Methodological Approaches for Life-Cycle-Analysis using Input-Output Tables

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Abstract

Life-cycle-assessments are chosen as an evaluation criterion for the sustainability of commodities. To assure a holistic analysis, they investigate products or services over the entire life-cycle, i.e. from cradle to grave. The material balance analysis is the common way to analyze the influence of a particular product on the environment. Such an analysis is highly time-consuming and depends on available data. The evaluation of indirect effects is often challenging. Especially the energy demand and emissions related to manufacturing facilities, i.e. factory buildings and machines, are excluded in many surveys due to missing data. Neglecting this effect in general, leads to a systematic error, especially for processes with low throughput.

The energetic and environmentally extended input-output analysis constitutes a macro-analytical computation method. It enables a great time-saving potential for performing life-cycle-assessments for products and services. Specific energy expenses and specific emissions are calculated for the different commodities of the production sectors listed in the input-output tables. The direct energy demand or emission as well as the one of the upstream process chain are contained. Data concerning depreciation and gross fixed capital formation can be used to calculate the energy demand and emissions related to the manufacturing facilities.

A methodological comparison of different approaches to consider the effect of manufacturing facilities will be performed. The approaches will be implemented in classical / monetary and in hybrid-unit models. Extensions to analyze the effect on greenhouse gas emission and energy induced air pollution will lead to an energetic and environmentally extended input-output model.

Keywords

Life Cycle Assessment (LCA)
Energetic and environmentally extended Input-Output Analysis (IOA)
Cumulated Energy Demand (CED)
Depreciation
Gross fixed capital formation

Abbreviations

CED	Cumulated (Primary) Energy Demand
IOA	Input-Output Analysis
IOM	Input-Output Model
IOT	Input-Output Table
LCA	Life Cycle Assessment
MBA	Material Balance Analysis
PCA	Process Chain Analysis

1 Background and introduction to life cycle assessment

In former times a high demand was placed on cost efficiency, quality and safety for the production of commodities. The industrialization process and the associated growing standard of life and changing consumer behavior resulted in increasing environmental problems. To these belong e.g. the anthropogenic climate change leading to global warming, continuous resource depletion and forest decline. This background led to an additional requirement for the production of commodities – the sustainability.

The idea of sustainability has been firstly mentioned in German literature in the context of the German forestry in the beginning of the 18th century [CARLOWITZ 1713]. The aim was not to cut more timber than the amount that grows back at the same time. That ensured the satisfaction of future generations' demand of timber.

Nowadays sustainability of commodities, i.e. products as well as services, are estimated by life cycle assessments (LCA) [DIN EN ISO 14040]. Within such an assessment, the environmental impact of the whole life cycle "from raw material recovery, through production, use, waste treatment, recycling up to final disposal" [VDI 4600] of the commodity is analyzed – i.e. from cradle to grave or cradle to cradle, respectively. All material, energy and emission flows (inputs and outputs) as well as other environmentally relevant parameters are investigated. They are classified by impact categories, such as primary energy consumption and climate change, which represent the most common impact categories. Specific indicators sum up the environmental impact of an impact category and make it possible to compare different commodities. To the mentioned impact categories, the cumulated (primary) energy demand (CED) and the global warming potential are the corresponding indicators.

To perform an LCA, [DIN EN ISO 14044] structures the single analyzing steps and [VDI 4600] gives detailed instructions about the system boundaries to calculate the CED.

1.1 Methodological approaches for life cycle assessments

Different methodological approaches exist to calculate the indicators with certain advantages and disadvantages.

The process chain analysis (PCA) is a straightforward approach. Over all production stages, every energy demand and emission is added up. A great dependence on detailed process data and its extremely time consuming balance process, due to the multiplicity of interactions in the process chains, are the weaknesses of this approach. However, the accuracy of the result is high, when all cut-off criteria are reasonably chosen.

A compromise between adequate accuracy and an acceptable expenditure of time can be reached by performing a material balance analysis (MBA). Here, a detailed analysis of the masses of each component of the commodity is performed. By means of energetic or emission related coefficients from databases, the material composition leads to the indicators. Additional data about the type of production and transportation processes, as well as data related to the use and the disposal phase, have to be added. However, many results of studies were implemented in these databases, but the basic data is still limited for uncommon products. Relying on the material composition, this methodology is more suitable for analyzing products than services.

In praxis, nondisclosure and expenditures of money and time for the involved organizations limit the availability of data in both of these approaches.

Energetic and environmentally extended input-output analyses (IOA) constitute the last approach. In particular for analysis on a macro level (e.g. households), the IOA is an appropriate tool. The basis for the analysis is the input-output table (IOT), which contain the intermediate usage matrix. This matrix represents the technology of a country, i.e. it includes all the inter-industrial process chains and lists the direct demand of intermediate sales (i.e. commodities in monetary values). For this purpose, the national economy is subdivided into production sectors and equally defined category of goods. Hence, an analysis is limited to the number of commodities in the IOT, even though it is possible to disaggregate production sectors as well as category of goods. Internal consistency tests during development of IOT due to the input output framework improve the data quality. By calculating the Leontief inverse, the total demand, i.e. the direct as well as the indirect demand (Figure 1), of commodities can be identified. Monetary Input-Output models (IOM) use intermediate usage matrices on monetary basis and connect the energy and emission data later on. In contrast to that, hybrid unit models directly include the energy utilization in the intermediate usage matrix. An advantage of the IOA is that the price of a commodity is a common parameter and is used to calculate the indicator. If the investigated commodity is untypical for the category of goods, there is a potential of receiving inaccurate results.

Currently, there is a trend to combine PCA, MBA and energetic or environmentally extended IOA. The aim is to specifically use the strength of the methodologies and avoid their weaknesses.

1.2 Current challenges by performing life cycle assessments

During the production of commodities direct as well as indirect energy demand occur during all process stages (Figure 1). The indirect demand "is required for the provision of the appliances, machines and plants operating the process and for the conditioning of the process environment" [VDI 4600]. There are indirect material expenditures (e.g. for factory buildings) and indirect energy consumption (e.g. the electricity demand of machines).

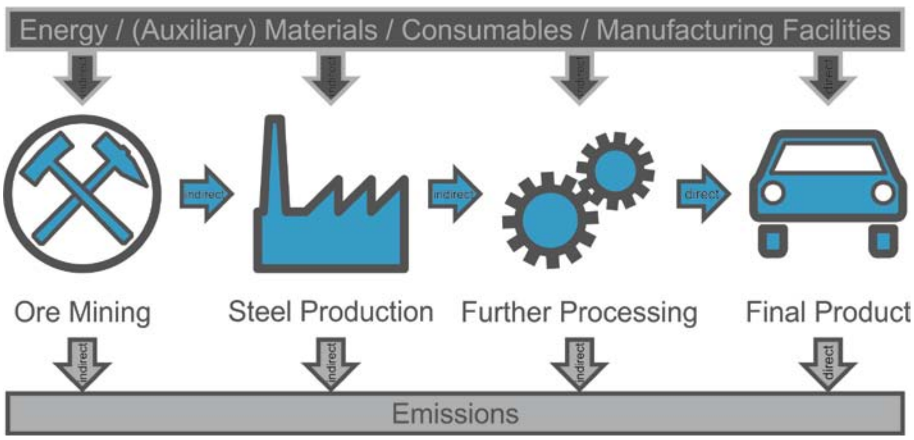

Figure 1: Simplified process chain with material, energy and emission flows

Often, the direct demand can be measured or data concerning inputs of energy, material, etc. is available. Determining the indirect demand in the field is often connected with certain challenges. Especially, the determination of the energy demand for manufacturing facilities, i.e. factory buildings and machines, is complicated. Within PCA, the estimation of the energy demand for these manufacturing facilities is extremely time consuming and highly complex. For MBA, additional data about the material composition of the whole manufacturing facilities is necessary. In most cases, this data is not ad hoc available or only on condition of tremendous expenses on time and money. Another challenge is the allocation of the indirect demand on the produced commodities. Manufacturing facilities are often used over several years and produce different kinds of commodities as well as co-products. There are several codes to allocate the demand on the commodities, which need additional data (e.g. concerning the machining time, throughput, service life, etc.).

Similar to these challenges, mentioned for the indirect energy demand, the same difficulties exists for the determination and allocation of indirect green house gas emissions or other environmentally relevant parameters.

Many surveys exclude the energy demand and emissions of the manufacturing facilities due to the mentioned challenges. Nevertheless, the direct and indirect energy demand of the manufacturing facilities "should not be neglected (in general), since they may prove to be the decisive contributions to the total cumulated energy demand, for example in the case of processes with low throughput" [VDI 4600]. Referring to that issue, [DIN EN ISO 14044] says: "The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study. Any decisions to omit life cycle stages, processes, inputs or outputs shall be clearly stated, and the reasons and implications for their omission shall be explained."

Therefore, it is necessary to be able to estimate and evaluate the relevance and impact of the total effect of manufacturing facilities on the conclusions of an LCA. Here, the energetic and environmentally extended IOA is a useful tool, as described below.

1.3 Estimating the effect due to investment evoked by depreciation

As mentioned before, PCA and MBA are challenging methodologies to estimate the total effect of manufacturing facilities. For practical purposes, the demand on time and money are often too high. To find a remedy, the IOA is a methodology which can be used to estimate this total effect.

The depreciation constitutes a yearly value for the investment in manufacturing facilities to assure a production in the following periods and keep the facilities up to date. Thus, it can be interpreted as a demand of manufacturing facilities. The monetary value of the depreciation is a function of the service lives of these facilities. [DESTATIS 2012] states that the depreciation, calculated in the German national accounts, measures the decline in value of the fixed assets during one period due to normal wear and tear and economical obsolescence. They are listed as current replacement prices for each production sector in the IOT for Germany. For the year 2007, the average proportion of the depreciation to the production value of the respective production sector is 7.7 %, the maximum is 68.4 % [DESTATIS 2010]. Assuming a correlation between the machines and buildings related to the depreciation and the energy demand for these machines and buildings, this contribution should not to be neglected.

Referring the yearly depreciation of a production sector to the production value of this sector (also a yearly value), the depreciation per one unit of value of this sector is calculated. This factor might be interpreted as an imaginable direct investment per one unit of value of the commodity for the whole process environment. With the help of the energetic or environmentally extended IOA the total monetary and environmental effect can be accounted for.

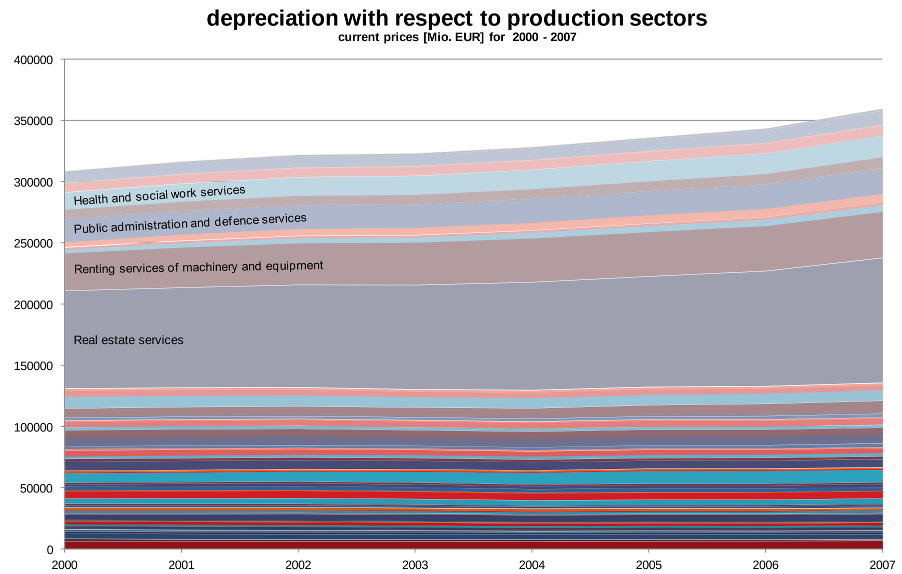

Figure 2: Time series of depreciation with respect to production sectors

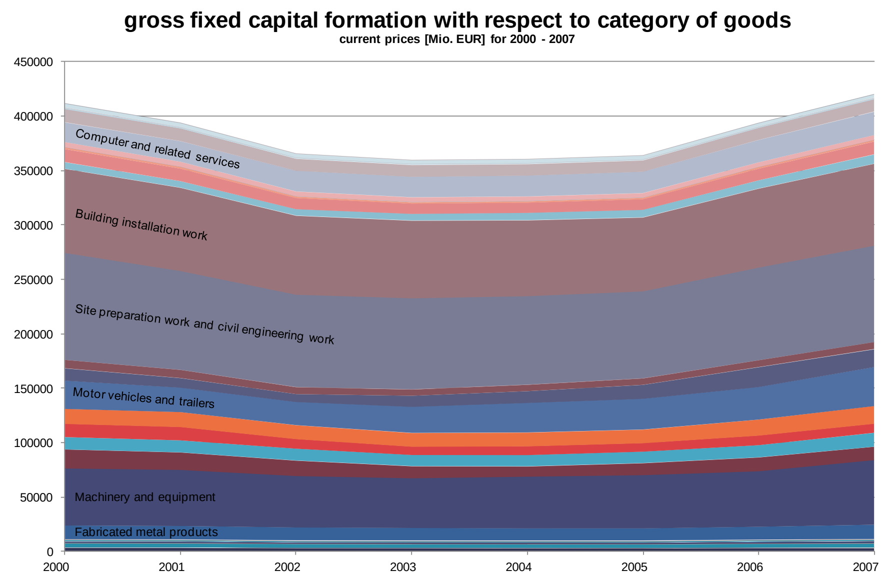

Figure 3: Time series of gross fixed capital formation with respect to category of goods

Additional information about the gross fixed capital formation can be helpful for the distribution of the depreciation to the categories of goods. [DESTATIS 2012] defines it as purchases of new as well as used assets minus sales of used assets. In this context, assets are manufacturing facilities with service lives greater than one year. They can be subdivided into machines (inclusive vehicles and equipment), buildings and other assets. Problematic is that the gross fixed capital formation is based on the period of the IOT (i.e. one year) and therefore cyclical (Figure 3), while the depreciation respects a yearly proportion of service lives (i.e. several years; Figure 2).

2 Methodological approaches to include additional demand due to investment evoked by depreciation

Especially dynamic IOM, like e.g. [TURNER 2009] or [IDENBURG 2000], adapt the manufacturing capacity over time by means of the depreciation and gross fixed capital formation. In the focus of this research are static IOM to include the additional demand due to investment evoked by depreciation. The literature research displayed two differential methodologies. [DRAKE 1996] endogenizes the gross fixed capital formation by an additional production sector. Another approach by [WENZEL 1996] endogenizes the depreciation, by calculating an additional square matrix.

Other studies, like [FLASCHEL 1982], excluded the “problem of how to treat fixed capital and depreciation”. [BULLARD 1978] and [WILTINH 1998] performed it for a monetary IOM. [BENDERS 2012] considered a proportion of the consumer price for capital goods.

2.1 Implementation by an additional production sector / commodity

[DRAKE 1996] converted the gross fixed capital formation from the final demand into the intermediate usage matrix. Therefore, a new production sector as well as a new category of goods was created. By taking the gross fixed capital formation column as the new production sector and the depreciation from the primary inputs as the new row, the intermediate usage matrix was expanded (Figure 4).

		Production Sector				**Final Demand**			
		PS	SS	TS	Gross Fixed Capital Formation	…	Gross Fixed Capital Formation	…	Sum
Category of Goods	Primary Sector (PS)	€	€	€	€	€	€	€	€
	Secondary Sector (SS)	€	€	€	€	€	€	€	€
	Tertiary Sector (TS)	€	€	€	€	€	€	€	€
	Depreciation	€	€	€	€				
Primary Inputs	…	€	€	€					
	Depreciation	€	€	€					
	…	€	€	€					
	Sum	€	€	€					

Figure 4: Aggregated IOT with new production sector and category of goods

This calculation assumes an identical structure of investment in all production sectors. Specifically, there is no differentiation in the type of investments, i.e. among buildings and machines. The CED 2007 calculated in the German environmental accounting per production value differs for machines (4.4 MJ/EUR) and buildings (5.1 MJ/EUR) (calculated with data from [DESTATIS 2010], [DESTATIS 2011]). Problematical, is that the sum of gross fixed capital formation differs from the sum of the depreciation. That is due to the above mentioned problem concerning the different periods. On the one hand, the depreciation represents a mean value over several years, and on the other hand, the gross fixed capital formation is cyclical (Figure 2 and Figure 3). The methodology can be implemented in a monetary IOM, but also in hybrid unit IOM, like shown in [DRAKE 1996].

2.2 Implementation by an additional matrix

[WENZEL 1996] developed a calculation method for monetary IOM to endogenize the depreciation and calculate the related energy demand. Different methods of endogenization were investigated. In the IOM, the endogenization of the depreciation is performed by a square matrix $\boldsymbol{W}$ with equal numbers of rows and columns like the intermediate usage matrix. This matrix is added to the intermediate usage matrix $\boldsymbol{Z}$ and results in the new intermediate usage matrix $\boldsymbol{Z_W}$. New input-coefficients $\boldsymbol{A_W}$ as well as Leontief-coefficients $\boldsymbol{C_W}$ are calculated and result in new energy intensities $\boldsymbol{E_W}$:

$$\boldsymbol{Z} + \boldsymbol{W} = \boldsymbol{Z_W} \Rightarrow \boldsymbol{A_W} \Rightarrow \boldsymbol{C_W} \Rightarrow \boldsymbol{E_W} \quad \textbf{Equation 1}$$

When $\boldsymbol{E}$ describes the energy intensities without considering the effect of depreciation, then the contribution of the depreciation $\boldsymbol{W_W}$ to the energy intensities can be calculated by:

$$\boldsymbol{W_W} = \boldsymbol{E_W} - \boldsymbol{E} \quad \textbf{Equation 2}$$

In [WENZEL 1996], the matrix $\boldsymbol{W}$ was calculated by means of the following four calculation methods:

- Intermediate-Inputcoefficients
  These inputcoefficients are calculated by referring the intermediate sales $\boldsymbol{z_{ij}}$ to the column sum of the intermediate sales (input). Note the difference to the technical coefficients, which are normalized to the production value. Therefore, the depreciation of a production sector is allocated on the basis of the proportion of the demand of intermediate sales in this production sector.
- Intermediate-Outputcoefficients
  Here, the intermediate sales $\boldsymbol{z_{ij}}$ are normalized to the row sum of the intermediate sales. The depreciation of a production sector is distributed by the proportion of the delivered intermediate sales of this production sector (output).

- Equal distribution
  This mathematically simple allocation distributes the depreciation of a production sector equally on the categories of goods.
- Gross fixed capital formation
  In this case the matrix W is calculated by distributing the depreciation (demand of intermediate sales) by the proportion of the gross fixed capital formation (output of intermediate sales).

For this methodology, there is a linear correlation between the value of the depreciation and the energy demand of the manufacturing facilities assumed. Manufacturing facilities, which were built in previous years, are proportionately accounted to the contemporary energy demand and with respect to the contemporary investment structure and technology of the given period.

3 Further proceeding and prospects

Both methodological approaches will be compared and their differences will be stated and discussed. At first a monetary IOM will be built up and both approaches will be implemented. Monetary IOM do not accurately reflect the energy flows in the case of unequal interindustry energy prices [MILLER 2009]. The assumption of uniform energy prices is in almost every case not justifiable. For Germany, implied energy prices for electricity and district heating in 2007 are, for example, 3.1 EUR Ct/kWh for chemical commodities and 18.4 EUR Ct/kWh for water supply. The average for all production sectors is about 10.5 EUR Ct/kWh (calculated with data from [DESTATIS 2010], [DESTATIS 2011]). Therefore, an additional hybrid unit IOM will be established in a second step and both approaches will be applied. Hence, a new allocation method for calculating the matrix $\boldsymbol{W}$ for hybrid unit IOM has to be developed.

Furthermore, an improvement of the approach shall be achieved by subdividing the depreciation into depreciation of machines and depreciation of buildings. In this context, it is to be analyzed how to deal with the immaterial assets in the depreciation. In this context, immaterial assets are e.g. pool tests in oil and gas exploration, computer programs or copyrights.

In addition, the aim is not only to determine the energetic effect, but also to determine the amount of carbon dioxide, greenhouse gas emissions as well as emissions concerning energy induced air pollution in this context.

Acknowledgment

The PhD project is supported by a scholarship of the Graduate School of Energy Efficient Production and Logistics – a collaborative initiative of the Ruhr-University Bochum and TU Dortmund University, funded by the Ministry of Education, Science and Research of the German State of North-Rhine Westphalia.

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