Chapter for CALCAS deliverable D18, 2009
"Guidelines for applications of deepened and broadened LCA"

Hybrid approaches combining IOA and LCA

1. Introduction
This chapter presents the topic of IO-based LCA and hybrid LCA, with a focus on guidelines for current best practice and identification of gaps for future research. It has been primarily written by Bo Weidema from 2.-0 LCA consultants with Reinout Heijungs (Leiden University) as a co-author from the CALCAS project.

The chapter is structured as follows. First, we define and describe the different elements. Next, in section 3 we discuss the main strengths and weaknesses of the different methods. This leads to the guidelines of section 4, in the form of a number of recommendations and practical issues. We end with some research proposals in section 5.

2. Definitions and short descriptions
"Hybrid" basically means the combination of two otherwise distinct approaches. It is therefore used in many different contexts and care should be exercised when using the term. Preferably, a more precise term should be applied. In the context of LCA and IOA, hybrid is used in at least two meanings: *hybrid units*, that are the combination of physical and monetary units for different columns and rows in the same table, and *hybrid data*, that is the combination of process level data and industry level input-output data in the same database. We will deal with both of these meanings, but the focus of this chapter is on the latter.

Input-output (IO) is also a somewhat ambiguous term. It basically refers to a table or matrix (we use here the term table, since any table can be understood as a matrix[1]) where the rows and columns represents either activities or products as inputs or outputs of activities. *Activities*, which can refer to sectors, industries, processes, unit processes, etc., can moreover refer to the production of goods and services, to the consumption of these, and to the processing of waste. Thus, some examples of activities are "production of high-density polyethylene bags", "power plants", "banking", "chemicals production", "storage of radio-active waste". On the other hand, we have *products*, which can refer to commodities, goods, services, wastes, intermediate flows, etc. Thus, some examples of products are "high-density polyethylene bags", "electricity", "financial services", "chemicals" and "radio-active waste".

Two types of input-output tables are of interest here: Supply-Use tables (also known as Make-Use tables) and Direct Requirements tables. The term IO table is often used to signify the latter.

Supply-use tables are, as the name indicates, divided in two, the supply table and the use table. Both tables have activities on one axis and products on the other. The supply table stores data on the supply of products from each activity, and the use table stores data on the

[1] Matrix notation is very commonly used to present input-output economics. However, for an introductory text like the present, matrix notation would be an unnecessary complication for some readers, not made up for by an equivalent improvement in readability by readers familiar with matrix notation. All calculations using either or both data types can be performed with or without matrix calculation, although matrix calculation of course immensely helpful in practice.

use of products by each activity. Together, the two tables can be interpreted as providing the production function of an activity, that is, what production factors (inputs) are required to produce the outputs of an activity. This is illustrated in Figure 1. Supply-use tables are used by national authorities to accumulate and balance enterprise reported data on supplies and use of products, as basis for deriving national economic indicators such as the GDP. The transpose of the supply table is sometimes referred to as a *make table*.

Direct requirements tables have either activities or products on both axes and are derived from the supply-use tables through simple mathematical operations (see description in the below guideline). By convention, rows always indicate supplies or suppliers, while columns indicate use or users. An *activity-by-activity* table stores data on the supply (output) required from each activity as input to each of the other activities in order for them to produce their output, while a *product-by-product* table stores data on the products (supplies) required (used) to produce other product outputs.

Supply and use tables	Activity
Supply of products	**V'**
Use of products	**U**

Direct requirement table	Products used
Products supplied	**A**

*Figure 1. Supply-use and product-by-product direct requirements tables, in which one column represents a production function for an activity or a product, respectively. When presented in this way, the use table is - by convention - named **U**, the supply table is named **V'**., and the direct requirements table is named **A**.*

An activity in a supply-use table, as illustrated in Figure 1, often has more than one product output. In contrast, each row and column in a product-by-product direct requirements table represents only one product. In LCA terms, we can say that the *columns in a supply-use table represent "unallocated" multi-product unit process datasets*, while the *columns in a product-by-product direct requirements table represent "allocated" single-product unit process datasets*. In this context, the term product-by-product may be confusing, since the columns still represents an activity, namely the abstract, artificially constructed single product activity, so that the term "product" for the columns merely signifies that the activities each have only single product output. The confusion is enhanced by the somewhat loose way in which some practitioners use product names to indicate activities or the other way around. Leontief (1936) for instance has classes like "agriculture", "flour and milling products", "canning and preserving", "bread and bakery products", and so on.

Input-Output analysis (IOA) was developed by the U.S. economist W.W. Leontief in the 1940's and onwards. He constructed detailed direct requirements tables of the U.S. economy, based on the industry reporting to Federal authorities, and used these to analyse the change in outputs required from each activity to produce an output of a product for final consumption.

This linear model of the economy inspired many other studies and won Leontief the Nobel Prize in 1973.

Life Cycle Assessment (LCA) developed from the engineering analysis of cumulative energy requirements in the 1960's and early 1970's, although it was not until the early 1990's that the term LCA obtained its current meaning. Due to the relative isolation of the economic and engineering disciplines, IOA and LCA developed in parallel, without much interaction until the late 1990's.

Some pioneering IOA studies (for an overview, see Miller & Blair 1985) can be said to be *Input-output based LCIs* or *Environmentally extended monetary IOAs*, typically focusing on one specific environmental parameter, such as energy resources. For such studies, the monetary supply-use table is extended by information on the parameter(s) of interest for each of the included activities.

Physical IOA was introduced by Ayres & Kneese (1969), applying the physical mass-balancing principle to the IO structure. In fact, Leontief's first paper (1936) starts with physical IOA. Later, Leontief moved to monetary IOA. Ayres & Kneese took up physical IOA and added the mass balance to that.

A traditional LCI unit process, either multi-product or single-product, can be stored in the same format as an IO activity, and vice versa. Both data types can therefore be stored in the same database, and both can be used in the same life cycle calculations. This is utilised in hybrid analysis, in which two approaches can be distinguished: Tiered and integrated analysis, the latter also being known as embedded analysis.

Tiered hybrid analysis is adding a separate IO table to provide upstream inputs to a table of process level data, see Figure 2. In this approach, some duplication of activities occurs, since the activities represented in the process level table are also included in the IO data.

Tiered hybrid direct requirement table	Products used	Products used
Products supplied	Process direct requirement table	
Products supplied		IO table

Embedded hybrid direct requirement table	Products used	Products used
Products supplied	Process direct requirement table	
Products supplied		Residual IO table

Figure 2. Illustration of two approaches to hybrid analysis: To the left, a tiered hybrid table, where the self-contained product-by-product IO part provides inputs to the process-level part, but where the process-level part does not deliver inputs to the IO part. To the right, an integrated or embedded hybrid table, where the scaled-up process level data are subtracted from the data for the product-by-product IO table they belong to, to derive residual IO data, and where the two types of data provide inputs to each other. Note that we have also here chosen to represent the process-based LCA table in a product-by-product format, yet referring to it as a process table.

Integrated or embedded hybrid analysis is using a database where the process level data are embedded into the IO data, leaving only the residual of each IO activity after subtraction of the embedded process level data. The process level data and the residual IO data are fully integrated, exchanging inputs both ways, and the resulting database is as representative of the entire economy as the original IO table, just at a higher level of detail.

3. Application dependency and present limitations of the methods

Physical and/or monetary units: If we assume an LCA context which includes physical, social and economic impacts, it is an obvious limitation to use only monetary units to model physical flows, as in Input-output based LCI or Environmentally extended monetary IOA, just as it is an obvious limitation to use only physical data to model social and economic impacts. However, the data availability is often determining for what type of analysis is performed. IO tables are much more readily available in monetary units than in physical units, just as a mass balance may be easier to establish than a monetary balance at the process level. When available, physical data are often less uncertain than monetary data (Miller & Blair 1985), and certainly more stable over time. However, service transactions do often not have a physical component, and tend therefore to be overlooked in a purely physical model. Because the two data sources complement each other, an analysis that combines both monetary and physical data will always be preferable. Some LCA databases and software are only able to calculate with one property or unit for each flow, which implies that a mass balance and a monetary balance for the same activities or products can only be performed by duplicating the tables, which is more cumbersome and implies additional probability of creating errors.

Limitations in process level data: Physical process level data are often incomplete, because the collection procedure involves many separate physical flows, some of which may be small and even unknown to the operators of the activity. Although each of these flows may be small, the sum of such missing flows may be significant, and accumulated over the tiers in a product system the missing part of the product system may be larger than the part accounted for. Availability of data may also vary significantly between different activities, resulting in inconsistencies in the way environmental data are reported. For example, a specific toxic emission may be available for the metal working industry, while a much larger emission of the same substance emitted from the chemical industry is unknown. When summing up over the product system, it appears as if the largest problem occurs in the metal working industry. The mentioned limitations are obviously less severe for analyses where the upstream activities constitute a minor part of the total system to be analysed. In all other cases, it is preferable if the missing parts of the process level data can be completed by IO data.

Limitations in IO data: The primary data reported from the enterprises are aggregated by the national statistical agencies, partly to maintain confidentiality of the individual enterprise data, but also simply to limit the size of the resulting tables. For many applications of IO data, for example to construct the national accounts, detail in presentation is not a crucial issue, while consistency of classifications across time and across geographical areas are more in focus. The aggregation makes the data less useful, more uncertain, for use in IOA and LCA. For such purposes, some statistical agencies provide less aggregated data, closer to the original sources. Some of the IO data are not directly measured, but indirectly estimated. The resulting uncertainty may be large if the data are to be used in detailed analyses of specific products. Emission data are typically not consistently available at the level of IO activities, but are calculated from statistical data on for example fuel inputs, using emission factors based on estimates of the composition of inputs, combustion conditions, abatement technologies, etc. This implies that emissions data for IO activities are less detailed than for process level data and often limited to the general (air) emissions for which international reporting requirements exist to UNFCCC, the EU NEC Directive 2001/81/EC, the Convention on Long-Range Transboundary Air Pollution, etc. The mentioned limitations are less severe when the data are used in studies at the societal level, but can be very misleading if applied to very specific products, where a combination of IO data with the more detailed process level data is preferable.

Tiered and/or integrated analysis: In a tiered analysis, the activities represented in the process level part of the table are also included in the IO data part. This duplication of activities does not necessarily lead to double-counting, as long as the table is not used to represent the full economy, but it does imply that the same activity is modelled with less precision upstream than in the "foreground" processes represented by the process level table. In other words, the detailed data provided at the process level is not utilised in the upstream modelling of the same activity. This also implies that the IO table remains the same, even when better information becomes available at the process level. In integrated hybrid analysis, an improvement in the process level data applies equally to all instances of this activity, irrespectively of where in the life cycle it occurs, and as more process level data become available, the part of the table constituted by residual IO data becomes smaller and smaller. However, integrated analysis has higher requirements on data quality, expertise, and resources. Integrated analysis is therefore most relevant when creating LCI databases that can be used by many users and for many analyses.

4. Guidelines and recommendations for application

This section describes rules for good practice in EIO-LCA and hybrid LCA. It touches a large variety of subjects, and should be considered more as providing a description of activities to be done than as a set of bullet points.

The balancing principle

For each activity, the law of conservation of mass and energy applies. This implies that the mass and energy in and out of each activity is the same, when taking into account changes in stocks. Only for activities involving nuclear reactions these balances interact. This is also true for each element. Thus, separate mass balances, energy balances and elementary balances apply to all activities except those involving nuclear reactions. Likewise, although there is no "law of conservation of money", a monetary balance also applies to each activity, expressed in the so-called *accounting equation,* which is the foundation for the double-entry bookkeeping system. At the level of products, a similar balancing principle applies, namely that all products used, must also be produced (or vice versa), taking into account changes in stocks.

What is accounted for in the core part of an IO table is the supply and use of intermediate products. If adding imported products to the supply, and exported products and final consumption to the use, the IO table can be balanced per product. To balance the supply and use of an activity, non-product inputs and outputs must also be accounted for. The nature of non-product inputs and outputs are quite different between monetary and physical accounting.

In a monetary IO table, the difference between the value of the outputs (revenue) of an activity, and the value of the inputs of intermediate products (including investments) to this activity, is the expenditures on primary production factors. These can be divided in *labour costs* (wages and other remunerations), *net taxes* (taxes minus subsidies), *net operating surplus* (entrepreneur's income or profit), and *rent* (payment to resource owners). In national accounting practice, rent is included with the net operating surplus and the payments to the primary production factors including investments are together called *value added*, although in formal terms neither investments nor rent are part of the value added by an activity. In national accounting, the value added of an activity is the same as its contribution to the gross domestic product (GDP).

In an IO table in mass units, the difference between the mass of the products of an activity and the mass of the inputs of intermediate products to this activity, is made up by inputs of natural resources, inputs of wastes from other activities, minus net additions to stock, minus outputs of wastes, and minus emissions. The same applies for an energy balance.

The balance per product in the monetary IO table requires that each product is provided in the same kind of values in the supply and the use table. Since this is not necessarily the case, one or more *valuation tables* are added to the right of the supply table in Figure 3, providing the necessary translation between the values of the supply table and the values of the use table. By nature, the original data for a supply table are given in *producer's prices*, while the original data for a use table are given in *purchaser's prices*. The difference is *trade and transport* margins, that is, the cost of the services of wholesalers, retailers and transports. Because trade and transport margins differ not only from product to product but also between users of the same product, a table expressed in producer's prices is more homogeneous than one in purchaser's prices. An even more homogeneous table is obtained if also *product taxes and subsidies* are eliminated from the prices. The resulting price is known as the *basic price*. It is common practice to express the supply table in basic price, and place the trade and transport margins and the product taxes and subsidies per transaction in one or more valuation tables to the right of the supply table. In publication, these tables may be aggregated into single columns.

Before transforming a supply-use table to a product-by-product direct requirements table, it is normal practice to express also the use table in basic prices, by subtracting the valuation tables from the use table, adding the trade and transport margins, aggregated per activity, as inputs from the activities supplying the trade and transport services, and placing the product taxes and subsidies in a separate row below the core table. These taxes and subsidies belong to the value added, but are not included when value added is calculated at basic price.

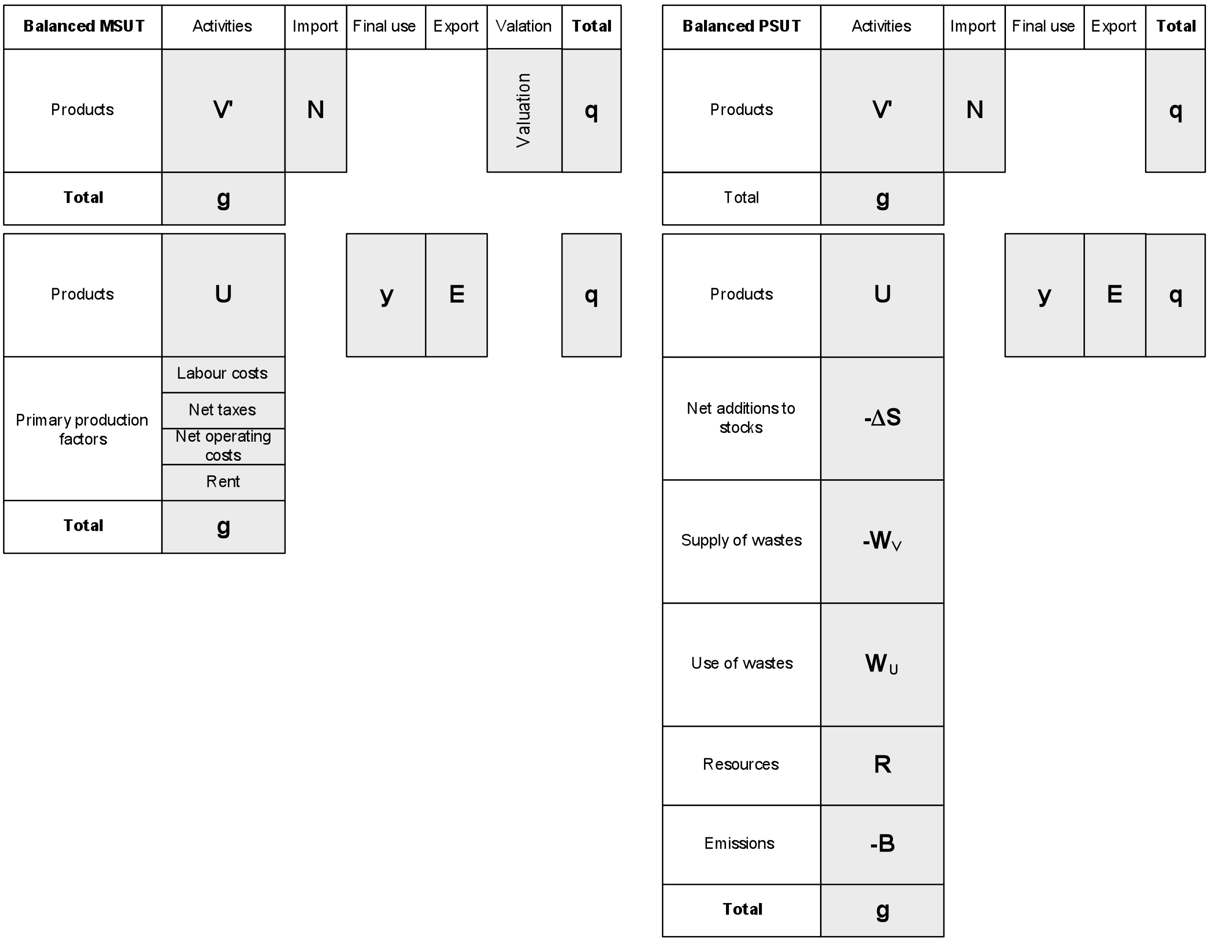

Figure 3. Monetary and physical supply-use tables and the additional tables needed to balance them.

An alternative to the use of a valuation table is to introduce a set of market activities, one for each product, as part of the core supply-use table, see Figure 4. Each market activity uses the corresponding industry product in basic prices and supplies the same product in *average* purchaser's prices. The difference comes from the inputs from the trade and transport service industries, and the taxes less subsidies, which in this approach are added to the products at the market. If different users pay different prices for the same market product, the difference to the average trade and transport margins must be added directly to the using activity as a (positive or negative) input from the trade and transport service industries. With this approach, the original supply table can be maintained in purchaser's prices, thus closer to the original statistical data. The tables can still be balanced per product, because each product is provided in the same valuation in the supply and the use table: Industry products are valued in basic prices and market products are valued in purchaser's prices.

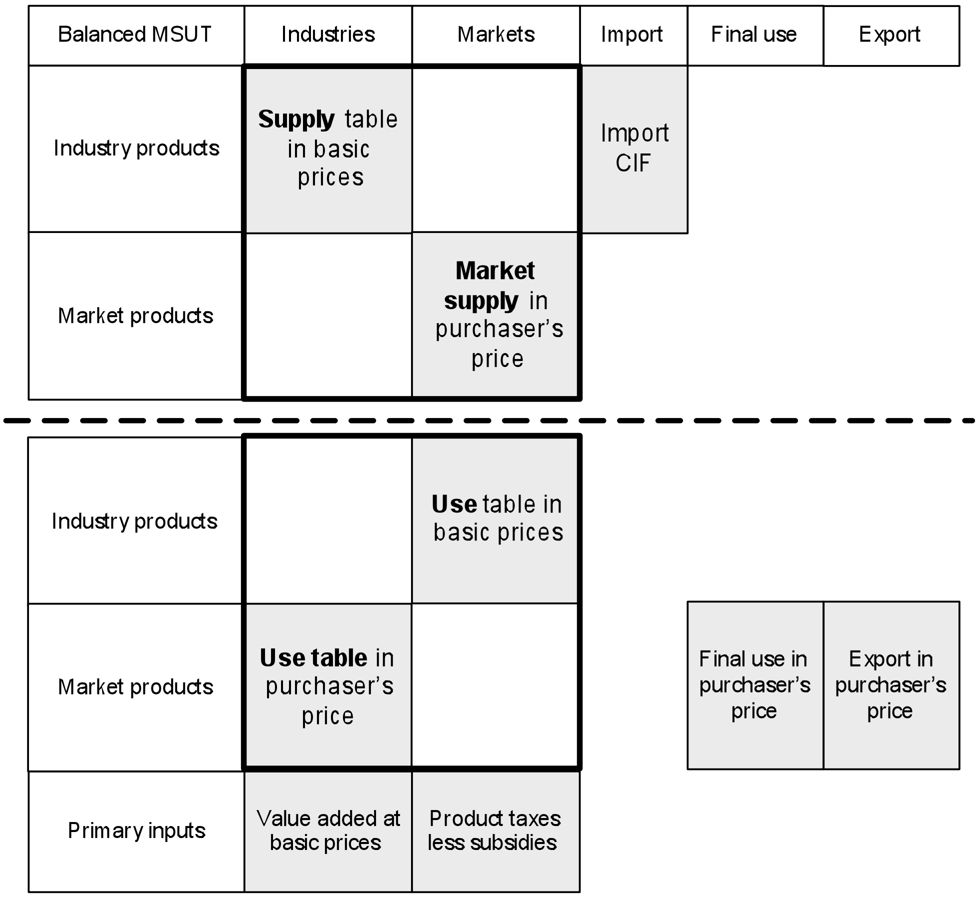

Figure 4. A balanced monetary supply use table using market activities instead of valuation tables.

In a physical IO table, where price valuation is not of concern, the concept of market activities may still be of interest since market activities can be used to model product losses during transport and trade. By assigning a negative mass flow to the product of the waste treatment services, the market activity for the treatment of a specific waste may be applied to distribute the physical amount of this waste over the different waste treatment services, a more disaggregated modelling of waste treatment scenarios can be integrated directly in the core supply-use table, eliminating the need for the two satellite tables for waste in Figure 3.

Hybrid units.

The advantage of using the same unit, either monetary or physical, for all exchanges between activities in a table is that the table can then be balanced per activity. This is an important validation tool, and ensures consistency and completeness of the tables. A table in mixed units, that is, where the outputs of different activities have different units, can only be balanced per product, not per activity.

However, a table in hybrid units has other advantages, namely that each product can be expressed in its "natural" unit, that is, the unit which best describes the main function of the product. This reduces the uncertainty of the data. For example, the natural (SI) unit for an energy carrier is Joule. Any other unit (kg, m^3, Euro) would have a higher variability between different suppliers of the same energy carrier, as seen from the perspective of the customer.

To obtain the advantages of a table in hybrid units, while maintaining the option to balance the table per activity, it is necessary to express each flow in terms of its properties in different units of interest, price in monetary units, energy content in energy units, dry mass, water content, and elementary contents in mass units. The balancing algorithm will then be able to use the same property for all flows for each balance. If the software used for the analysis does not support multiple properties of each flow, an alternative approach is to store multiple tables; one hybrid table and one additional table for each property that is to be balanced.

Uncertainty in IO data

At the basic level, monetary IO data are collected and reported by each single enterprise. In some cases, reporting is done at a level below the enterprise, known as Kind-of-Activity-Units (KAUs). These units are intended to be more homogeneous than the enterprise and therefore to reduce the problem of multiple products from one activity. The division in KAUs is equivalent to the subdivision of an activity used to avoid issues of co-production in LCA. The subdivision in KAUs may vary greatly from country to country, which is to some extent also reflected in the share of by-products reported in supply-use tables for different countries. In a country with a good division in KAUs, by-products will typically make up 3-5% of the total product output, while values of 10-15% are often seen for countries relying on data at the enterprise level only. A problem with KAU reporting is that it may underestimate activities that are common for the whole enterprise, that is, unless specifically required, the data from the sum of the KAUs may not add up to the data of the enterprise, and these data gaps then have to be dealt with later. Even when KAUs are not used for reporting, the concept can still be used by the statistical agency to disaggregate enterprise data, for example by separating out a transport supplying activity from a manufacturing industry and placing this part in the transport industry. Effectively, this can only be done by applying the same assumptions about input structures of the industries as applied in dealing with co-products (see later about these transformations).

The coverage of data collection for monetary IO tables varies from 100% to smaller samples, especially for small enterprises. Also, not all data are necessarily collected every year, and some data are therefore interpolated for years where data are not collected. The data are also sometimes collected at a higher level of product aggregation than used in the published tables. When the collected data arrive at the statistical agencies, data from several activities are aggregated. In this process of aggregation, the variation of the sample may be established, but this may not be done and at least this uncertainty is not reported specifically when data are made publicly available. Secondly, when necessary, data are disaggregated to the level of product detail used by the statistical agency, and missing data are estimated and distributed to balance the tables. The balancing principle is applied to identify implausible data and errors, and to adjust data from the least credible sources. This balancing exercise involves subjective assessments of data quality, so that the data with the least quality are more likely to be adjusted. While these data quality assessments and the additional uncertainty they introduce could be documented and estimated, this is either not done or at least not externally reported. Weidema et al. (2005) estimated the aggregation uncertainty of IO data, based on the variation between the same tables at different levels of aggregation, and found a very clear, close to linear, increase in variation as more commodities are aggregated. The largest aspect of uncertainty can also be expressed as allocation uncertainty, because the total values are often known with higher precision than the values for each activity (for example, the financial balance sheet of a company is closely audited, while the classification of each item in the balance sheet is not; the total extraction of natural resources may be closely monitored, while the use in each activity is not). For a study of a specific product, these allocation and aggregation uncertainties may be significant, while it is less important for studies at the level of the whole economy.

It would be preferable if statistical agencies in general provided actual uncertainty estimates for each of their data points, but even just such data from one country, based on a detailed analysis of uncertainty in the actual generation of an IO table, would be helpful to establish better uncertainty estimates of IO data in general. The estimates for each data-point in the IO tables may be propagated in the IOA or LCA using the same uncertainty propagation techniques as for process level data.

Physical IO data are typically based on physical information in resource statistics, production statistics, and trade statistics (imports and exports). The same aggregation uncertainties apply and the same lack of reporting of the uncertainty of the statistical data points can be found as for monetary data.

Adapting monetary IO data for LCA

The IO tables published by national statistical agencies do not include the *consumption stage* as an activity, but as a column outside of the activity table. In LCA, the consumption stage is an activity in parallel to any other activity, with inputs of products and natural resources, and outputs of wastes and emissions. The product outputs of the consumption stage are needs fulfilments such as meals, leisure, communication, safety and security, etc. To prepare an IO table for use in LCA, the final use column should be integrated into the core activity part of the table, and modelled as an activity with product outputs. It may be further sub-divided to reflect the interaction between different products and activities in the households, for example that cars and transport fuels are used together in the household activity 'car driving', which may then provide its part of its product to the household activity 'shopping', which again can deliver part of its product to 'meal preparation'. In this way, the structure of the household activities can be modelled and improvement options investigated in more detail. In a few countries, the statistical agencies produce *household satellite accounts*, in which the household production is modelled in parallel to the industry production in the core IO table. When this is done, the productive time use of the households is typically monetised, so that the household processes also have imputed labour costs that contribute to the household value added, which can then be added to the GDP to produce the *Gross Economic Product* (GEP), which reflects the value of the full societal production.

In the IO tables published by national statistical agencies, capital formation (investments, infrastructure, capital goods) are not included in the core activity part of the table. Product supplies that go into capital formation are represented by a separate column in final consumption, outside of the activity table, and the depreciation of the investment expenditures is represented by a separate 'use of fixed capital' row outside of the activity table. In LCA, the capital goods are seen as part of the production function of each activity, in the same way as other product inputs. To prepare an IO table for use in LCA, the 'capital formation' column and 'use of fixed capital' row should be integrated into the core activity part of the table. This is done by applying an *investment table*, which has the same format as the use table and provides information on the distribution of the 'capital formation' on activities. If an investment table is not available from the national statistical agency, it may be constructed by extrapolation from another country's investment table, normalised to the total output of each activity. Since the incorporation the 'capital formation' into the core activity part of the IO table represents a specification of the 'use of fixed capital' row under a steady-state-assumption, this row must then be eliminated to avoid double counting of the use. Because the 'use of fixed capital' row is determined from depreciation allowances, its sum is not necessarily equal to the sum of the 'capital formation' column. The incorporation of the 'capital formation' column and the simultaneous elimination of the 'use of fixed capital' row may therefore give rise to small discrepancies between the total inputs and outputs of each activity. These discrepancies must be adjusted in the net operating surplus.

In a physical IO table, the net additions to stock, as represented by the investment table, is also participating as an output in the mass balance of each activity, to match the input of capital goods. To maintain all mass flows of each activity in the same column, it is most convenient simply to include the investment table (in mass units) as a separate table below the core IO table, with a negative sign (representing an output that should be subtracted in the mass balance).

The IO tables published by national statistical agencies reflect the situation in a specific year, for example the specific production of new cars, the emissions from the current fleet (composed of cars of many ages), and the waste treatment of old cars scrapped in this year. In both LCA and IOA modelling, long-lived products are typically represented by steady-state models, for example a car will typically be modelled with the current production technology, the average life time emissions and the current waste treatment technology, all divided by the lifetime of the car. Effectively, this means that the net additions to stock are simply contributing as physical inputs to the waste treatment activities of the current year. A better model would be possible if LCI data were available in forecasted time series, so that the fuel use of the car could be obtained as inputs during its future life time, the waste treatment based on a future waste scenario, and the accompanying emissions placed at their correct point in time. Due to their internal consistency, IO tables are well suited as basis for making consistent forecasts of the entire economy.

Transformation of a supply-use table to a product-by-product direct requirements table
To be used in IOA or LCA calculations, the supply and use table or the direct requirements tables must be invertible, which means it must be square, that is, they must have as many activities as products. Original supply-use tables of national statistical agencies are often rectangular, in the sense that they have more products than activities. Either the activities must be disaggregated, which requires additional information to be meaningful, or several products must be aggregated to the level of an activity, implying the assumption that these products have the production function. The assignment of products to activities will normally be guided by the correspondence table between the product and the activity classification. For process-level data, the reverse problem may occur that there are more activities than products. In this case, either the products must be disaggregated per activity or several activities that supply the same product must be aggregated.

As the activities in a supply-use table have multiple products (*co-products*), they cannot be used directly for IOA or LCA, since these techniques require that each activity have only one product output. Transforming a supply-use table to a product-by-product direct requirements table can be done in two principally different ways, by *substitution* or by *partitioning*. Substitution is also known in LCA terminology as *system expansion* and in the terminology of IO economics the operation is known as the *by-product technolog*y model. For practical purposes the results of applying the by-product technology model is strictly identical to the more well-known *commodity technology model* (Suh et al. 2009), but since the results of the latter model are less transparent, it will not be further discussed here. Partitioning is also known in LCA terminology as *co-product allocation* and in IO economics the equivalent operation is known as the *industry technology model* because it effectively assumes that all product outputs of an industry activity have the same production function relative to the partitioning parameter. A number of other methods exist, which are all variations of the above.

In the *substitution method*, the co-products are divided in *determining products* and *by-products (dependent products)* and the output of the by-products are assumed to substitute the supply of the same product from the marginal supplier to the market for the by-product. In practice this substitution is modelled by eliminating the by-product output and placing it as a negative input to the same activity. In this way, the monetary, mass and energy balances of the co-producing activity are maintained (from a balancing perspective, a negative input is the same as a positive output), while the negative input leads to a substitution of the supplying activities of this input. This simple substitution procedure requires that each activity has only one determining product, which is not the case when there is more than one product output without an alternative production route. We come back to the more complicated procedure required when there is more than one determining product, after first describing the partitioning method.

In the *partitioning method*, the co-producing activity is simply partitioned into as many activities as there are co-products, each having only one of the co-products as outputs, the output of the others being set to zero, and the remaining entries in each new activity are then scaled by ratio of the new output to the output of the original co-producing activity, expressed in the units of the partitioning parameter. Typically, revenue is used as partitioning parameter, which is often argued to reflect the causal relationship between the size of the activity and its revenue steam, where an increase in the activity can be expected to be proportional to the increase in revenue. When all the product outputs to be partitioned are expressed in the unit of the partitioning parameter, such as is the case in a single-unit supply-use table, it is unnecessary to duplicate the activities, and each column in the direct requirements table can therefore be expressed simply as the market-share-weighted sum of the production functions of the activities supplying the product. It should be noted that the columns in a partitioned direct requirements table cannot be balanced for any other parameter than the one used for the partitioning. For example, if the partitioning is done with revenue as partitioning parameter, then inputs and outputs of mass and energy will not balance. This, in combination with the underlying improbable assumption that all product outputs of an industry activity have the same production function, are the main reason that the partitioning method is generally dissuaded. While still very popular in process level LCAs, partitioning is hardly used for the transformation of IO tables in empirical research (Beutel 2008).

If there is more than one determining product for an activity, the simple substitution described above will not result in a single-product activity. In this situation, the following operations are required to also deal with the multiple determining products. As a first step, the activity is partitioned according to revenue, following the partitioning method above, but without adjusting the outputs of the co-products differently than any other output. Effectively, this is a duplication of the activity, where each of the partitioned activities is scaled to the output of one of the determining products. This reflects the above described causal relationship, which is valid when there are no alternative production routes that determine the price of the products, but without the violation of the balancing principle that follows from artificially adjusting the outputs of the co-products. The resulting partitioned activities are therefore still multi-product activities. The following steps are performed for each of the resulting partitioned activities. As the second step, the product for which the partitioned activity is scaled is increased, so that the partitioned activity now yields the same revenue as the original activity, and the amount of product needed is at the same time added as an input, representing a reduction in use of the partitioned product by the marginal user of this product. This reflects that an increase in demand for the product is only partly met by an increase in the activity. Since the same amount of product is added as input and output, the activity is still balanced.

As the third step, the outputs of the other determining products are eliminated by placing them as negative inputs, representing the increased consumption of the marginal consumer of these products, resulting from the increase in the co-producing activity. As for the simple substitution, a negative input is the same as a positive output, so that the monetary, mass and energy balances of the resulting activities are maintained, while the negative input in this case leads to a substitution of the consuming activities of this input, because there are no alternative production routes. Finally, the non-determining products are dealt with as described for the simple substitution situation.

Although national statistical agencies publish direct requirements tables, it can generally be recommended to use instead the original supply-use data and to perform the transformation (substitution or partitioning) yourself, because:

- The operations performed by the statistical agencies to arrive at the direct requirements table are seldom reported in a transparent way, and often the methods deviate more or less from what is described above, especially in terms of the additional efforts that are often made to eliminate negative values; efforts that may in fact corrupt basically sound data. Some agencies do not publish product-by-product tables, but instead industry-by-industry tables, which are less relevant for LCA.
- Supply-use data are published with less delay and usually more frequently and with more product detail than the corresponding direct requirements table.
- When starting from the supply-use data, you can perform both of the above transformations, and thereby compare the results of these on the same statistical data basis, which may be relevant for different kinds of analyses.
- When starting from the supply-use data, you can include other data sources obtained for the same activities as in the supply-use table, for example natural resource and energy inputs, waste statistics, emissions data, and work hours, and ensure that these are included in the transformation in exactly the same way as the intermediate inputs.

Statistical classifications

Although UN classification systems exist both for activities and products (ISIC and CPC, respectively), different statistical agencies use different activity and product classifications. Especially the North American Industry Classification System (NAICS) is a widely used activity classification. Correspondence tables exist between many of the classifications, but in case of overlapping categories these do not eliminate the need for manual interaction during translation. Furthermore, all classification systems are regularly being revised, which adds to the work required when combining several tables. And even when statistical agencies follow the same classification, there may be subtle exceptions and differences in interpretations that make an error-free translation difficult. If possible, the original classifications should be maintained when translating, allowing later revisions.

In most cases, it is uncomplicated to assign process level data to activity and product classes. Sometimes, it may be difficult to determine the level of processing that causes a product to move to a different classification, for example how much beneficiation a mined product can receive before it should be classified as a manufactured product. Subtle differences, such as the fact that alumina is a product of the chemical industry, while aluminium is a product of the non-ferrous metals industry, may also cause problems for the uninitiated. Recycling processes are usually integrated with the activities that produce the virgin products, so that the 'Materials recovery' class only covers the collection and possibly some sorting and cleaning.

It may be difficult to determine whether an activity takes place internally in an industry or in a separate industry. For example, some capital goods may be produced within each industry rather than in a separate construction or machinery industry, some waste treatment may take place internally rather than at an external treatment plant, some fuels may be used for transport activities by own lorries rather than in the transport industry. These problems resemble those of recording data at the level of KAUs described above under uncertainty, and should preferably be dealt with in the same way, namely by sub-dividing the activities to produce only one product, identifying the relevant industries in which to place such internal activities. KAU reporting distinguishes own-account production or products for own final use, from products for sale or non-market products (products that are paid via general taxes or similar). From an LCI perspective, these distinctions are irrelevant, since the production functions do not depend on where the product is used or how it is paid for.

A process level LCI database will typically have more activity sub-division than statistical agencies, for example typically all internal heat production that is not a by-product of the manufacturing will be placed in one or a few technically defined activities (and classified under 'Steam and air-conditioning supply'), rather than included in each manufacturing activity, and all agricultural field operations will be recorded separately from the crop production (and classified under 'Support activities for plant production'), disregarding whether these operations are performed by the farmer or by a contractor. The more detailed the subdivision, the more non-monetised internal trade will be recorded.

Geographical resolution
Most IO tables are produced at a national level, but some organisations use these national data to produce more or less standardised versions covering more countries, but still with the national resolution. Some better-know examples are Eurostat, the OECD and GTAP. Some countries, like the USA and Spain, produce sub-national tables covering different regions.

To account for imported products being different than nationally produced, the national tables need to be linked, at least to a Rest-of-World (RoW) table. Since IO-tables are not available for all countries, one of the larger and more detailed tables, such as the one for USA, is often used as a proxy for the RoW table.

Linking tables from different countries is done via import tables, where the import to each national activity is specified on supplying activity in the exporting country. Import tables are constructed by subtracting the imported shares of each element in the use table, based on the ratio of import to domestic supply, as provided per product in the supply table. If more tables are linked, and the share of import from each supplying country is unknown, the linking may be made via a table representing a global trade pool, to which all unspecified exports are supplied, and from which all unspecified imports are drawn.

When the importing table have lower resolution than the exporting table, the imports need to be distributed over the exported products. Without more specific information, the best key to apply is the export column of the exporting country.

Monetary IO tables are usually provided in the current national currency. If two countries with different currencies are linked, the import table must include the exchange rate between the importing country and the exporting county's currencies. A verifiable exchange rate should be applied, such as the annual averages provided by International Monetary Fund in their International Financial Statistics. Note that while purchase power standards may be relevant when comparing and aggregating impacts, they are *not* relevant when translating direct trade values.

Derived from the supply table in purchaser's prices, the import table will be expressed in "free-on-board" (FOB) prices, that is, excluding international trade and transport margins. These margins are expressed by the difference to the import values in "cost-insurance-freight" (CIF) prices, as recorded in a 'CIF/FOB adjustments' row, and are separately imported from the supplying country or from another country supplying these services. To ensure that the inputs and outputs of these international trade and transport services are included in the assessment, the 'CIF/FOB adjustments' row must be linked to the exporting trade and transport industries.

Input-output based LCI (Environmentally extended monetary IOA)
The simplest form in which IO tables can be applied for environmental assessments is to provide an environmental extension to the monetary supply-use table. To maintain all information for each activity in the same column, it is most convenient simply to include the environmental exchanges in separate rows below the core use table.

Data on natural resources are available from resource statistics, and it is usually obvious which extracting activity they are inputs to. Some emissions data are available from national emission registers, and others can be derived by using an emission factor approach. Without detailed activity data, the emissions will typically be limited to those that can be derived from fuel inputs.

Data on social externalities, for example labour rights violations, may also be collected at the level of IO activities, but systematic work in this field is still in its infancy. Some economic externalities, for example direct perverse subsidies, can be derived from the information in the 'taxes less subsidies' row in the primary factor part of the IO tables, while indirect subsidies, for example via trade barriers, are less easy to identify, and have to be derived from other sources. The recording of economic internalities, are obviously the strong point of IO tables, and life cycle costing (LCC) can therefore be performed very simply by using the value added as a costing parameter. This may be further enhanced by the distribution of the primary factors on different income groups, for example through data on work hours performed by persons with different educational levels or from different income groups. With this information, distributional analysis can be performed for the social and economic part of the assessment.

The calculation procedures for an input-output based LCI are identical to those of a process level LCI. The only difference is in the detail of the activities included, and that all transactions between the activities are recorded in monetary rather than physical units.

Constructing physical supply-use tables
A physical supply-use table is constructed by applying data on physical flows of activities and the relation between monetary and physical flows (prices). Product prices and/or data on physical flows may be obtained from production, imports, and export statistics. When combined with resource statistics and emissions data, the mass balancing principle allows building up a supply-use table that matches the monetary supply-use table. For respiration, digestion and combustion processes, it is important to include oxygen and carbon, both as natural resource inputs and in emissions. To avoid the need for water balancing, it is recommended to enter data and perform calculations in dry mass. In this context it should be noted that the digestion of (dry) biomass will give rise to an output of respiratory water, which is therefore – somewhat counterintuitive – to be included in the *dry* matter balance.

The flow for which least data is available is wastes, and waste is therefore mainly estimated as a residual. A separate table for physical outputs of wastes, and a table for input of the wastes to waste treatment and recycling activities complete the physical balance, see Figure 3. The two waste tables balance each other, since all wastes outputs are received as inputs by other (treatment) activities. An alternative to the two separate waste tables is to integrate this information into the core part of the IO table by assigning the waste as a negative mass flow to the product of the waste treatment services.

Tiered hybrid analysis

Having identified missing inputs in process level data, that is, inputs for which no process level data are available, these missing inputs can be linked to supplies from the corresponding activity class in the monetary or physical IO table. Since missing process level inputs will typically be known in physical units, linking to a physical IO table will usually be simpler and provide a more precise result. If only a monetary IO table is available, the monetary value of the missing inputs needs to be estimated.

The described procedure can only be used for known missing data, that is, inputs that are known to be missing but for which upstream process level data are not available. However, many inputs are simply unknown, and can only be identified by comparing the process level data to IO data for the closest fitting activity class. By estimating the monetary value of all the intermediate inputs to the activity and comparing this value to the expected sum of intermediate inputs (the value of the output minus the average value added for this kind of activity), an estimate of the unknown missing data can be established. The nature of the unknown missing inputs may be estimated by comparison to the input coefficients of the IO activity, or it may simply be accepted as unknown and linked to an average output of all IO activities.

Constructing an embedded hybrid database

To embed process level data into a supply-use table, the two types of data structures must first be adjusted to match each other. Many of the necessary adjustments have already been described above:

- The integration of valuation table or market activities into the core part of the supply-use table, depending on which of the two methods have been applied for the process level data.
- The integration of final consumption activities into the core part of the IO table.
- The integration of the investment table into the core part of the IO table.
- The assignment of process level data to activity and product classes.
- Constructing a physical IO table in parallel to the monetary.

Some further necessary adjustments are:

- Adjusting the geographical specification of imports in the use table to match that of the process level data. Since process level data typically do not have a geographical import specification, this implies that the embedding should be performed before any geographical specification of imports in the use table.
- Adding to the IO table flows of complementary products, such as packaging, to match the modelling of these flows in the detailed process level data (in a physical IO table, packaging is typically not included with the product flows, and therefore appears to become waste at the producer rather than at the user).
- Checking the mass balances of the process level data to ensure that their quality is adequate for integration. The same concerns and conventions as used when making the physical supply-use table applies to the process level data.

- Adding to the process data the price and production volume data for the geographical area, since these are required to scale up the process level data to the level of the geographical economy of the IO table.
- Adding to the process level database import and export activity datasets for each product, based on trade statistics for the specific geography. These are required for the balancing of the product flows after embedding.

A final issue concerns the non-monetised internal activities that typically have a higher occurrence in the process level LCI database than in the corresponding supply-use table, as mentioned above under statistical classifications (with the example of internal heat production being recorded under 'Steam and air-conditioning supply' rather than included in each manufacturing activity). In some cases, like the agricultural services and the purchase of animal feed, the amounts will be included in the supply-use table when supplied by a contractor or by another farmer, but not when supplied by the farmer herself. Since the true values, that is, the total amount of these intermediate products, are better known from the process level LCI data, these values should be used to adjust the supply-use table before integration. Whenever an internal activity is added, the product supply increases, but so does the use of this added product. As price information is often not available for internal processes, prices must be imputed from the costs of the inputs, adding an average amount of added value for the industry in question. The resulting monetisation of internal activities will increase the total monetary output but the total value added remains the same (because the same money "changes hands" more often, but with a proportionally smaller amount of value added between each exchange).

The process based LCI data and the supply-use table will now have the same structure, and the integration can be performed. The integration consists of 5 steps:

- The process level LCI data are scaled up to the level of the geographical production volume.
- The up-scaled LCI data are summed up for each product-activity classification level of the supply-use table, and these aggregated data are subtracted from the corresponding cell content in the supply-use table. The result is a residual for each cell in the supply-use matrix. These may be represented as 'residual IO activity' datasets, at this time only using inputs from other 'residual IO activity' datasets.
- For each of the products in the up-scaled process LCI database, a monetary and a mass balance at the geographical level is performed, thereby identifying the missing use of each product.
- The missing use is distributed to the residual IO activity datasets, using the size of the activity residuals for the corresponding product group as distribution key, and subtracting the distributed missing use from the corresponding residual data, thereby obtaining a *remaining residual* for each cell in the original use table. The residual IO activity datasets now have the relevant inputs from all other activities.
- The remaining residual, representing input of unspecified products, is redistributed over all non-market activity datasets, using the monetary value of the production output as distribution key. To maintain the balance per activity, the value added of the activities are adjusted accordingly, most simply by subtracting the distributed remaining residual from the net operating surplus of each activity.

Emissions can be added to the residual IO activities, but since the residual activities per definition cannot have any process-specific emissions, emissions can only be added on the basis of emission factors relating to specific inputs, such as fuels. Since fuels are primarily inputs of the specific heat producing activities, it will in most cases only be for this residual heat producing activity that emissions can be meaningfully added. Even when no emissions are added for the residual IO activities, they play a role in increasing the completeness of the life cycle emissions of all products in the database, since they serve as (previously missing) links to other activities that *do* have emissions.

Meaningful waste outputs (or materially specified inputs of waste treatment services) can be added to the residual IO activities based on their mass balances.

5. Research & development lines

The research recommendations can be divided into three areas: data, methods and experience.

Data

In the short term (3-5 years) improvements in the process databases are required, so that they can be more easily integrated with the supply use data, implying the use of a recognized process and product classification, adding economic and production volume data, and applying mass and monetary balancing consistently to all activity datasets.

For the mid term (5-10 years), improvements should focus on data availability from statistical agencies. The primary data on physical flows needs to be improved, and the aggregation level in published data kept at the necessary minimum to protect confidentiality. Linking of physical and monetary data and balancing of physical tables should be performed already at the statistical agencies. Statistical agencies should document their estimation procedures better and report on uncertainty, preferably for each cell in the supply-use tables.

Methods

Concerning methods, although the main principles of IO-based and hybrid LCA appears to be clear, there are still many details to be filled in, especially on the harmonization of the two in a tiered or integrated way. Traditional LCA is based on a steady-state, IOA on a 1 year account, with information on capital formation and depreciation. These two different systems should be reconciled. Likewise, process-based LCA is a global network of activities, whereas IOA is a regionally delimited system excluding households and treating imports and exports in an aggregated way.

Experience

Many IOA (including EIOA) and LCA studies have been performed and published. The hybrid approaches have been demonstrated, in most cases using small stylized examples of 5 products with hypothetical data. Application to real case studies should be encouraged, in order to demonstrate the added value of integrated LCA, and to discover more practical issue like how to resolve the mismatch in activity and product classifications, how to obtain the links between physical and monetary data, how to include uncertainty analysis and demonstrating the application of consistent allocation procedures.

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