Chapter 14
Methods in the Life Cycle Inventory of a Product

Sangwon Suh and Gjalt Huppes

Introduction

Life Cycle Inventory analysis (LCI) is defined as a phase of Life Cycle Assessment (LCA) involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle (ISO 14040 1998a). The concept of LCI has been adopted for cleaner production as early as the 1960s, and has had broad industrial and academic application in the last decades (Vigon et al. 1993). Compared to the other phases of LCA, LCI has been considered a rather straightforward procedure except for several issues such as allocation (see e.g. Fava et al. 1991). Reflecting this belief, the method used for LCI compilation has rarely been questioned, although a large number of software, LCI databases and case studies have been released so far. However, contrary to the common belief, different methods have been available for LCI, and they often generate significantly different results. Therefore, it is necessary to assess advantages and limitations of different LCI methods and properly select suitable one(s) for each specific application. It is the aim of this paper to review and compare available methods for LCI compilation, and guide LCA users to properly select the most relevant methods for their analyses in relation to the goal and scope of the study as well as the resources and time available. With adaptations, the results are applicable outside the realm of LCA as well.

This paper is organized as follows: first available methods of LCI compilation are presented. Two computational approaches, process flow diagram and matrix inversion, are assessed, and then methods that utilize economic Input-Output Analysis

S. Suh (✉)
Department of Bioproducts and Biosystems Engineering, University of Minnesota,
Twin Cities, MN, USA
e-mail: sangwon@umn.edu

G. Huppes
Industrial Ecology Department, Institute of Environmental Sciences (CML), Leiden University,
Leiden, The Netherlands

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

(IOA) are described with special attention to hybrid analyses. Secondly, these methods are summarized and compared in terms of data requirements, uncertainty of source data, upstream system boundary, technological system boundary, geographical system boundary, available analytical tools, time and labor intensity, simplicity of application, required computational tools and available software tools. Finally, conclusions are drawn, and compliance of these methods to ISO standards and future outlooks are discussed.

Methods for LCI Compilation

In parallel with the direct computation using process flow diagram methods, also matrix inversion and IOA have been adopted for LCI compilation over a decade ago. In this section theory and principles of matrix representation of product systems, input-output (IO) approaches and combinations of these two are described.

Process Flow Diagram

LCI compilation using a process flow diagram appears in early LCA literatures including Fava et al. (1991), Vigon et al. (1993), and Consoli et al. (1993) and has been the most common practice among LCA practitioners. Process flow diagrams show how processes of a product system are interconnected through commodity flows. In process flow diagrams, boxes generally represent processes and arrows the commodity flows. Each process is represented as a ratio between a number of inputs and outputs. Using plain algebra, the amount of commodities for fulfilling a certain functional unit is obtained, and by multiplying the amount of environmental interventions generated to produce them, the LCI of the product system is calculated. Figure 14.1 illustrates a simple process flow diagram.

In the product system shown in Fig. 14.1, a unit of toaster is produced using 1 kg of steel and 0.5 MJ of steam, and is then used for 1,000 times and disposed of.

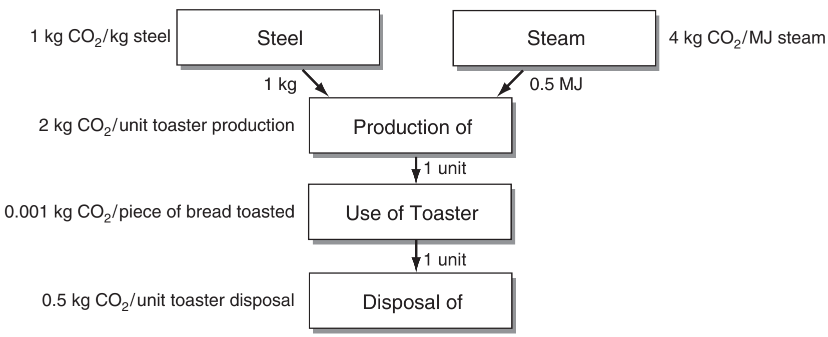

Fig. 14.1 Process Flow Diagram of a Simplified Product System

Producing1 kg of steel, 1 MJ of steam and 1 unit of toaster requires 1, 4 and 2 kg of CO_2 emission, respectively. Toasting 1 piece of bread and disposal of 1 unit of toaster emits 0.001and 0.5kg of CO_2, respectively. Suppose that the toaster under study produces 1,000 pieces of toast during its life time, and the functional unit of this product system is given by ‘1,000 piece of toast’. Then one can calculate the amount of commodity requirements and resulting environmental intervention as follows:

$$\begin{aligned}&\left(\frac{1\,\text{kg CO}_2}{\text{kg steel}}\cdot 1\,\text{kg steel}\right)+\left(\frac{4\,\text{kg CO}_2}{\text{MJ steam}}\cdot 0.5\,\text{MJ steam}\right)\\&+\left(\frac{2\,\text{kg CO}_2}{\text{unit toaster prod.}}\cdot 1\text{unit toaster prod.}\right)+\left(\frac{0.001\,\text{kg CO}_2}{\text{piece of toast}}\cdot 1000\,\text{toast}\right)\\&+\left(\frac{0.5\,\text{kg CO}_2}{\text{unit toaster disposed}}\cdot 1\text{unit toaster}\right)=6.5\,\text{kg CO}_2\end{aligned}\tag{14.1}$$

Computing LCI directly from a process flow diagram is not as easy as presented by Equation (14.1) if following conditions are not met:

- Each production process produces only one material or energy.
- Each waste treatment process receives only one type of waste.
- The product system under study delivers inputs to, or receives outputs from another product system.
- Material or energy flows between processes do not have loop(s).

Conditions from ‘a’ to ‘c’ are related to the multifunctionality problem. A detailed treatment of allocation as the solution to this problem is out of the scope of this paper but can be found elsewhere (Lindfors et al. 1995; Ekvall 1999; Huppes and Schneider 1994; ISO/TR14049 2000; Guinée et al. 2002). Condition ‘d’ requires that all processes in the product system under study do not utilize their own output indirectly. For example, suppose that production of 1 kg steel requires 0.5 MJ of steam and production of 1 MJ of steam also needs 0.5 kg of steel. This implies that the production of steel indirectly requires its own process output, steel through steam production process, and *vice versa*. A process flow diagram of this product system can be drawn as in Fig. 14.2.

Consoli et al. (1993) explicitly mentioned this problem and suggested to use an iterative method to find the solution. The example above is solved using the iterative method as follows

$$\begin{aligned}&\left(\frac{4\,\text{kg CO}_2}{\text{MJ steam}}\cdot 0.5\,\text{MJ steam}\right)+\left(\frac{1\text{kg CO}_2}{\text{kg steel}}\cdot 0.25\,\text{kg steel}\right)\\&+\left(\frac{4\text{kg CO}_2}{\text{MJ steam}}\cdot 0.125\,\text{MJ steam}\right)+\cdots\left(\frac{1\text{kg CO}_2}{\text{kg steel}}\cdot 0.25\,\text{kg steel}\right)\\&+\left(\frac{4\,\text{kg CO}_2}{\text{MJ steam}}\cdot 0.125\,\text{MJ steam}\right)+\left(\frac{1\text{kg CO}_2}{\text{kg steel}}\cdot 0.0625\,\text{kg steel}\right)+\cdots\end{aligned}\tag{14.2}$$

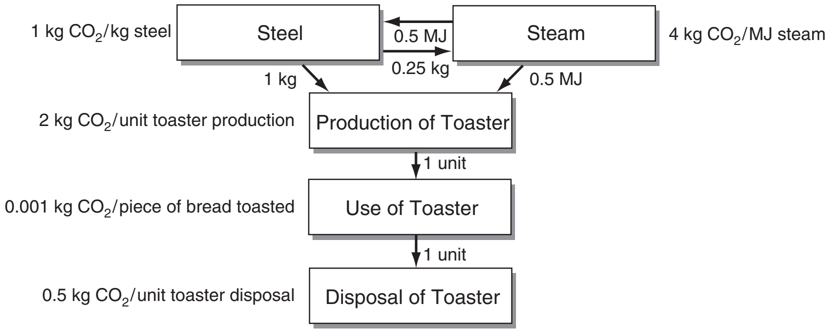

Fig. 14.2 Process Flow Diagram with an Internal Commodity Flow Loop

Up to the third iteration Equation (14.2) makes up 3.5625 kg CO_2. If added to the result in Equation (14.1), the LCI of the new product system in Fig. 14.2 becomes 10.0625 kg CO_2. As the number of iterations is increased, the result approaches the ultimate solution, although the speed of convergence becomes slower.

Instead, the exact solution can directly be calculated using infinite geometric progression. The general formula of Equation (14.2) can be written by

$$(4 \cdot 0.5)\sum_{n=0}^{\infty} 0.25^n + 0.25\sum_{n=0}^{\infty} 0.25^n + 0.25\sum_{n=0}^{\infty} 0.25^n + (4 \cdot 0.125)\sum_{n=0}^{\infty} 0.25^n \tag{14.3}$$

and since $\sum_{n=0}^{\infty} a^n = 1/(1-a)$ for $0 < a < 1$, the Equation (14.3) is solved by

$$= 4 \cdot \frac{0.5}{1-0.25} + 2 \cdot \frac{0.25}{1-0.25} + 4 \cdot \frac{0.125}{1-0.25} = 4 \tag{14.4}$$

Thus the total inventory of the product system shown in Fig. 14.2 becomes $6.5 + 4 = 10.5$ kg CO_2.

Matrix Representation of Product System

Although often overlooked, there are more computational approaches in LCI compilation using process analysis. The matrix inversion method was first introduced to LCI computation by Heijungs (1994). Basically Heijungs (1994) utilizes a system of linear equations to solve an inventory problem. We define $n \times n$ LCA technology matrix $\widetilde{\mathbf{A}} = \|a_{ij}\|$ such that an element, a_{ij} shows inflows or outflows of commodity i of process j for a certain duration of process operation, and especially inflows and outflows are noted by positive and negative values, respectively (for discussions on rectangularity see Heijungs and Suh (2002). We assume that processes at stake are being operated under a steadystate condition, so that selection of a specific temporal window for each process does not alter the relative ratio between elements in a column. Each entry of a column vector $\tilde{\mathbf{x}}$ shows the required process operation time of each process to produce the required net output of the system.[1] Then commodity net output of the system $\tilde{\mathbf{y}}$ is given by

$$\widetilde{\mathbf{A}}\tilde{\mathbf{x}} = \tilde{\mathbf{y}}, \tag{14.5}$$

which shows that the amount of a commodity delivered to outside of the system is equal to the amount produced minus the amount used within the system. Rearranging (14.5), the total operation time $\tilde{\mathbf{x}}$ required to meet the total commodity net output $\tilde{\mathbf{y}}$ is calculated by

$$\tilde{\mathbf{x}} = \widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{y}}. \tag{14.6}$$

Let us further define a $p \times n$ matrix $\widetilde{\mathbf{B}} = \|b_{ij}\|$ of which an element b_{ij} shows the amount of pollutants or natural resources i emitted or consumed by process j during the operation time that $a_{\cdot j}$ is specified. Suppose that $\widetilde{\mathbf{A}}$ is not singular then the total direct and indirect pollutant emissions and natural resources consumption by the system to deliver a certain amount of commodity output to the outside of the system is calculated by

$$\widetilde{\mathbf{M}} = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{k}}, \tag{14.7}$$

where $\widetilde{\mathbf{M}}$ is the total direct and indirect environmental intervention matrix, and $\tilde{\mathbf{k}}$ is an arbitrary vector that shows the functional unit of the system.

The commodity flows of the product system shown in Fig. 14.1 can be expressed by the LCA technology matrix as well:

$$\widetilde{\mathbf{A}} = \begin{bmatrix} 1 & 0 & -1 & 0 & 0 \\ 0 & 1 & -0.5 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \tag{14.8}$$

The columns indicate steel production, steam production, toaster production, use of toaster and disposal of toaster from left to right, while each row is assigned to steel (kg), steam (MJ), toaster (unit), bread toasted (piece) and disposed toaster (unit).

The environmental intervention matrix, and the commodity net output of the system are given by

$$\widetilde{\mathbf{B}} = \begin{bmatrix} 1 & 4 & 2 & 1 & 0.5 \end{bmatrix} \tag{14.9}$$

and

$$\tilde{\mathbf{k}} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1000 \\ 0 \end{bmatrix}, \tag{14.10}$$

respectively.

[1] The term ‘operation time’ is used here for convenience, while various synonyms including ‘occurrence’ (Heijungs, 1994), ‘scaling factor’ (Heijungs and Frischknecht, 1998) can be found in LCA literatures. In this work we followed Heijungs (1997).

The inventory result of this product system is now calculated using (14.7) as

$$\widetilde{\mathbf{M}} = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{k}} = 6.5, \tag{14.11}$$

which is identical to the result shown in Equation (14.1). The matrix inversion method shows its strength as the relationships between processes become more complex. For example, Equation (14.7) directly calculates the exact solution for the system shown in Fig. 14.2 without using the iterative method or infinite progression. The LCA technology matrix in Equation (14.8) can be modified to represent the product system in Fig. 14.2 as

$$\widetilde{\mathbf{A}}' = \begin{bmatrix} 1 & -0.5 & -1 & 0 & 0 \\ -0.5 & 1 & -0.5 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix}, \tag{14.12}$$

and the Formula (14.7) provides the inventory of the system by

$$\widetilde{\mathbf{M}}' = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}'^{-1}\tilde{\mathbf{k}} = 10.5, \tag{14.13}$$

which confirms the previous solution derived by the infinite geometric progression.

Additionally, representing product systems in a matrix provides various analytical tools as well. For instance, Heijungs and Suh (2002) provide a comprehensive treatment on matrix utilization and its analytical extensions for LCA practitioners Suh and Huppes (2002), and Suh and Huppes (2002a) introduces a supply and use framework and economic models developed by IO economists, including (Stone et al. 1963; ten Raa et al. 1984; ten Raa 1988; Kop Jansen and ten Raa 1990; Londero 1999), to deal with the allocation problem by using this matrix expression (Suh and Huppes 2002a).

IO-Based LCI

The result of the methods described in the Process Flow Diagrams and Matrix Representation of Product System sections of this chapter are referred to as LCIs based on process analysis. In principle, all processes in an economy are directly or indirectly connected with each other. In that sense, process analysis based LCI is always truncated to a certain degree, since it is practically not viable to collect process-specific data for the whole economy, and this problem has led the use of IOA in LCI.

In the original work by W. Leontief the input-output table describes how industries are inter-related though producing and consuming intermediate industry outputs that are represented by monetary transaction flows between industries

(Leontief 1936). The input-output model assumes that each industry consumes outputs of various other industries in fixed ratios in order to produce its own unique and distinct output. Under this assumption, an $m \times m$ matrix $\mathbf{A}$ is defined such that each column of $\mathbf{A}$ shows domestic intermediate industry outputs in monetary values required to produce one unit of monetary output of another's. Let $\mathbf{x}$ denote the total industry output, then $\mathbf{x}$ is equal to the summation of the industry output consumed by intermediate industries, by households as final consumers, and by exports which is left out for convenience here. I.e.,

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y}, \tag{14.14}$$

where $\mathbf{y}$ denotes total household purchase of industry outputs. Then, the total domestic industry output $\mathbf{x}$ required to supply the total household purchases of domestic industry outputs is calculated by

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}, \tag{14.15}$$

where $\mathbf{I}$ denotes the $m \times m$ identity matrix. The model by Leontief has been further improved notably by R. Stone by distinguishing commodities from industry outputs (ten Raa et al. 1984; United Nations 1968). Although very rarely utilized for IO-based LCI, the supply and use framework, which has later been incorporated in the System of National Accounts (SNA) by the UN, has a particular importance for LCA applications of IOA, since LCA is an analytical tool based on the functionality of goods and services, and a supply and use framework makes it possible to distinguish different functions from an industry output (see Suh 2001).

Environmental extensions of IOA can easily be made by assuming that the amount of environmental intervention generated by an industry is proportional to the amount of output of the industry and the identity of the environmental interventions and the ratio between them are fixed. Let us define a $q \times m$ matrix $\mathbf{B}$, which shows the amount of pollutants or natural resources emitted or consumed to produce unit monetary output of each industry. Then the total direct and indirect pollutant emissions and natural resources consumption by domestic industries to deliver a certain amount of industry output is calculated by

$$\mathbf{M} = \mathbf{B}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{k}, \tag{14.16}$$

where $\mathbf{M}$ is the total domestic direct and indirect environmental intervention matrix, and $\mathbf{k}$ is an arbitrary vector that shows net industry output of the system, which will be supplied to the outside of the system. IO-based LCI uses basically the Formula (14.16).

Applications of IOA to LCA started from early 1990s. (Moriguchi et al. 1993) utilized the completeness of the upstream system boundary definition of Japanese IO tables for LCA of an automobile (Moriguchi et al. 1993). Later, this line of approach has been further enriched using more comprehensive environmental data in the US (Lave et al. 1995). Since all transaction activities within a country are, in principle, recorded in the national IO table, it is often argued that the system boundary of an IO-based LCI is generally more complete than that of process analysis (see e.g. Hendrickson et al. [1998], Lave et al. [1995], Lenzen [2001]). However, this argument requires some conditions to be fulfilled. First, it should be clearly noted that the IOA itself can provide LCIs only for pre-consumer stages of the product life cycle, while the rest of the product life cycle stages are outside the system boundary of IOA. Second, the amount of imported commodities by the product system under study should be negligible. Otherwise errors due to truncation or misspecification of imports may well be more significant than that due to cut-off in process based LCI.[2] Thirdly, data age of IO-based LCIs is normally older than process-based one, since it takes 1 to 5 years to publish IO tables based on industry survey. Therefore, IO-based LCIs are a less desirable choice especially for the product systems that heavily rely on imported goods or newly developed technologies.

Another limitation of IO-based LCI is due to the aggregation of industries and commodities. Generally, IO tables distinguish not more than several hundred commodities, so that a number of heterogeneous commodities are included within a commodity category, diluting differences between them. Suh and Huppes (2001) empirically showed in a case study that due to this aggregation problem, the result of IO-based LCI can be much less than that of process based one, and the converse may be true as well (Marheineke et al. 1998).

Nonetheless, the biggest practical obstacle in applying IO technique to LCI is the lack of applicable sectoral environmental data in most countries. Although there are some fragmental emission inventory databases available, differences in the level of detail, base year and industry classification make it difficult to construct well-balanced sectoral environmental data in most countries.

So, IO-based LCI methods can provide information on the environmental aspects of a commodity on the basis of a reasonably complete system boundary using less resources and time. For a commodity of which the product system heavily relies on imports and newly developed technologies, however, applicability of IO-based LCI methods is rather limited.

Hybrid Analysis

IO-based inventory is relatively fast, and upstream system boundary is more complete within the national level, while process-based LCI provides more accurate and detailed process information with a relatively more recent data. Linking process-based and IO-based analysis, combining the strengths of both, are generally called *hybrid method* (Wilting 1996; Treloar 1997; Marheineke et al. 1998; Joshi 2000;

[2] By endogenising imports in the use matrix, it is assumed that imported goods are produced under the same input-output structure of the domestic economy, which can significantly reduce the truncation error. However, the assumption of identical input-output structure of imported goods may still induce errors.

Suh and Huppes 2002b). So far hybrid analysis has been adopted to LCI compilation in different ways, that will be distinguished here as tiered hybrid analysis; IO-based hybrid analysis; and integrated hybrid analysis.

Tiered Hybrid Analysis

The concept of tiered hybrid analysis appears from the 1970s (Bullard and Pilati 1976; Bullard et al. 1978). Bullard and Pilati (1976) and Bullard et al. (1978) combined process analysis similar to the method described in the Process Flow Diagrams section of this paper, with IOA to calculate net energy requirements of the US economy.

Tiered hybrid analysis utilizes process-based analysis for the use and disposal phase as well as for several important upstream processes, and then the remaining input requirements are imported from an IO-based LCI. Tiered hybrid analysis can be performed simply by adding IO-based LCIs to the process-based LCI result. (Moriguchi et al. 1993) introduced the tiered hybrid approach in LCA, and Marheineke et al. (1998) also used the tiered hybrid approach in a case study of a freight transport activity (Moriguchi et al. 1993; Marheineke et al. 1998). Model II by Joshi 2000) describes this approach as well (Joshi 2000). The Missing Inventory Estimation Tool (MIET) by Suh (2001) and Suh and Huppes (2002b) is a database to support tiered hybrid analysis using 1996 US IO table and environmental statistics (Suh 2001; Suh and Huppes 2000). Entering the amount of commodity used by the product system either in producers' price or purchasers' price, MIET returns inventory results as well as characterized results of the commodity.

Tiered hybrid analysis provides reasonably complete and relatively fast inventory results. However, the border between process-based system and IO-based system should be carefully selected, since significant error can be introduced if important processes are modeled using the aggregated IO information. Second, there are some double-counting problems in tiered hybrid analysis. In principle, the commodity flows of the process based system are already included in the IO table, so that those portions should be subtracted from the IO part. Third, the tiered hybrid model deals with the process-based system and the IO-based system separately, so that the interaction between them cannot be assessed in systematic way. For example the effects of different options at the end of the product life cycle, which can change the industry-interdependence by supplying materials or energy to the IO-based system, cannot be properly modeled using the tiered hybrid method.

IO-Based Hybrid Analysis

Treloar (1997) employed the IO-based hybrid approach for the analysis of energy requirements in Australia (Treloar 1997). Joshi (2000) also used the same line of approach for LCA of fuel tanks (Joshi 2000). Generally, the IO-based hybrid approach is carried out by disaggregating industry sectors in the IO table, while the tiered hybrid method is applied for the use and end-of-life stages of the product life cycle (Joshi 2000). Suppose that industry j and its primary product i in an IO table is to be disaggregated into two (e.g. j_a, j_b, i_a and i_b). Then the augmented IO table can be constructed as:

$$\mathbf{A}' = \begin{bmatrix} a_{11} & \cdots & a_{1ja} & a_{1jb} & \cdots & a_{1n} \\ \vdots & & \vdots & \vdots & & \vdots \\ a_{ia1} & \cdots & a_{iaja} & a_{iajb} & \cdots & a_{ian} \\ a_{ib1} & \cdots & a_{ibja} & a_{ibjb} & \cdots & a_{ibn} \\ \vdots & & \vdots & \vdots & & \vdots \\ a_{n1} & \cdots & a_{nja} & a_{njb} & \cdots & a_{nn} \end{bmatrix}. \tag{14.17}$$

Columns $a_{\cdot ja}$ and $a_{\cdot jb}$ should be estimated using information on upstream requirements of the process, and rows $a_{ia\cdot}$ and $a_{ib\cdot}$ should be estimated using sales information. The environmental intervention matrix should be disaggregated as well using detailed emission data of the disaggregated processes. This procedure can be performed in an iterative way, so that the augmented IO table becomes accurate enough to perform a comprehensive analysis. The LCI up to the pre-consumer stage, using IO-based hybrid analysis, is calculated by

$$\mathbf{M}' = \mathbf{B}'(\mathbf{I} - \mathbf{A}')^{-1}\mathbf{k}'. \tag{14.18}$$

Inventory results for the remaining stages of the product life cycle, including use and disposal, should be added manually as described in section on Tiered Hybrid Analysis. Since this approach partly utilizes the tiered hybrid method, the interactive relationship between pre-consumer stages and the rest of the product life cycle is difficult to model.

The disaggregation procedure is the most essential part of IO-based hybrid approach. Joshi (2000) suggested using existing LCIs for information sources of detailed input requirements, sales structure and environmental intervention.

Integrated Hybrid Analysis

Suh and Huppes (2000) suggested using hybrid analysis from the perspective of both LCA and IOA (Suh and Huppes 2000). These authors generally assume that information from IO accounts are less reliable than process specific data due to temporal differences between IO data and current process operation, aggregation, import assumptions etc. Therefore, the IO table is interconnected with the matrix representation of the physical product system (as described in the section on Matrix Representation of Product Systems) only at upstream and downstream cut-offs where better data are not available. Since information on the process-based system is gathered by direct inspections and questionnaires, purchase and sales records for cut-offs required to link the process-based system with the IO table may be relatively easy to obtain. The general formula of this hybrid model is

$$\mathbf{M}_{\mathrm{IH}} = \mathbf{B}_{\mathrm{IH}}\mathbf{A}_{\mathrm{IH}}^{-1}\mathbf{k}_{\mathrm{IH}} = \begin{bmatrix} \widetilde{\mathbf{B}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{A}} & \mathbf{Y} \\ \mathbf{X} & \mathbf{I}-\mathbf{A} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{\mathbf{k}} \\ \mathbf{0} \end{bmatrix}. \quad (14.19)$$

Matrix **X** represents upstream cut-off flows to the LCA system, linked with relevant industry sector in IO table, and **Y** does downstream cut-off flows to the IO system from the LCA system. Each element of **X** has a unit of monetary value/operation time while that of **Y** has a unit of physical unit/monetary value. This model has been applied to several recent LCI studies including Suh and Huppes (2001), Vogstad et al. (2001) and Strømman (2001).

Since all stages of the product life cycle, including use and disposal phases, can be expressed by the LCA technology matrix, $\widetilde{\mathbf{A}}$, this approach does not need to apply a tiered hybrid method to complete an LCI, and thus full interactions between individual processes and industries can be modeled in a consistent framework.

Comparison Between Methods

Methods so far described are compared with criteria of data requirements, uncertainty of source data, upstream system boundary, technological system boundary, geographical system boundary, available analytical tools, time and labor intensity, simplicity of application, required computational tools and available software tools. (Table 14.1). As shown in Table 14.1, it is not that one specific method is superior to all others, but decisions can be made to select the most relevant tool based on goal and scope, and available resources and time.

Since both process analysis methods require process-specific information, data requirements as well as time and labor intensity are considered to be higher than for other methods. Compared to process-based analyses, methods that utilize IOA generally show smaller data requirements, that is, assuming that IO-based LCIs are already available. Integrated hybrid analysis is an exception, since it relies on full process analysis, and then utilizes IO-based LCI only for cut-offs. For both tiered hybrid and IO-based hybrid analysis, there are several criteria for which judgment can be case specific, since the boundary between detailed process-based analysis and IO-based analysis may vary. For example, time and labor intensity will rise, and source data uncertainty will be lowered as the process-based part becomes larger for these methods.

In terms of system boundary, three criteria are distinguished. Regarding the upstream system boundary, methods that utilize IOA show higher completeness, while process-based analyses are generally superior for other system boundaries. There are numerous analytical tools that have been developed in IOA field. Most of them

Table 14.1 Comparison Between Methods for LCI Compilation

	LCI based on process analysis		Input-output based LCI	Hybrid LCI		
	Process flow diagram	Matrix representation		Tiered hybrid analysis	IO-based hybrid analysis	Integrated hybrid analysis
Data requirements	Commodity and environmental flows per process	Commodity and environmental flows per process	Commodity and environmental flows per sector	Commodity and environmental flows per sector and process	Commodity and environmental flows per sector and process-based LCIs	Commodity and environmental flows per sector and process
Uncertainty of source data	Low	Low	Medium to high	Depends	Depends	Low
Upstream system boundary	Medium to poor	Medium to poor	Complete	Complete	Complete	Complete
Technological system boundary	Complete	Complete	Medium to pore	Depends	Depends	Complete
Geographical system boundary	Not limited	Not limited	Domestic activities only	Depends	Domestic activities only	Not limited
Applicable analytical tools	Rare	Abundant, e.g. in Heijungs and Suh (2002) [10]	Rare	Rare	Abundant	Abundant

Time- and labor intensity	High	High	Low, if environmental data available	Depends	Depends	High
Simplicity of application	Simple	Simple	Simple	Simple	Complex	Complex
Required computational tools	Excel or similar (no matrix inversion)	Matrix inversion (e.g. MatLab, Mathematical)	Excel similar	Excel or similar	Matrix inversion (e.g. MatLab, Mathematical)	Matrix inversion (e.g. MatLab, Mathematical)
Available software tools	Most available LCA software tools	CMLCA	MIET, EIOLCA	MIET + LCA software tool	–	CMLCA

can be applied for part of IO-based hybrid analysis, although use and disposal phases should be treated separately.

In terms of the simplicity of computation both IO-based and integrated hybrid analysis are considered to be more complicated than other methods, since these two approaches require some understanding on IOA. There are several computational tools and databases mentioned in Table 14.1. Chain Management by Life Cycle Assessment (CMLCA) is a software tool originally developed for education purposes although it can be successfully utilized for real case studies (Heijungs 2000). Economic Input-Output Life Cycle Assessment (EIOLCA) is a web-based IO-based inventory calculator that provides the amount of water usage, conventional pollutants emission, global warming gas releases and toxic pollutants emissions per sector output in monetary unit (Green Design Initiative 2008). Currently 1997 US environmental IO data is available from their web site. The Comprehensive Environmental Data Archive (CEDA) database is a commodity-based environmental IO database containing over 1,300 environmental intervention that are connected to over 80 major Life Cycle Impact Assessment (LCIA) methods (Suh 2004, 2005). The CEDA 3.0 database uses 1998 annual IO table of the US that distinguishes 480 commodities, and its new version uses 2002 IO table and environmental emission data. Abundant analytical tools from both matrix representations of product system as well as IOA can be applied to integrated hybrid analysis.

Finally, the mechanisms of the three hybrid methods in linking the process-based system part with the IO-based system part are compared. The computational structure of tiered hybrid, IO-based hybrid and integrated hybrid approach can be noted by matrix expressions shown in Equations (14.20), (14.21) and (14.19), respectively, with Equation (14.19) here repeated for easier comparison.

$$\mathbf{M}_{\mathrm{TH}} = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{k}} + \mathbf{B}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{k} \tag{14.20}$$

$$\mathbf{M}_{\mathrm{IOH}} = \widetilde{\mathbf{B}}\,\widetilde{\mathbf{A}}^{-1}\tilde{\mathbf{k}} + \mathbf{B}(\mathbf{I}-\mathbf{A}')^{-1}\mathbf{k}' \tag{14.21}$$

$$\mathbf{M}_{\mathrm{IH}} = \begin{bmatrix} \widetilde{\mathbf{B}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{A}} & \mathbf{Y} \\ \mathbf{X} & \mathbf{I}-\mathbf{A} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{\mathbf{k}} \\ \mathbf{0} \end{bmatrix}. \tag{14.19a}$$

By arranging (14.20) and (14.21) for better comparison they can be noted as

$$\mathbf{M}_{\mathrm{TH}} = \begin{bmatrix} \widetilde{\mathbf{B}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{A}} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}-\mathbf{A} \end{bmatrix}^{-1} \begin{bmatrix} \tilde{\mathbf{k}} \\ \mathbf{k} \end{bmatrix} \tag{14.20a}$$

$$\mathbf{M}_{\mathrm{IOH}} = \begin{bmatrix} \widetilde{\mathbf{B}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B}' \end{bmatrix} \begin{bmatrix} \widetilde{\mathbf{A}} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}-\mathbf{A}' \end{bmatrix}^{-1} \begin{bmatrix} \tilde{\mathbf{k}} \\ \mathbf{k}' \end{bmatrix} \tag{14.21a}$$

Equations (14.20′), (14.21′) and (14.19) show the solution model of tiered hybrid analysis, IO-based hybrid analysis and integrated hybrid analysis, respectively. $\widetilde{\mathbf{B}}$, $\widetilde{\mathbf{A}}$

and $\tilde{\mathbf{k}}$ represent the environmental matrix, technology matrix and arbitrary final demand vector of the process-based part, respectively, while **B**, **A** and **k** those of the IO part. Prime (′) indicates an augmented (disaggregated) matrix or vector. Especially, $\widetilde{\mathbf{B}}$ and $\widetilde{\mathbf{A}}$ for IO-based hybrid analysis (Equation (14.21)) contain environmental interventions and commodity flows for the use and disposal phase of the product life cycle.

It is not difficult to see, by substituting **X** and **Y** in (14.19) with **0**, that the tiered and IO-based hybrid approaches in (14.20′) and (14.21′) are special cases of the more general formulation of hybrid approach in (14.19). Note here that **k** and **k**′ in (14.20′) and (14.21′) are equivalent with **X** in (14.19) (see Heijungs and Suh 2002). Two differences are that first, the tiered hybrid and IO-based hybrid analyses contains **0** matrices in the hybrid technology matrix, while the integrated hybrid analysis shows **X** and **Y** instead of **0**s. This difference clearly points out that there are no formal linkages between process-based system and IO-based system within the models of tiered and IO-based hybrid analysis. Instead, the linkages are given outside of the model by the final demand vector, which is the second visible difference. The final demand vector which is exogenously given for the net external demand contains **0** for integrated hybrid analysis, while others have **k** or **k**′ instead of **0**. The vectors **k** and **k**′ in Equation (14.20′) and (14.21′) show the amount of the commodities in the IO system that is used by the process-based system. In contrast, **X** and **Y** of integrated hybrid analysis show the commodity flows both from the IO system to the process-based system and from process-based system to the input output system, in Equation (14.19). In case the flows outgoing from the process-based system to the IO-based system are negligible, Equation (14.19) may generate a similar result with that from Equation (14.20), although often it is not the case, as large scale processes, such as steel or electricity generation processes, that are dealt with in the process-based system may supply only small portion of their outputs to the process-based system under study. These differences are graphically illustrated in Fig. 14.3.

The bold outer line shows the overall system boundary and the dotted line shows the boundary between the process-based system part and the IO system part. The shaded area indicates the IO system and the white one the process-based system. The dotted area in (b) indicates the disaggregated IO system, while the full white

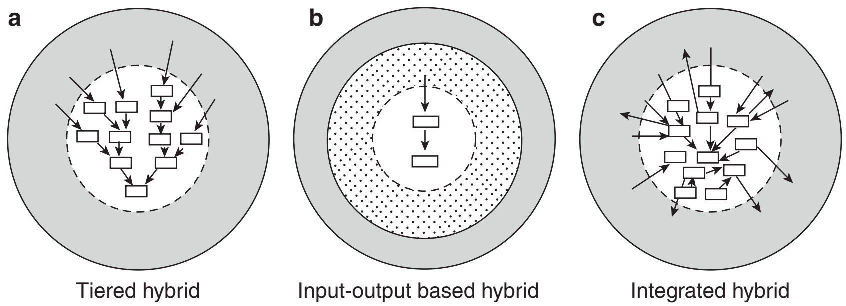

Fig. 14.3 Interactions Between Process-Based System and IO System of Hybrid Analyses

refers to use and post-use processes only. In the tiered hybrid analysis, commodities going into the process-based system are modeled using the IO-based system. Notice that only one direction of arrows, from the IO-based system to process-based system, is possible in tiered hybrid analysis. In the IO-based hybrid analysis, only two process types, for use and disposal, are described by the process-based system, in white, while many commodity flows are described in the disaggregated IO part, the dotted area. In the integrated hybrid analysis, the major part of commodity flows are represented by the process-based system, and cut-offs are linked with the IO-based system. Notice that here arrows can go both directions, from the IO-based system to the process-based system (upstream cut-offs/links) and from the process-based system to the IO-based system (downstream cut-offs/links) forming a network structure rather than a tree.

ISO Compliance

The issue related to compliance with ISO standards is briefly discussed. ISO 14040 and ISO 14041 generally define the framework without specifying which computation method is to be used (ISO 14040 1998a; Green Design Initiative 2008). Therefore, both LCI computation methods using process flow diagram and matrix representation are considered to be compatible with ISO standards. Methods that utilize IOA can be considered differently. According to ISO, LCA is compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system *throughout its life cycle*[3] (ISO 14040 1998a). Thus, what is so-called cradle-to-gate analysis, which is the case for IO-based LCI is not an LCA study in strict sense of ISO standards, since it does not contain the use and disposal phase within its scope. This implies that IO-based inventory alone is not considered as ISO compatible LCI in general sense. However, if combined with inventory result from other stages of life cycle, as is the case for hybrid methods, the scope of the analysis is fully in line with the ISO standard. Then the ISO compliance of introducing external model such as IO accounts can be questioned for hybrid methods. ISO 14041 (clause 4.5), "Modeling product systems" mentioned about the practical difficulties of describing all the relationships between all the unit processes in a product system and opens up possibilities of using models to describe key elements of physical system (ISO 14041 1998b). Hence, in principle, there are no restrictions in using IO accounts to describe upstream process relationships if the model and assumptions are clearly noted.

A second issue where non-compliance might occur is in allocation (ISO 14041 1998b). However, in ISO 14041, a range of options is given, with a requirement on transparency and on application of several methods if more of them apply. Such refinements are not yet discussed in this paper. However, the options of allocation by substitution or by partitioning both can be developed in pure IOA and

[3] Italics by current authors.

in hybrid analysis as well, which suggests possible compliance to ISO standards (see Suh and Huppes 2002a). For more detailed discussion on the issue of ISO compliance and system boundary problem, see Suh et al. (2004).

Conclusions and Discussion

Having made the survey, which methods for inventory construction can be recommended for LCA users? Although this very much depends on the specific features of the case at hand, especially considering goal and scope and available resources and time, some main guidelines can be given.

Matrix representation of product systems clearly is superior to the flow diagram method for all but the most simplified systems. Pure IO-based LCI can at best be used as a first proxy. So the next question is how does hybrid LCI compares to process-based analysis?

When comparing this pure process-based LCI with the integrated hybrid analysis, the latter has a clear advantage in terms of the quality of the result, especially in terms of system completeness. With information on the monetary value only for cut-off flows and with improved availability of environmentally extended IO data, preferably regionalized, the additional data requirements and the added complexity both may become quite limited. This seems a best choice for the future, if not for now already. However, it adds to the cost of already expensive and time-consuming full process LCA.

What may be the role of the other two types of hybrid analysis? The tiered hybrid analysis has the appeal of easy extension on existing simple partial LCA systems in filling in the gaps. However, the connection between the two inventory subsystems is made externally, ‘by hand’. The only partial links between the systems remain a source of error which is difficult to assess. The IO-based hybrid analysis is conceptually more mature. Although use and post-use processes are not incorporated in the IO part, and the links between the systems remains external, the IO-based hybrid analysis shows higher resolution for the IO-based system and does not have problems of overlap: the processes based system does not contain commodity flows represented in the IO table.

With time and money available, the choice clearly is for the integrated hybrid analysis. However, what if time and money are scarce? Then a different choice can be made. A rational strategy at a case level could be to consider a step-wise approach, where tiered hybrid approach is performed first by specifying upstream cut-offs ($\mathbf{k}$ or $\mathbf{X}$). With additional resources and time available, then the next step will be specifying downstream cut-offs ($\mathbf{Y}$) and further disaggregating IO table ($\mathbf{A}'$). The step-wise approach can start with few important processes worked out in detail, that is quite cheap and fast. Then, focused on where main contributions and uncertainties are, a stepwise build-up of resolution can follow, until a sufficient quality of result has been developed. In this development, there always is a full and consistent system definition, with resolution being added as required.

Prerequisites for this highly important development are in the field of databases and software. LCA databases are to be adapted to the integrated hybrid method by supplying monetary data on process flows. IO data bases, still available mainly at the single country level, should develop into a regionalized, trade-linked global system. High-quality IO database can be set up on the basis of supply and use tables, with detailed commodity flows available in most primary data sources where the supply and use tables are constructed from. Also, the environmental data in the IO part, present now for a few countries only in greater detail, can become available for many more countries. Since most commercially available LCA software is not able to handle matrix inversion for LCI computation, a software tool development that enables hybrid analysis by broader LCA users is also required.

Acknowledgment Reprinted from Sangwon Suh and Gjalt Huppes, Methods in Life Cycle Inventory (LCI) of a product, */Journal of Cleaner Production/*, 13(7), 687–697, Copyright (2005), with permission from Elsevier.

References

Bullard, C. W., & Pilati D. A. (1976). *Reducing uncertainty in energy analysis* (CAC-Doc. No. 205). Urbana, IL: Center for Advanced Computation.

Bullard, C. W., Penner, P. S., & Pilati D. A. (1978). Net energy analysis – handbook for combining process and input-output analysis. *Resources and Energy, 1*, 267–313.

Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A. A., De Oude, N., Parrish, R., Perriman, R., Postlethwaite, D., Quay, B., Siéguin, J., & Vigon, B. (1993). *Guidelines for life-cycle assessment: A code of practice*. Washington, DC: SETAC.

Ekvall, T. (1999). *System expansion and allocation in life cycle assessment, with implications for wastepaper management*. Ph.D. dissertation, Chalmers University of Technology, Göthenburg, Sweden.

Fava, J. A., Denison, R., Jones, B., Curran, M. A., Vigon, B., Selke, S., & Barnum, J. (1991). *A technical framework for life-cycle assessment*. Washington, DC: SETAC.

Green Design Initiative. (2008). *Economic input-output life cycle assessment*. Carnegie Mellon University, US, http://www.eiolca.net.

Guinée, J. B., Gorree, M., Heijungs, R., Huppes, G., Kleijn, R., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H. A., de Bruijn, J. A., van Duin, R., & Huijbregts, M. A. J. (2002). *Handbook on life cycle assessment. Operational guide to the ISO standards*, Dordrecht, The Netherlands: Kluwer.

Heijungs, R. (1994). A generic method for the identification of options for cleaner products. *Ecological Economics, 10*, 69–81.

Heijungs, R. (1997). *Economic drama and the environmental stage – formal derivation of algorithmic tools for environmental analysis and decision-support from a unified epistemological principle*. Ph.D. dissertation, Leiden University, Leiden, The Netherlands.

Heijungs, R. (2000). *Chain management by life cycle assessment (CMLCA)*. CML, Leiden University, The Netherlands, http://www.leidenuniv.nl/cml/ssp/cmlca.html.

Heijungs, R., & Frischknecht, R. (1998). A special view on the nature of the allocation problem. *International Journal of Life Cycle Assessment 3*(5), 321–332.

Heijungs, R., & Suh, S. (2002). *The computational structure of life cycle assessment*. Dordrecht, The Netherlands: Kluwer.

Hendrickson, C., Horvath, A., Joshi, S., & Lave, L. (1998). Economic input-output models for environmental life cycle assessment. *Environmental Science and Technology, 32*(7), 184–190.

Huppes, G., & Schneider, F. (1994), *Proceedings of the European workshop on allocation in LCA*, CML, Leiden, The Netherlands.

ISO 14040. (1998a). *Environmental management – life cycle assessment – principles and framework*. Geneva, Switzerland: International Organisation for Standardisation.

ISO 14041. (1998b). *Environmental management – life cycle assessment – goal and scope definition and inventory analysis*. Geneva, Switzerland: International Organization for Standardization.

ISO/TR14049. (2000). *Environmental management – life cycle assessment – examples of application of ISO 14041 to goal and scope definition and inventory analysis*. Geneva, Switzerland: International Organisation for Standardisation.

Joshi, S. (2000). Product environmental life-cycle assessment using input-output technique. *Journal of Industrial Ecology, 3*(2–3), 95–120.

Kop Jansen, P., & ten Raa, T. (1990). The choice of model in the construction of input-output coefficients matrices. *International Economic Review, 31*, 213–227.

Lave, L., Cobas-Flores, E., Hendrickson, C., & McMichael, F. (1995). Using input-output analysis to estimate economy wide discharges. *Environmental Science and Technology, 29*(9), 420–426.

Lenzen, M. (2001). Errors in conventional and input-output-based life cycle inventories. *Journal of Industrial Ecology, 4*(4), 127–148.

Leontief, W. W. (1936). Quantitative input and output relations in the economic systems of the United States. *Review of Economic Statistics, 18*(3), 105–125.

Lindfors, L.-G., Christiansen, K., Hoffman, L., Virtanen, Y., Juntilla, V., Hanssen, O-J., Rønning, A., Ekvall, T., & Finnveden, G. (1995). *Nordic guidelines on life-cycle assessment, Nord (1995:20)*, Copenhagen: Nordic council of Ministers.

Londero, E. (1999). Secondary products, by-products and the commodity technology assumption. *Economic Systems Research, 11*(2), 195–203.

Marheineke, T., Friedrich, R., & Krewitt, W. (1998). *Application of a hybrid-approach to the life cycle inventory analysis of a freight transport task*, SAE Technical Paper Series 982201, Total Life Cycle Conference and Exposition, Austria.

Moriguchi, Y., Kondo, Y., & Shimizu, H. (1993). Analyzing the life cycle impact of cars: The case of CO_2. *Industry and Environment, 16*(1–2), 42–45.

Stone, R., Bacharach, M., & Bates, J. (1963). Input-output relationships, 1951–1966. *Programme for growth* (Vol 3). London: Chapman & Hall.

Strømman, A. (2001). *LCA of hydrogen production from a steam methane reforming plant with CO_2 sequestration and deposition*. Paper presented at the 1st Industrial Ecology Conference, Leiden, The Netherlands.

Suh, S. (2001). Missing *inventory estimation tool (MIET) 2.0. CML*, Leiden University, The Netherlands, http://www.leidenuniv.nl/cml/ssp/software/miet.

Suh, S. (2004). *Comprehensive environmental data archive (CEDA) 3.0 users' guide*, http://www.iel.umn.edu/CEDA3_Users_Guide.pdf.

Suh, S. (2005). Developing a sectoral environmental database for inputoutput analysis: The comprehensive environmental data archive of the US. *Economic Systems Research 17*, 449–469.

Suh, S., & Huppes, G. (2000). Gearing input-output model to LCA – part I: General framework for hybrid approach. CML-SSP Working Paper, CML, Leiden University, Leiden, The Netherlands.

Suh, S., & Huppes, G. (2001). *Applications of input-output analysis for LCA – with a case study of linoleum*. Paper presented at the Annual SETAC-Europe Meeting, Madrid, Spain.

Suh, S., & Huppes, G. (2002a). *Economic input-output analysis for allocation in LCA*. Paper presented at the Annual SETAC-Europe Meeting, Wien, Austria.

Suh, S., & Huppes, G. (2002b). Missing inventory estimation tool using extended input-output analysis. *International Journal of Life Cycle Assessment 7*(3), 134–140.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., & Norris, G. (2004). System boundary selection in life cycle inventories using hybrid approaches. *Environmental Science and Technology, 38*(3), 657–664.

ten Raa, T. (1988). An alternative treatment of secondary products in input-output analysis: Frustration. *Review of Economic Statistics, 70*(3), 535–538.

ten Raa, T., Chakraborty, D., & Small, J. A. (1984). An alternative treatment of secondary products in input-output analysis. *Review of Economic Statistics, 66*(1), 88–97.

Treloar, G. (1997). Extracting embodied energy paths from input-output tables: Towards an input-output-based hybrid energy analysis method. *Economic Systems Research 9*(4), 375–391.

United Nations. (1968). *A system of national accounts: Studies in methods*, Series F, No. 2 Rev. 3, New York.

Vigon, B. W., Tolle, D. A., Cornaby, B. W., Latham, H. C., Harrison, C. L., Boguski, T. L., Hunt, R. G., & Sellers, J. D. (1993). *Life cycle assessment: Inventory guidelines and principles*, EPA/600/R-92/245. Washington, DC: USEPA.

Vogstad, K-O., Strømman, A., & Hertwich, E. (2001). *Environmental impact assessment of multiple product systems: Using EIO and LCA in a LP framework*. Paper presented at the 1st Industrial Ecology Conference, Leiden, The Netherlands.

Wilting, H. C. (1996). *An energy perspective on economic activities*. Ph.D. thesis, University of Groningen, The Netherlands.