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Life-cycle assessment for energy analysis and management

Helias A. Udo de Haes *, Reinout Heijungs

Institute of Environmental Sciences, Leiden University (CML), P.O. Box 9518, 2300 RA Leiden, The Netherlands

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Abstract

Life-cycle assessment (LCA) is a form of chain analysis in which structural pathways in the economic system are delineated and connected to environmental problems. As such, it can be seen as an extension of, or a complement to, energy analysis. The main developments over the past 30 years are sketched in a perspective that puts an emphasis on standardization and scientific consensus creation. We end with a logical next development: a closer cooperation and harmonization with the domain of energy analysis, and an expected growing interest from the energy-application side.

Keywords: Life cycle assessment (LCA); Energy analysis; Energy systems

1. Introduction

Economic activity is closely associated with depletion of resources and pollution of the environment. This can be studied at the level of single processes or activities, but also at a higher systems level of networks of processes. At this higher level, structural pathways are investigated that connect consumption of products to many segments of the industrial web. By doing so, one enters the field of chain analysis, where several analytical tools are available for decision-support, like life-cycle assessment (LCA), environmental input–output analysis (env-IOA) and material flow analysis (MFA). In this article, we will

* Corresponding author. Tel.: +31 71 5277461; fax: +31 71 5275587.
E-mail address: udodehaes@cml.leidenuniv.nl (H.A. Udo de Haes).

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concentrate on LCA. Readers interested in the other tools and their relationships are referred to [1].

The main aim of LCA is to quantify potential environmental impacts of products over their full life-cycle. A life-cycle approach is also called a "cradle-to-grave" approach. Such an approach enables a fair comparison between products, which fulfil the same function, with respect to their environmental burdens. First of all, this is true for finalised products, that is, for products which are already on the market. In this context, a life-cycle approach helps to avoid problem shifting between the different processes which are part of the life cycle of a product. Materials may be quite harmless in their use phase and may therefor be preferred, but they may imply toxic emissions during their production or waste management. A well-known example concerns PVC. Secondly, LCA can also contribute to product design. It can help to design products which have a minimal environmental burden over their life cycle. For instance, during the design of products, attention can be paid to the reuse of the product, or at the recycling of its constituting materials in the waste-management stage.

LCA is a quantitative tool. The results of LCA are as much science based as possible, and aim to inform stakeholders in a production–consumption chain, thus contributing to rational decision-making. At the same time, LCA can also be of use inside a company. By implementing an LCA study on a product, the processes of the product system can be identified which largely appear to contribute to its total environmental burden. This may help to guide environmental management of a company, for instance to support its investment decisions or to influence its supply management. This reasoning can be particularly true for decisions in the energy sector. Here, LCA is quite often used, as shown by articles in this journal. At the same time, however, it is clear that the use of LCA in this sector is not sufficiently in line with international methodological development. An overview of the history and state-of-the-art of LCA and its application can therefore be of interest.

In this paper, we will sketch the main developments regarding LCA, from a perspective related to both its content and its application. In a closing section, we will revert to the question regarding the specific relationship between LCA and energy.

2. Early history of LCA

LCA originated in the early 1970s (see for overviews, e.g. [2–4]). This happened at the same time in four countries, the UK, Switzerland, Sweden and the US. At that time, the modelling was rather simple, focussing on the use of energy and the production of final waste as results of the studies. There was a close link with energy analysis, LCA calculating the so-called "embodied energy" of a product. Objects of analysis were household products, like beverage containers, detergents and diapers. But even this simple set-up produced interesting results. The numerous studies on beverage containers of course demonstrated the high embodied energy value of aluminium, in contrast to glass. Glass scored even better if it was reused or recycled. But these original studies also brought to light that the collected glass was often transported over long distances for recovery, such as from London to Scotland, thus spoiling the gain. The winner in this battle were the reusable plastic bottles, particularly also because of their light weight.

Also the diapers gave results which were not directly in line with intuitive perceptions. Cotton diapers are reused many times, but they have to be washed and in this way need quite an amount of energy. Paper diapers on the other hand produced a lot of waste, thus leading to an unresolved outcome of the comparison. However, when coupling waste incineration with energy recovery, the picture changed: the amount of produced waste largely decreased and the energy balance further shifted in favour of the paper diapers.

Results as indicated above are in fact based on large numbers of studies. Individual LCA studies clearly could produce quite conflicting results. This was due to the fact that the methodological basis at that time was chaotic. It was the companies themselves which performed the studies and which also defined their own methods. The results generally pointed at the environmental superiority of the product of the company which performed the study; they were then used for market claims: "my product is more environmentally friendly that the product of my competitor". These unwarranted claims have for quite some time damaged the image of LCA. Still, already the early LCAs have stimulated critical thinking as opposed to intuitive assumptions about the environmental characteristics of products.

3. Role of SETAC since the end of the 1980s

In 1989 the Society of Environmental Toxicology and Chemistry (SETAC; http://www.setac.org/) offered a home to LCA. This has been very positive for its development. A first outcome was that, at world level, a consistent terminology could be established. Before that time LCA was known under many names, such as for instance "resource and energy product analysis" or "ecobalance". Also initiatives were undertaken to establish a fixed technical framework, consisting of a number of distinct steps. Of great importance were the achievements in the field of methodology development.

A first methodological aspect was the definition of the functional unit, i.e., a unit of function to which are impacts are attributed. The reason for establishing such a functional unit lies in the comparability of products. One cannot compare one milk bottle with one carton, if the milk bottle is used 25 times and the carton just once. Comparability arises if the environmental burdens are attributed to a unit like "the packaging of 1000 l of milk", using 1000 cartons or 40 bottles. Likewise one can investigate the environmental burdens connected with the production of 1 kWh electricity, using different fuel mixes.

Another issue concerned the definition of the boundary between economy and environment. It makes quite a difference if a land fill is regarded part of the environment (then all waste put in the land fill is an emission to the environment), or if it is regarded part of the product system (then only the emissions from the land fill are emissions to the environment).

Yet another important methodological problem concerned what has become known as "allocation of multiple processes". Multiple processes are processes which fulfil more than one function. An example concerns waste incineration combined with electricity production. The question is: to what extent should the emissions of this incineration process be allocated to the waste management service, and to what extent to the production of electricity? It becomes even more complicated if heat is also produced in a co-generation process. A comparable question arises with recycling. If a waste material is recovered as secondary material, how should the environmental burdens connected with this recovery process be allocated? Which part has to be taken up by the original product, and which part by the secondary product? Different schools originated, some focusing on material characteristics of the processes and others rather on their economic value.

There were also points of agreement. Thus it became clear that the analysis of a full life-cycle cannot go in hand with high spatial and temporal detail. LCA studies typically were performed at world level without any spatial differentiation, and with steady-state modelling. An important development in the field became known as "life-cycle impact assessment". In the original studies, waste was just expressed in kilograms. Now the different emissions were attributed to a number of impact categories. Within each category, the different substances were added up on basis of so-called characterisation factors. Such factors are well known in the field of climate change (the global-warming potentials) and in the field of stratospheric ozone depletion (the ozone-depletion potentials). But likewise, such factors were developed for acidification, for eutrophication, for photochemical oxygen creation, and for toxic substances. Comparable developments started at the input side, adding up different types of fossil fuels and ores.

SETAC, being a scientific organisation, presents its work at yearly congresses. Working groups have been established for more coherent activities; also two scientific journal have been established by SETAC (*Environmental Toxicology and Chemistry* and *Integrated Environmental Assessment and Management*), which are open for, but not specifically focused on LCA.

4. Role of ISO in the 1990s

In 1994, the International Organisation for Standardisation (ISO; http://www.iso.org/) started with its 14040 series on LCA. Up to now, it has resulted in four standards [5–8] and several technical reports. At the moment, the standards are being integrated into two encompassing standards, one for general description and one covering all normative statements. ISO standards are characterised by their normative language, the "shalls", "shoulds", and "mays". If something shall be done, it is required in order to meet the standard; if something should be done, a real attempt must be made; if something may be done, it is an option open to the practitioner. This rigid context was precisely what was needed to bring about coherence in the different schools of LCA thinking and practice. But to be clear, ISO did not impose one standardised methodology.

A first aim concerned a standardised technical framework, much more elaborate than was developed under SETAC. Secondly, a technical framework was established, separating as much as possible subjective and objective elements in the LCA process. This framework started with a subjective "phase", as it was called, "goal and scope definition", defining amongst others the product or products to be investigated, the desired level of detail of the study, the types of impact to be analysed, and the intended application of the results. Then two rather objective phases followed, life cycle inventory analysis (or LCI), analysing the processes of the product system in terms of their extractions and emissions, and life cycle impact assessment (or LCIA), assessing the environmental impacts thereof. Then followed again a more subjective phase, life cycle interpretation, in which the results were compared with the aims of the study. Non-attainment could then lead to further study or to adjustment of the original aims.

Furthermore, a number of main methodological requirements were established with respect to the issues studied in SETAC, without prescribing the methods themselves. Finally, a number of procedural requirements were defined. These particularly dealt with the set-up of peer reviews. Both, the methodological and the procedural requirements were differentiated with respect to the type of envisaged application: the most strict requirements being set for "comparative assertions disclosed to the public", i.e., the market claims which had spoiled the process in the seventies.

5. Clash of viewpoints

The standardisation process under ISO appeared not to be a mere technical matter. Rather, quite different viewpoints emerged, underlying methods and practices. Two main schools of thought could be identified; one seeing LCA primarily as support for decision making, and the other seeing LCA primarily as a source of scientifically proven results. The first viewpoint was shared by the representatives of a number of European countries. This view implied that value choices are deemed acceptable in the process, if these are agreed upon in an authorised procedure. The second viewpoint was shared by the North American representative, by some European countries and by a number of developing countries. In this viewpoint value choices are to be avoided as much as possible and left to the decision makers themselves.

Compromises were found, however, but this took quite some years. The key was found in distinguishing between different types of application, connected with different requirements, as was indicated above. To give an example: for the underpinning of market claims it was regarded acceptable to use the global-warming potentials and the ozone depletion potentials, authorised by the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organisation (WMO) respectively, but not the toxicity potentials under development in SETAC.

6. Role of UNEP/SETAC life-cycle initiative

Since the end of the 1990s, a third organisation is active in the field of LCA, that it the United Nations' Environment Programme (UNEP; http://www.unep.org/), through its office in Paris. In 2002, the organisation started a co-operation with SETAC in the so-called UNEP/SETAC Life-Cycle Initiative (http://www.uneptie.org/pc/sustain/lcinitiative/). The main aim of this initiative is to bring LCA and other life-cycle approaches into practice. The initiative consists of three programmes: an LCI programme, an LCIA programme, and an LCM programme, that is a programme on life-cycle management. The first two programmes focus on the development of recommended practices in the field of LCA, thus stimulating application of the tool. Other aims are the development of simplified methods and of publicly-available databases. The third programme has a broader scope, including other tools and approaches which can support management of products or services during their life cycle.

A main driver for UNEP in this initiative is to enhance the use of life-cycle approaches by stakeholders in developing countries. This fits well in life-cycle thinking in general, as many life cycles have their origins in these countries. But this is easier said than done. It is becoming increasingly clear that this goal cannot be achieved by mere provision of information and by capacity building. Quite often, industrial processes in developing countries will be less modern than those in the industrialised countries, thus yielding higher environmental burdens per functional unit. The use of LCA will then support selection against the resulting materials or products. In addition, tools like eco-labelling ask for costly quality-control, which in general cannot easily be earned by higher prices or higher sales.

Real progress seems only possible, if life-cycle approaches are combined with technical and/or financial support. This is becoming common practice in large companies which enter into "sustainability agreements" with local stakeholders on the supply of resources. Such agreements imply environmental requirements on production methods, but at the same time can involve technical and social support. In the same vein, the UNEP/SETAC initiative now aims to link its activities to UNEP's cleaner-production centres in developing countries.

7. Methodological developments

The roles of SETAC, ISO and the UNEP/SETAC life cycle initiative have been described above as attempts to organize and harmonize the rather spontaneous developments that took place scattered throughout several major universities, large companies and consultancies. Although SETAC, ISO and UNEP have greatly stimulated these activities, they have by no means taken over them. LCA remains a field of innovation and discovery, and the organizations mentioned act as places where developments are submitted for discussion and organisation, and the main lines for consensus are established.

Among the places of methodological exploration we mention the following.

(1) LCA is a field of academic study and a tool for academic research. There are several LCA research groups at universities, LCA is part of the academic curriculum in several fields of study (see e.g. [9]), and numerous PhD-theses have been produced or are being produced on LCA or with the use of LCA (see e.g. [10]). Several scientific journal are entirely or for a substantial part devoted to LCA (e.g., the International Journal of Life-Cycle Assessment http://www.scientificjournals.com/sj/lca/, the Journal of Industrial Ecology http://www.ingentaconnect.com/content/mitpress/jie, and the Journal of Cleaner Production http://www.sciencedirect.com/science/journal/09596526).

(2) At the national level, several countries have initiated their own LCA programmes. We mention textbooks originating in the Netherlands [11] and Denmark [12,13], websites to facilitate the application and use of LCA in the US (http://www.epa.gov/ORD/NRMRL/lcaccess/), and in Germany (http://www.netzwerk-lebenszyklusdaten.de/cms/content), and projects like OMNIITOX (http://omniitox.imi.chalmers.se/officialmirror/) and the recent European Platform on LCA (http://lca.jrc.it/).

(3) Several software and database providers have initiated methodological studies to enhance the realm of their software and data; see, e.g., the Eco-indicator 99 [14].

8. Scientific results so far

What scientific results have so far been achieved? We mentioned already the common terminology and the common technical framework, enabling open exchange of information and good comparability between studies. Furthermore, a rigorous mathematical formulation has been developed for the different phases of LCA, fundamentally based on subsequent matrix inversions [15].

Then there is a variety of methods, databases and software, both for the LCI phase and for the LCIA phase which are largely compatible with the ISO requirements (see e.g. [16]).

The process of establishing recommended practices of the UNEP/SETAC initiative has just started.

As already indicated, the home basis for these developments is SETAC. But there is an open exchange with other disciplines and communities, like particular environmental-risk assessment (ERA), life-cycle costing (LCC), input–output analysis (IOA), eco-efficiency analysis, and industrial ecology with tools such as substance-flow analysis (SFA) and material-flow accounting (MFA).

9. Applications to date

Main applications concern both product comparison and product design. The type of products has changed in the course of time. Whilst in the early phase the focus was on consumer products, sold by a shop or retailer, in the last decade also larger products and services have been included. Examples include: the management of municipal solid-waste, waste-water treatment, electricity production, the use of building materials, the production of automobiles and of ICT. This goes in hand with a more strategic use of LCA, combining it with environmental-management systems of companies. Traditionally, environmental-management systems focus on the processes within the company itself. The combination with LCA or other life-cycle approaches enlarge this focus to "green procurement", i.e., the environmentally-responsive purchasing of materials. An example concerns Unilever, which performs LCA studies on a great number of products and now uses this information to establish agreements with the suppliers of its resources like palm oil, soy and fish.

A strong driver for the use of LCA lies in its integration with policy instruments. Examples include the European packaging directive, the European waste-management directive, the European integrated product policy and the different types of environmental labelling, particularly including the Type I and Type III labelling according to ISO 14024 and 14025, respectively. Type I labels aim at consumers and are the well-known eco-labels on consumer products. Type III labels aim to provide business-to-business information in the form of product declarations. These are fact sheets, attached to products or materials, with relevant life-cycle information, in part based on LCA. This tool is most well developed in Japan.

10. Examples of LCA applications

We will discuss some examples in somewhat more detail, with a focus on energy aspects. Our first example concerns the design of new cars. Here, the aim is to make cars lighter, in order to make them use less fuel. To some extent this is successful, although it is largely compensated for by the inclusion of new heavy devices, including safety measures. But apart from that, striving for lighter weight implies trade-offs. Thus the substitution of steel by aluminium indeed reduces weight, but at the same time introduces a material with a high embodied energy which only "earns itself back" after a considerable driving distance. The substitution of steel by plastics often involves the use of composite materials, which are more difficult to recycle. The use of LCA helps to clarify these trade-offs. This is usually done in two stages. During the design of a car, simple criteria are used, for instance: low weight and low fuel-use. Then, after the car has been completed and put on the market, a full LCA is performed, aiming at an adjustment or further elaboration of the design criteria. Thus LCA plays a role in what is called the learning curve of product design.

A second example concerns the different concepts of waste hierarchy and integrated waste-management. The waste hierarchy implies a fixed order of waste management options, from most to least preferable: product reuse, materials recycling, back-to-monomer (if at stake), incineration with energy recovery, incineration without energy recovery, and finally land fill. A step down on this ladder is only to be taken if the higher step appears to be impossible. A major example of this approach concerns the "Duales System Deutschlands" (or DSD), aiming at the reuse or recycling of household packaging materials. Industries have the responsibility for the collection and recovery of the packaging materials they produce. Together they have established DSD which under quite high costs indeed achieves the required reuse and recycling rates. In contrast to this waste hierarchy, there is the integrated waste-management approach, originally advocated by Procter and Gamble, and for instance is the basis of the Dutch household waste-management system. Here the aim is more open: the best option from both an environmental and an economic perspective should be preferred, thus striving at the most cost-effective solutions. The outcome is different indeed. Specific flows are still recycled, including paper and glass. But other flows, including most packaging materials and also the organic fraction are increasingly incinerated in combination with co-generation of electricity and heat. The reasons are the lower net costs of the processes involved, and the increasing priority of greenhouse-gas emission abatement.

A third example concerns the use of bio-materials. In the quest of fossil-fuel reduction, the use of bio-fuels makes a contribution. But LCA can play a role in investigating the role of bio-materials in a broader perspective. Then it turns out that the use of these materials first as feedstocks, and thereafter as biofuels is a more environmentally-rewarding strategy. Examples are the use as building materials, or for the production of industrial feedstocks such as ethanol. The use of LCA also helped in fighting the too simple categorisation of building materials in "good" and "bad" categories. Of course, there are examples which fit well in either of these categories; plastics including CFCs as propellants are of course to be phased out. But furthermore, much depends on the type of application. For instance, PVC pipes which have a long life-span and can thereafter be recycled, may meet relatively little objections.

11. Limitations of LCA

LCA also has its limitations, quite a lot in fact. Firstly, there is the problem of the definition of the system boundary: at which level are processes to be included? In the above indicated case of the transportation of collected glass, the fuel of the trucks is generally included, not the production of the trucks and even less the building of the factory in which the trucks were constructed. There is always a process behind a process. In general, LCA stops before the capital goods, in this case the production of the truck, but this is arbitrary and it is unknown what the relevance is of the not-included processes.

Directly connected with the analysis of the full life-cycle are the limitations regarding spatial and temporal resolutions. As was indicated in Section 3 of this paper, in general the analysis is performed at world level without any spatial differentiation, and the analysis typically has a steady-state character. This also implies that only impacts are taken into account which occur in a regular time frame: potential catastrophes are left out of consideration. In other words, LCA is not suitable for a precautionary approach. Furthermore the analysis is linear, both regarding the processes of the product system and the processes in the environment. The latter implies that no background concentrations of toxic substances are taken into account. Such substances may be harmless below given thresholds, but this does not find expression in the analysis. For heavy metals, still other limitations are involved. Some metals are toxic at high concentrations but essential for life functions at low concentrations; examples particularly include copper and zinc. And most metals can occur in different forms, "species" as they are called, with large differences in toxicity. Typically organic species like methyl-lead or methyl-mercury, are much more toxic than anorganic metal species. These aspects cannot find expression in the analysis.

Furthermore, some types of impact cannot be easily included in LCA. LCA is in fact developed for impacts with an input–output character: extractions from the environment and emissions to the environment can both be well linked to a functional unit. This is more difficult with impacts related to land use which therefore are under-represented in LCA. Outside the scope, by definition, are social and economic impacts, for LCA as an environmental tool. For economic aspects a sister-tool to LCA in development, that is Life Cycle Costing (LCC).

Looking at the field of energy analysis, the above implies that the use of fossil fuels and renewables can in general be well investigated. Hydropower, with its generally considerable impact on land use, and nuclear power, with its unlikely but potentially catastrophic impacts, cannot be analysed over their full scope of impacts. This may seem disappointing, but such limitations are in fact true for every analytical tool. The more specialised a tool is to fulfil specific requirements, the less it is suitable for meeting other aims. But the question is, what should be done to overcome the different limitations. Three main lines for overcoming the limitations of LCA are discussed elsewhere [17].

12. The potential of LCA for energy analysis and management

LCA and related tools aim to analyse the environmental problems associated with products and services throughout their full life-cycle. Obviously, a substantial part of these environmental problems relate in one way or another to energy and related thermodynamic concepts. We will discuss these connections below.

First, energy is involved in all life cycles. For instance, in comparing several types of baby diapers, one will encounter energy use during production, transport, washing of cotton diapers, and energy recovery related to the incineration of paper diapers. These energetic aspects are fully incorporated in the calculations, and aggregated with the non-energy related processes in the life cycle. As such, in these studies, energy does not show up as a separate result of the inventory analysis or the impact assessment, but is translated into inventory issues like extraction of crude oil and emission of carbon dioxide, or into impact-assessment issues like depletion of resources and climate change.

Secondly, one can perform a separate analysis of the energetic aspects of a life cycle. This type of analysis started its development earlier than LCA, and is known as energy analysis. Some variants of traditional energy analysis, like process analysis versus IO-based energy analysis (see e.g. [18]), have their analogues in LCA (see e.g. [19]). Other tool developments, like second-law analysis or exergy analysis, have not or not yet led to similar developments in LCA, even though attempts to establish such connections are being made (see e.g. [20]).

Thirdly, LCA can be applied to analyse energy systems. This can range from small scale, like the comparison of two types of batteries, to the grand scale of comparing the electricity-generation structures of whole countries. The intermediate scale, for instance comparing fossil fuels with biofuels is also an active domain of research; see e.g. [21].

Already, LCA of energy systems is an important field of study, both in its sheer number of publications and in its policy interest. We foresee that energy analysis and LCA will continue to mature, and that they will do this in a converging direction. LCA has adapted findings from energy analysis, and energy analysis is broadening its scope to cover environmental impacts in an LCA-oriented way. To what extent the two analytical tools will finally merge is not yet clear. Given the need for tailored and focused tools, it may well be that both LCA and energy analysis will continue to exist as distinct members of a coherent family of tools for chain analysis.

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