commented in Heijungs and Frischknecht (1998), Guinée *et al.* (2002) and Heijungs and Suh (2002). They demonstrate that systems with multi-function problems can, when these processes are not involved in the product system that provides the specified functional unit, be solved in an exact way without entering the allocation procedure. The solution of the inventory problem would be obtained in this case by calculating the pseudo-inverse of the technology matrix, as its normal inverse cannot be calculated.

In our case-study of the incineration system, there are two processes that need a closer look: "incineration and co-electricity production" and "slag treatment". In the incineration process, one waste is treated (MSW) and one product is co-produced (co-electricity), indicating a multifunctional problem. In "scrap treatment", the slag resulted from incineration is treated with the recovering of steel. The solutions to the allocation problem can be the split of the multifunctional process into virtual processes providing only one functional flow by using the allocation factors, or a process must be subtracted from the system so that any other process provides the same functional flow as the co-production (Guinée *et al.* (2002), Heijungs and Frischknecht (1998)). Here we adopt the first solution. The process of waste incineration needs to be partly allocated to the system of waste incineration and partly to the system of co-electricity production. The process of slag treatment needs to be allocated between slag treatment and steel recovery. It means that for further calculations the multifunctional process of incineration of waste should be split in waste incineration and electricity co-production unit processes and "slag treatment" in slag treatment and steel recovery unit processes (see Figure A2.1). For reasons of better understanding, the processes of utilities production are not included in the representation of allocation, but only the multifunctional processes.

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[32] see Guinée *et al.* (2004).

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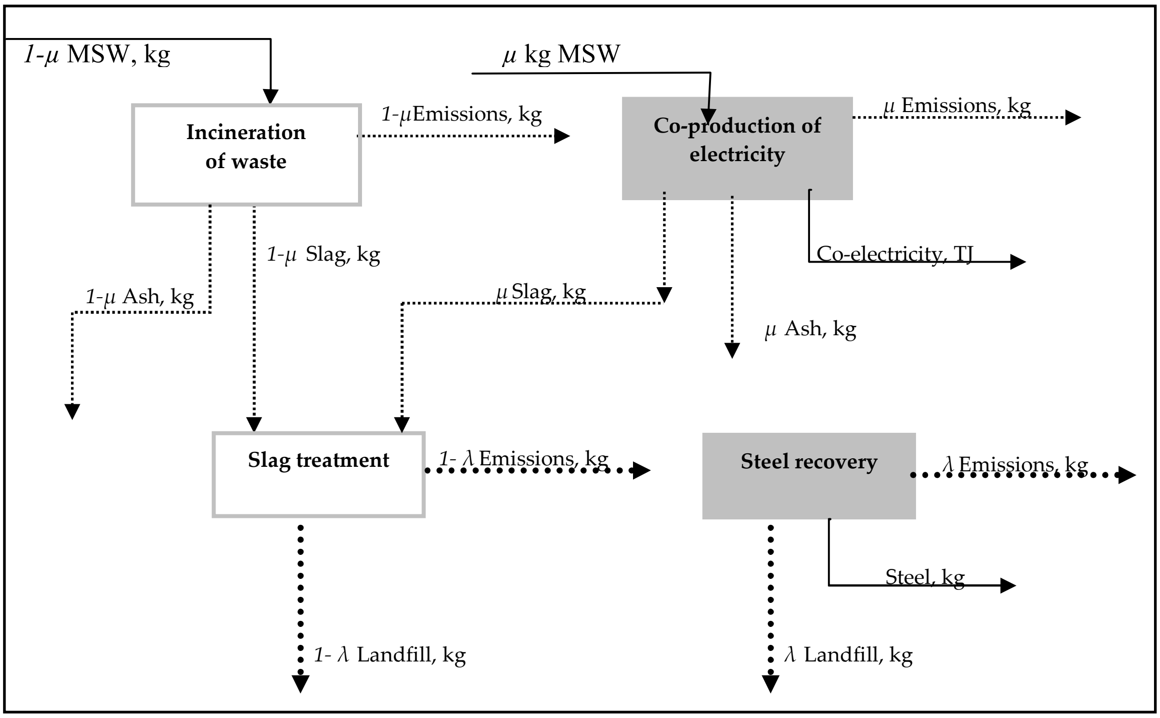

Figure A2.1 Allocation in the incineration system

The allocation factors in the multifunctional processes are identically calculated as $\mu_1 = \frac{p_1}{p_1 + p_2}$ and $\mu_2 = \frac{p_2}{p_1 + p_2}$; this means to multiply all the non-functional flows of the incineration process (auxiliary materials, emissions, slag and ash) by a factor of μ_1 for the single (unit) process of incineration and by a factor of μ_2 for the single process of co-electricity production (see Figure A2.1). Identical for the process of slag treatment divided into scrap treatment and steel co-production unit processes: the non-functional flows of slag treatment process (emissions and landfill) are to be multiplied by a factor λ_1 for the unit process of scrap treatment and by λ_2 for the steel recovery unit process.

As $\begin{matrix} \mu_1 + \mu_2 = 1 \\ \lambda_1 + \lambda_2 = 1 \end{matrix}$ and the positive outputs are co-electricity generated and recovered steel, in Figure A2.1 we considered directly that $\begin{matrix} \mu_2 = \mu \\ \lambda_2 = \lambda \end{matrix}$ and $\begin{matrix} \mu_1 = 1 - \mu \\ \lambda_1 = 1 - \lambda \end{matrix}$. This method of dealing with allocation in multifunctional processes is known as "the partitioning method" (Heijungs and Suh, 2002). The computational method for LCI is identical as presented in equation (2) in the text of chapter I, but the problem we still have to solve is how to choose μ and λ.

The amount of electricity co-produced in the process of MSW incineration is proportional to the amount of MSW incinerated. Also, the amount of steel recovered is proportional to the slag sent to treatment. As recommended by Ekvall and Finnveden (2001), in these cases, all the environmental burdens should be allocated to the investigated product; in our case the electricity co-produced in incineration and the steel recovered in slag treatment. It implies $\mu = 1$ and also $\lambda = 1$ and that we actually avoided allocation in both cases by attributing to generation of co-electricity and steel recovering all the environmental burdens associated with the incineration of MSW and respectively, slag treatment processes.

Annex 3: Sectorial classification

Table A3.1. Numbers assigned to the economic sectors specified in Spanish IO classification

No.	Sector name	No.	Sector name
1	Agriculture, livestock and hunting	41	Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel
2	Forestry	42	Wholesale trade and commission trade, except of motor vehicles and motorcycles
3	Fishing	43	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods
4	Anthracite, coal, lignite and peat	44	Accommodation
5	Petroleum Crudes and Natural Gas Extraction. Uranium and thorium ores extraction	45	Railway transport
6	Extraction of metallic ores	46	Other land transport; transport via pipelines
7	Extraction of non-metallic ores	47	Maritime Transport
8	Coke, refinement and nuclear fuels	48	Air and space transport
9	Electricity production and distribution	49	Activities annexed to transport
10	Production and distribution of gas, steam and hot water	50	Post and Communications
11	Collection, treatment and water distribution	51	Financial intermediation, except insurance and pension funding
12	Production, processing and preserving of meat and meat products	52	Insurance and pension funding, except compulsory social security
13	Manufacture of dairy products	53	Activities auxiliary to financial intermediation
14	Manufacture of other food products	54	Real estate activities
15	Manufacture of beverages	55	Renting of machinery and equipment without operator and of personal and household goods
16	Manufacture of tobacco products	56	Computer and related activities
17	Textile Industry	57	Research and development
18	Clothing and furs industry	58	Other business activities
19	Leather and Footwear Industry	59	Education; market
20	Wood and cork industry	60	Health and social services; market
21	Paper Industry	61	Other community, social and personal service activities; market
22	Publishing and Graphic Arts	62	Recreational, cultural and sporting activities; market
23	Chemical Industry	63	Other service activities
24	Rubber and Plastic Materials Industry	64	Public Administration
25	Manufacture of cement, lime and plaster	65	Education; no market
26	Manufacture of glass and glass products	66	Health and social services; no market
27	Manufacture of ceramic tiles and flags	67	Other community, social and personal service activities; no market
28	Manufacture of other non-metallic mineral products	68	Activities of trade unions and other membership organizations
29	Metallurgy	69	Recreational, cultural and sporting activities; no market
30	Manufacture of metallic products	70	Private households with employed persons
31	Machinery and Mechanical Equipment		
32	Office machines and computers		
33	Manufacture of machinery and electrical material		
34	Manufacture of electronic material		
35	Medico-surgical and precision instruments		
36	Manufacture of motor vehicles and trailers		
37	Manufacture of other transport material		
38	Furniture and other manufacturing industries		
39	Recycling		
40	Construction		

Annex 4: Preparation of the original data of the plant

Let us consider the real case of the municipal solid waste incinerator SIRUSA, located in Constantí, Tarragona. To determine the direct and indirect emissions associated with the activity of SIRUSA, besides the IO tables and emissions matrix at national level provided by INE for the year 2000, we need data on plant expenditures and incomes, and on its release of atmospheric emissions for the same year.

The first step in the data preparation is to list all the purchases of the plant and identify each expense with its appropriate sector in the Spanish economy. The original expenditures of the plant are given in purchaser's prices and the Spanish data in the IO tables are given in basic prices. Therefore, it is necessary to bring the expenditures of the plant to basic prices. The purchaser's prices p_{pp} are the sum of basic prices p_{bp}, trade m_c and transportation margins m_t and indirect taxes t (taxes on products less subsidies) on commodities:

$$p_{pp} = p_{bp} + m_c + m_t + t.$$

We compute the expenditures vector of the plant in basic values and in terms of commodities using:

$$p_{bp} = p_{pp} - \frac{m_c + m_t + t}{Q + m_c + m_t + t} p_{pp},$$

where Q is the total commodity output and the fraction that pre-multiplies p_{pp} is the margin and taxes coefficient per unit of commodity output in purchaser's prices.

Table A4.1 gives the expenditures of the plant by sector from which it buys, in basic prices. Because of the confidentiality of the economic data, all the numbers are expressed in percentages of the total expenditures.

Table A4.1. Expenditures of SIRUSA (values different of 0)

Code of the production sector in CNAE-93	**Name of the production sectors**	**Percentage from the total expenditures (%)**
14	Manufacture of other food products	0.23
17	Textile Industry	0.17
23	Chemical Industry	1.41
25	Manufacture of cement, lime and plaster	0.86
31	Machinery and Mechanical Equipment	0.08
32	Office machines and computers	0.92
39	Recycling	18.15
42	Wholesale trade and commission trade, except of motor vehicles and motorcycles	14.39
46	Other land transport; transport via pipelines	38.17
52	Insurance and pension funding, except compulsory social security	0.18
57	Research and development	0.03
58	Other business activities	18.62
64	Public Administration	6.78
TOTAL		**100.00**

For the sake of simplicity, we present here only the sectors from which SIRUSA buys goods and services for its functioning (entries different of 0).

The same treatment was applied to the products which SIRUSA sells to other sectors (ashes for the recovering of iron) and to the final demand (electricity).

Annex 5: Direct emissions of sectors from each SIRUSA buys (part of disaggregated NAMEA)

For the correspondence between sectors numbers and their names, see Annex III.

Table A5.1. Direct emissions of sectors from which SIRUSA buys

Sector No.	SO$_x$ (t)	NO$_x$ (t)	NMVOC (t)	CH$_4$ (t)	CO (t)	CO$_2$ (kt)	N$_2$O (t)	NH$_3$ (t)	SF$_6$ (kg)	HFC (kg)	PFC (kg)
14	865	9681	14621	1586	22193	2380	19	4	0	0	0
17	4393	4139	6154	377	7020	1116	119	18	0	0	0
23	49086	26483	84768	8022	31314	11818	8638	15164	0	560755	0
25	70184	90887	1736	445	50376	35665	952	16	0	0	0
31	3021	4200	4310	114	14414	1013	107	39	0	0	0
32	36	747	15535	17	3106	104	10	9	0	0	0
39	90	4710	1203	61	5194	340	13	6	0	0	0
42	3592	17255	6350	420	43325	1844	249	147	0	0	0
46	4127	174590	25362	3800	73089	19081	1116	104	0	0	0
52	167	33	5	8	72	44	6	0	0	0	0
57	389	94	44	15	424	80	11	1	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0
64	367	1304	3249	0	9515	0	38	0	0	0	0

Annex 6: Disaggregation of IO tables and NAMEA to include SIRUSA as independent sector

One of the limitations of IO analysis is the aggregation of data. The more disaggregated an economy is, more useful are the IO tables. Ideally, every product or service produced by an economy would be result of an individual sector that would have its emission intensity of a pollutant or its resource consumption coefficient. As billions and billions of goods and services are produced by an economy, it would be unfeasible to collect all the data on n^2 technological coefficients at that level of detail. Therefore, similar goods or services are grouped together under the same sector; e.g. the Spanish economy is disaggregated into 70 sectors. Prior to any calculation one has to ask: How much of the IO sector output is occupied by the good I am interested in?

Regarding the incineration plant SIRUSA producing electricity from waste, going back to the Spanish National Classification of Economic Activities CNAE-93 we could classify it in sector **61**, Other community, social and personal service activities; market, in the section dedicated to "Activities of cleaning public streets and residues treatment". The incineration of MSW does not even appear explicitly in the classification and much less the production of electricity from waste. Furthermore, the output of SIRUSA represents a 0.29% from the gross output of **61**, meaning that the incineration is far away from being a typical product of **61**. Considering the above, we proceed to disaggregate the generic sector **61** into two different sectors: SIRUSA (**61a**) and the remaining of the old sector **61** after resting the purchases and sales of SIRUSA (**61b**). This is made by introducing a new row and a new column in the original IO table, as illustrated in Table A6.1. After the disaggregation is important to check the sum over the totals of columns still equals the sum over the totals of rows.

Table A6.1. Disaggregation of the Spanish IO table

To From		Intermediate uses							Total intermediate demand
		1	2	….	61a = SIRUSA's purchases	61b = 61 - 61a	…	70	
Intermediate uses	1	**INTERMEDIATE USE MATRIX**							
	2								
	…								
	61a = SIRUSA's sales								
	61b = 61 - 61a								
	…								
	70								
Intermediate uses (sub-total)									Σ

In the case of the matrix of emissions, NAMEA, the disaggregation is made similarly by introducing a new row containing the emissions of SIRUSA in **61a** and the remaining of the original sector **61** after resting the emissions of SIRUSA being included in **61b** (see Table A6.2).

Table A6.2. Disaggregation of the Spanish NAMEA

	SO_x (t)	**NO_x (t)**	**NMVOC (t)**	**CH_4 (t)**	**CO (t)**	**CO_2 (kt)**	**N_2O (t)**	**NH_3 (t)**	**SF_6 (kg)**	**HFC (kg)**	**PFC (kg)**
1											
2											
…											
61a = SIRUSA's emissions											
61b = 61 - 61a											
…											
70											
TOTAL											