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Review

New Direction of Development in Environmental Life Cycle Assessment

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Abstract

The Life Cycle Assessment (LCA) method is widely used to assess the environmental impacts generated during the entire life cycles of products. The traditional process-based LCA (P-LCA), however, has some weaknesses. One of them is incompleteness resulting from the omission of environmental loads on the higher upstream orders of product system. This problem is called "truncation error." There are some relatively new initiatives to combine the conventional P-LCA with the economic Input Output Analysis (IOA) in one general approach defined as a hybrid LCA. It allows solving different problems, even those which seemed to be unsolvable until now.

Keywords: Life Cycle Assessment, Process-LCA, economic Input-Output Analysis, Hybrid LCA, Truncation error

Introduction

Life Cycle Assessment (LCA) is a technique of environmental management based on the life cycle concept. This concept is applied in a variety of approaches and methods, for example Life Cycle Cost Analysis (LCC) and Total Energy Cycle Assessment [1]. LCA consists of four phases:

- Goal and Scope Definition
- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Life Cycle Interpretation

The guidelines and principles for carrying out LCA studies are included in the group of ISO 14040s standards. Works on Polish versions of those documents are still continued [2-3]. Some of the standards already exist in the final version (ISO 14040, ISO 14041, ISO 14042, ISO 14043) while others are still under development as projects or technical reports (ISO 14047, ISO 14048, ISO 14049). There are various issues concerning the structure [4-7], the applications [8,10] and data documentation format [9] included in the documents. LCA is used for assessing the environmental aspects and potential impacts generated during the whole life cycle of products, from the beginning to the end. This way the environmental burdens connected with upstream and downstream components are analyzed. The upstream flows refer to the extraction of the raw materials and to the manufacturing of semi-products and services used in the production of the analyzed final product(s). The downstream flows relate to the exploitation and the final disposal stages. In LCA it is necessary to construct a model of the product system which includes all these processes and flows. The smallest portion of a product system for which data are collected is called "unit process". Therefore, the product system is a collection of materially and energetically connected unit processes which performs one or more defined functions [4]. Each unit process consists of inputs and outputs. There is some problem with the definition of the boundaries of unit process, which in practise can include one single technical step, a complete manufacturing plant or fully aggregated data. LCA studies can analyze large product systems with hundreds or even thousands of different unit processes and data. In these cases LCA becomes a very time- and cost-consuming task. It naturally leads to some simplifications and exclusions.

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Process Life Cycle Assessment (P-LCA)

The first formal study on LCA was made in Smugglers Notch in 1990, where the first SETAC workshop was organized [11]. From this time the interest in LCA subject has systematically been increasing. LCA studies have traditionally been carried out as bottom-up process analysis, where the main attention is paid to specific processes [12]. There are two main approaches to P-LCA today: prospective (change-oriented) and descriptive (retrospective). There are substantial differences between them in respect to decisions made and the way of modelling of the environmental impacts. In both cases, however, the product system is modelled by means of site specific information (for example from a certain company). This approach has advantages and disadvantages. The main value of P-LCA is that there are site and time specific data used in the analysis. This type of LCA analysis also enables a focus on details and detailed analysis. This is very valuable, because it allows to reflect real systems and to use knowledge and real data about specific systems, not "average" ones. However, it is a very difficult (if not impossible) task to model all the product system with the entire supply chain in this detailed way [13]. For this reason, the P-LCA is most often based on the incomplete models of product systems, because some simplifications and exclusions should be made. There are opinions that it leads to the loss of 50 percent of information [12]. This problem is called "truncation error" [12,14] and it results from omission of resource requirements and pollutant releases from higher order upstream stages of the product system. The lower order of the system boundary, the higher the truncation error. System boundaries are often defined by using data availability. The lack of appropriate information forces us to make cut-offs on different levels of product system. Sometimes, this kind of decision is also based on the conviction that the addition of higher upstream stages has a small effect on total results. This way the detailed, but incomplete, model is obtained. It introduces additional uncertainty into the LCA results. This sort of modelling in P-LCA leads to another consequence: the problem cannot be analyzed in the macro scale, but only in the micro. All socio-economic mechanisms and phenomena cannot be included, because there is not any analysis on the national and inter-sectors level. The introduction of the prospective, market-based methods [15] for P-LCA has been an important methodological improvement. It gives more realistic and complete modelling of the consequence of the change in product system. But it does not solve the problems of incompleteness of system and truncation error. It is necessary to seek other solutions. For this purpose there are some initiatives to combine the P-LCA with the Input-Output Analysis (IOA).

Input-Output Analysis (IOA)

The origins of economic Input-Output Analysis (IOA) go back to 1925, when Leontief published a short note about a table connected with the inter-industry flows in the Soviet economy. First, empirical application of this concept took place in 1936. In 1970, Leontief attempted to use this purely economic approach in environmental applications [16], which was improved in later years. IOA is an economic technique, which uses sectoral monetary transactions data for accounting of the complex inter-industry relationships in different economies [12]. In the simplest form, the result of IOA is an f x n matrix of factor multipliers where "f" means production factors (such as resources, pollutants, energy and labour) per unit of final consumption of products manufactured by "n" industry sectors. An IO-table gives an overview of the trade in a national economy. It shows a fate of the products in the market: they are sold from manufacturers either to the final consumers or they take part in further production in other industry sectors. IOA seems to be a tool of high relevance for LCA purposes, because it covers infinite orders of upstream production stages. This approach has one principle advantage over the P-LCA one: completeness. In the P-LCA the boundaries of product system are usually chosen on the second/third order but not in the IOA case. There are a few reasons to use IO tables in LCA [17]:

- IO tables allow to make a comparison of physical process and economic sector
- IOA enables to carry out of the life cycle impact assessment for the average products of economic sectors
- Data from IOA can be applied to each product and service

In order to use the IO tables in LCA studies special databases should be constructed. This way the data gaps in P-LCA can be fulfilled and the problem of incompleteness can be partially solved. Huge efforts have been made recently to create a combined structure of LCA called a hybrid LCA. The conventional P-LCA has a lot of different sources of uncertainty [18]. The IO-LCA also is faced with this problem. There are a few sources of the potential uncertainties in IO-LCA [12], which can increase the overall uncertainty.

The relationship between LCA and IOA is even deeper. Both approaches can be used in the economy-wide analyses to calculate so-called indirect flows associated with imports and exports. The LCA-based approach is especially recommended in the analysis of biotic and abiotic raw materials and products with the lower level of processing. For calculation of indirect flows for semi-manufactured and final products the IOA seems to be more valuable [19].

Hybrid LCA

In general, there are two ways of performing hybrid LCA. It can make a starting point in either P-LCA or IOA [12]. In the first case, the hybrid is based on the process-LCA and all data for the individual product are collected as in the traditional LCA studies, but the data gaps are fulfilled by IOA data (P-LCA based hybrid method) [20]. For example, typical LCA process analysis fails to take into account many minor systems flows. In hybrid LCA, these flows can be calculated from economic IO analysis [21]. Here, the IO data let fill data gaps and reduce incompleteness. This incompleteness is not eliminated, but considerably limited. Very often the collection of data is the most time-consuming part of P-LCA. Unfortunately, in this type of hybrid analysis, this problem is still serious. Here, the IO tables are simply used as the additional source of data, but the problem of truncation error is only partially solved. In the second case, the LCA study starts from IO-analysis (IO-based hybrid method) of one or more environmental impacts. The IO general data can be substituted with the specific process data by adding additional column to IO-tables on different levels of the aggregation. This way the general model can become more detailed. Treloar in his research [20-21] has suggested the following procedure: as the first stage, the LCA assessment is carried out mainly with IOA data. Next, the entire production system is disaggregated and decomposed into groups of processes called paths, which are classified according to the relative contribution to the final LCA results. Finally, the process data can be collected till the desired level of accuracy is reached.

Truncation Error

As mentioned earlier, the values of the truncation errors depend on the order of analysis. For the analysis which reaches the first order upstream processes, the truncation is about 50 percent. Similarly for the more sophisticated analysis (third order) the values of the truncation can range between 9 and 52 percent [22]. This problem can be reduced by combining traditional process LCA with the IOA. The comparison between values of the truncation errors for primary energy multipliers is carried out and can be found in [12]. This comparison includes the values for P- analysis (from zero to third order) and for input-output analysis (IO Analysis). In almost all cases clear lower values of the truncation error for I-O analysis can be observed. In the remaining cases, the values are comparable with those for the third order analysis. This means that the completeness of the product system is much higher in the case of IO analysis and even detailed analysis, which reaches to the third order processes is not able to equalize it.

Commentary

There is no doubt that the hybrid LCA currently is a widely accepted direction in the improvement of LCA. Among different challenges in the global development of LCA this concept plays a vital role [23-24]. It is worth mentioning that more and more papers are published and courses are organized which concern hybrid LCA issues [25-28]. First types of software which enable to carry out a hybrid LCA [29-30] are already available as well. They have been created on the basis of the results of the newest research in the field. The special databases [31] are necessary to develop programs for hybrid LCA, which should be compatible with the existing software for P-LCA. Taking into account the current state of the art, the hybrid LCA seems to be the future of environmental Life Cycle Assessment.

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