LCA as environmental assessment tool in waste to energy and contribution to occupational health and safety

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Life Cycle Assessment (LCA) is a set of tools and ideas in the field of Environmental Assessment and it is one of the most important management tools to understand product related environmental impacts. It covers the life span from the extraction of the raw materials to their disposal or reprocessing. The main developments over the past 40 years are shortly reviewed in a perspective that puts an emphasis on Waste to Energy issues. This aims to identify the advantages and limitations of LCA related to the models of production processes adopted as basis of environmental assessment in waste management. The importance of the concept of extended producer responsibility requires a risk assessment that takes into account a broader set of elements, including occupational health risks. The use of LCA as the sole tool to determine improvements to the process under investigation can be biased as the human factor is not always included in the system boundaries. Examples of inclusion of work environment issues in Life Cycle approaches as well as models that balance health, safety and environmental impact are presented.

1. Introduction

LCA is a tool for analyzing environmental impacts on a wide perspective, with reference to a product system or economic activity. Due to the constraints on resources or data availability, industrial companies perform most of the analyses based on a simplified approach (Life Cycle Approach), or apply the general principles to certain aspects of the production system (Life Cycle Thinking), even though they are usually all referred as LCA activities. Despite some limitations and methodological gaps LCA is recognized as a powerful set of tools in evaluating environmental impacts.

2. LCA

2.1 The history

LCA involves the evaluation of specific elements of a product system to evaluate its environmental impact. The core of the concept is the assessment of the impacts at each stage of the product life cycle, with reference to the notion of production, distribution, use and disposal including all necessary transportation steps.

The first studies on LCA date from the late sixties. In 1969 the Coca Cola Company funded a study to compare resource consumption and environmental releases associated with beverage containers (Udo de Haes et al., 2007). Similar studies were then started in the UK, Switzerland and Sweden. The early studies were closely linked with energy analysis. Due to the energy crisis of the early seventies, waste and outputs were initially not considered and attention was concentrated on calculating the total energy used in production. E.g. Bousted (1996) in the UK studied various types of beverage containers, including glass, plastic, steel and aluminium. This demonstrated the high embodied energy value of aluminium in contrast to glass. Glass scored even better when reused or recycled. The winners were the reusable plastic bottles as glass and aluminium were transported long distances to be recycled.

After the oil crisis subsided, the energy issues and the use of LCA in this application lost prominence. It was only in the late eighties that a new interest was found. In 1989 the Society of Environmental Toxicology and Chemistry (SETAC) started defining a common terminology and a methodology framework. A result of this work was the definition of the *functional unit*. This is a quantified description of the product systems to which impacts are attributed.

This standardization work was then picked up by the International Standard Organization (ISO) in 1994 with the first of its 14040 series ISO (1997, 1998, 2000 and 2004). The fixed context of the ISO offered coherence to the different methodologies and approaches in LCA without, nevertheless, imposing one. The ISO works have resulted in the definition of specific steps that allow the separation of the subjective and objective phases within the proposed method. The principles and framework for LCA in these documents include: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), life cycle interpretation phase and reporting.
These phases are the codification of the same steps individuated by SETAC in the previous years, with the exception that Life Cycle Improvement has been considered as an activity that should permeate all other phases and not one of its own. The Interpretation phase was added. The interest on this topic is witnessed also by newer versions, the latest of which published in 2006 (ISO 14040:2006 effectively replaces 14040:1997, 14041:1998, 14042:2000 and 14043:2000).

2.2 The general framework

2.2.1 Goal and Scope Definition

This is the first, subjective, phase of the application of LCA. At this stage it is necessary to identify the aim of the analysis as well as to select the system boundaries to ensure that no relevant part of the system to be investigated is actually omitted. Definition of the goal and the scope are critical elements, since the results will depend greatly on them.

The *goal* needs to state clearly and without ambiguity which is the application, what are the reasons why the study is carried out and who are the recipients of the results of the study.

The *scope* sets the borders of the assessment. Different elements should be considered in order to specify the scope correctly: product group, functional unit, the system and its boundaries, impact assessment boundaries, the data quality requirements, limitations.

The definition of the system boundaries (inputs and outputs) are critical in order to determine the amount of work to be done. The impact categories need to be chosen from a list of standard ones: assessing the boundaries will also limit the categories to be considered during the study. As for the goal, even the scope can adjusted during the iterative process of the analysis.

2.2.2 Inventory Analysis

Aim of this second phase is to perform mass and energy balances to quantify all the material and energy inputs, wastes and emissions from the system, i.e. the environmental burdens. The following main issues (as defined by ISO 14040:1997) should be considered during this phase: data collection, refining system boundaries, calculation, validation of data, relating data to the specific system and allocation.

Data can be specific (to the process, the company, and the geographical area) or more generic (for instance extracted from trade organizations or governmental institutions). It is possible to rely on quantitative or qualitative data in order to perform this phase. The results obtainable with LCA are very sensible to the set of data used. More generic and qualitative data could be used for a simplified analysis, to be reiteratively repeated on more specific and system related data. The data initially collected can be used to review the *system boundaries*. If the system is very complex, it might be necessary either to review the system boundary in order to include more data or to allocate the relevant environmental burdens to the system, making sure to approximate as much as possible the input-output relationship and characteristics. *Allocation* might be necessary in case of multi input or multi-output systems, where a direct relation between inputs and emissions is not evident. The inventory should then be interpreted considering all the specified uncertainties and lack of data. In particular, *validation* should also be considered and carried out during the whole process of data collection, in order to reduce eventual discrepancies and data quality issues later on.

2.2.3 Impact Assessment

In the third phase, and as a natural sequence of the work done in the Inventory phase, it is necessary to aggregate the environmental impacts quantified in the Inventory Analysis into a limited set of recognizable impact categories (e.g. global warming, ozone depletion, acidification etc.). This phase comprises the following steps: classification, characterisation, normalisation and weighting.

According to ISO 14042 (2000), there are three groups of categories to be considered: resource use, human health consequences and ecological consequences. These broad groups should include all categories like climate change, stratospheric ozone depletion, photochemical oxidant formation (smog), eutrophication, acidification, water use, noise, etc. It must be noted that, as of today, there is no consensus on a single list of impact categories. The impact categories should therefore be selected from a list of examples and be relevant to the system under investigation.

The second step in this phase is mainly a quantitative step: *characterisation*. In this step it is necessary to assign the relative contribution of each input and output to the selected impact categories. Pennington et al. (2003) propose a generic equation to calculate, from the inventory data, indicators for each impact category using generic characterisation factors.

$$CategoryIndicator = \sum_{s} CharacterisationFactor(s) \times EmissionInventory(s)$$

Where *s* indicates the chemical and the Factors can be found in literature as databases or are available in various LCA support tools.

The next step in this phase is the *normalization*. This activity is described by Stranddorf et al. (2003) as necessary to calculate the magnitude of the category indicator results relative to reference values where the different impact potentials and consumption of resources are expressed on a common scale. The goal of normalization is to set a common reference enabling comparison of different environmental impacts.

Since quantitative results of mentioned characterisation of impact categories not always are comparable, an additional step is necessary: *weighting*. It allows ranking and possibly defining the relative importance of these different results. Weighting can be a quantitative or qualitative activity often based on social or political considerations. Different weighting methods have been developed (Lindeijer, 1996).

2.2.4 Interpretation

This is the last phase as indicated by ISO 14040(1997). Interpretation is a systematic procedure to evaluate information from the conclusions of the inventory analysis and impact assessment of a product system, and present them in order to meet the requirements of the analysis as described in the goal and scope of the study.
The following tasks should be accomplished in this phase (Jensen et al. 1997):

1. Identify the significant environmental issues.
2. Evaluate the methodology and results for completeness, sensitivity and consistency.
3. Check that conclusions are consistent with the requirements of the goal and scope of the study, including, in particular, data quality requirements, predefined assumptions and values, and application oriented requirements.

2.3 Applications in the Waste to Energy Field

Waste treatment and Waste Management systems and techniques have been developed in recent years not only in order to reduce the environmental burden of land-filling, but also to address the energy aspect. Disposal of organic waste in landfills produces methane (CH_4), whose reduction is significant in fighting greenhouse gases emissions. At the same time waste treatment is recognized as a viable possibility for energy production. This possibility needs to be analyzed with specific tools to assess its environmental impact. A tool generally used to classify different approaches is *Waste Hierarchy*. This implies that some methods to handle waste are more opportune than others from an environmental point of view. Even though there is no consensus on the hierarchy, generally reducing the amount of waste is indicated as first priority. The other priorities (reuse, recycle, incinerate and landfill) are often contested and discussed. LCA has found various applications in the Waste to Energy (W2E) field. The biggest contributions in this field are the ones regarding Municipal Solid Waste (MSW) systems and alternatives analysis. Different studies tried to assess the environmental impacts of MSW systems (Harrison et al.,2000), or compared different scenarios of solid waste management (Denison, 1996; Mendes et al., 2004; Lee et al., 2007; Finnveden et al. 2004). Finnveden and Lee provide good examples on how to use LCA as a tool to analyze different MSW.

The goal of the first study was to identify advantages and disadvantages of different methods to treat solid waste (land filling, incineration, recycling, digestion and composting) and to identify critical factors, including background systems which may affect the results. The study confirms that waste hierarchy is usually a good starting point for waste policy making, but LCA can support it in identifying situations in which such approach is not valid. Analogous results can also be found in Moberg et al. (2005). The study exposes also the fragility of LCA to data gaps and base assumptions. In particular all assumptions on time aspects, system boundaries and characterisation models affect the final results significantly. In few cases, this means changing the order of the preference of the proposed waste hierarchy.

The role of national policies is paramount in the development of MSW and W2E issues. Lee et al. (2007) provide an LCA based comparison of landfill, incineration, composting, and feed manufacturing to treat food waste (that accounts in Korea to 30% of MSW). This study also compares the situation of food waste treatment in 1997 and 2005 (following a legislation aimed to reduce land filling). While the categories of global warming and human toxicity decreased significantly (50 % and 70 % for the reduction of land filling), acidification, eutrophication, and ecotoxicity increased impressively. This is due to emission in the recycling process and highlights the need for better control and inclusion of work environment. The role of LCA as decision support tool in waste management and W2E issues is further confirmed by studies on bottom ash, originating from municipal solid waste incineration (MSWI), as a potential road construction material (Olsson at al., 2006), and on waste hierarchy for MSW and paper treatments (Liamsanguan et al., 2007; Schmidt, 2007).

3. Limitations of LCA Approaches

Even though LCA is a powerful tool to assess the environmental impact of product/services, some important limitations have been evidenced in the past years. The main limitations are all related to the LCA methodological approach, especially data quality and collection, definition of system and time boundaries, process modelling.

The *quality* and *availability of data* influence the results significantly. Some of the steps of LCA can be re-iterated to better tune the analysis to the systems under investigation. It is therefore suggested to start with easily accessible data and eventually to refine the data quality with reference to the results. In some cases it is unavoidable to introduce simplification and limitating assumptions due to uncertainty of specific data. For instance, toxicological categories as well as some energy production impact categories are deeply affected by lack of data (Lee et al., 2007). There can be different type of data uncertainty (Schmidt et al., 2007), and it must be noted that the methodological uncertainties are sometimes larger than the data ones. The *time aspect* is often critical in including or excluding some effects of the systems under analysis. LCA should consider environmental impacts on the longest possible timeframe, possibly an infinite one. Most of the studies, nevertheless, use shorter time periods bringing to contestable conclusions (for instance, in MSW treatments, landfills act in a limited period of time as carbon sinks and therefore become a more favourable solution than incineration).

The holistic approach of LCA, one of its main strengths, is also a cause of complexity. Having to collect and analyse data from so many different elements, can be cumbersome. This is the reason why most of the times some assumptions are taken and the *system boundaries* are modified in order to leave out some elements. In particular the upstream elements of the supply chain are usually not included in the analysis, due to the inherent difficulty in gathering complete information for elements outside the specific product system. Results of LCA are often used for process optimisation. The applicability depends greatly on the *model of the process* that has been adopted at the beginning of the study. This model is frequently simplified to take into consideration all possible inputs and outputs and mostly does not include *health and safety* elements. This is very reductive because any kind of results from LCA cannot be applied directly in process improvements: choices that reduce the environmental impact might not always be applicable for human or industrial constraints or in some cases can prove to be dangerous.

3.1 The human factor: Work environment in LCA

As noted previously, one of the main limitations of the LCA methodology, as described by ISO 14040, is the lack of inclusion of work environment issues. This does not mean that safety and health analysis of processes are not carried out by the company. Most frequently these issues are addressed ex-post, to analyse the suggestions indicated by the application of an environmental oriented LCA. There is still a tendency for companies to treat safety, health and environment (SHE) as separate issues (Crawley 2002). This adds complexity to environmental management systems, and makes the companies loose out on possible synergies between environmental and safety issues. From an economical point of view, this practice is not optimal; since design could be taken too far before it is found too dangerous from a work environment perspective. The first efforts in including the human factor in LCA have been in Scandinavia. The Nordic countries have produced different approaches for Work Environment- LCA (WE-LCA).
Antonsson (1995) proposed a method based on five quantitative and two qualitative impact categories. The LCA is carried out in a similar way as for the external environment, with the four steps of goal and scope definition, inventory analysis, impact assessment and interpretation. The method requires the use of an inventory of effects, instead of emissions, followed by the impact assessment. The quantitative impact categories are: deaths due to work related accidents, workdays lost due to work related accidents, workdays lost due to illness, hearing loss and allergies. The qualitative impact categories are: carcinogenic impact and impact on reproduction. Data for the quantitative categories can be collected from single companies or trade statistics organizations. It must be noted that the final result will depend greatly on the quality and precision of this set of data. The level of detail has to be balanced against the goals

of the analysis. Another source of uncertainty is the fact that not all impact categories can be estimated quantitatively. Work environment issues have been left out not only from LCA methodology, but also from environmental technology databases and reports of Best Available Technologies (BAT). In a project conducted for the EC on selection of the International Cleaner Production Information Clearinghouse (ICPIC) system, Ashford (1997) evidenced:

- Complete lack of information regarding the interactions of human beings with the production processes, materials, or products.
- No information regarding the physical or economic context for the processes
- Limited information regarding the physical form of the substances at certain stages in the process so that, the physiologic route of entry can not be anticipated.

This stresses a serious lack of integration of safety concerns with legislation, regulations and policies addressing environment and more generally industrial ecology.

The role of personal risk perception and involvement in occupation health and safety issues in environmental management systems has been interestingly analysed by Honkasalo (2000). In industrial environments risks seem to be perceived differently depending on the level of involvement of the perceiver. Risks caused by global environmental issues are not tolerated easily, because the perceiver feels that they cannot be affected. Risks taken voluntarily (eg safety risks) are more accepted. This is one of the reasons for the over-estimation of environmental issues compared with the SHE ones. Employee participation is another difference between environmental management systems (EMS) and work environment related approaches. In safety and health issues it is absolutely necessary to make sure that workers are involved and can actually influence the process.

The Danish Environmental Agency (Schmidt et al., 2004) defined guidelines on how to calculate the potential Work Environment impacts per functional unit by adding the impacts from a number of processes and activities. Based on the collection of goods statistics, it aims at calculating the number of reported accidents per produced weight unit on the sector level. The steps are the same as for the environment oriented LCA. The following impact categories are included in the assessment: Fatal accidents; Total number of accidents; CNS function disorder; Hearing damages; Cancer; Muscolo-skeletal disorders; Airway diseases (allergic and non allergic); Skin diseases; Psycho-social diseases. The first step is the inventory procedure, where material flows are calculated for the product (with a set of data obtained from the statistical office). The material flows are aggregated on relevant processes in the database and for each process the weight is multiplied with the impacts per weight unit for each of the affected categories. One of the main challenges is to match the actual activities with data sets in the database (many thousand product groups must be related to a small number of sectors, less than 300). Aim of the normalisation activity is to relate the total number of accidents and work related diseases with the population. Interpretation can follow the inventory or after the normalisation. It is possible to establish an overview of how much each of the activities contributes to the single effect categories. After the normalisation it is possible to depict the most important impact categories in the life cycle of a product. The method described is undoubtedly a comprehensive approach to determine the impact of work environment issues with an LCA approach. The associated database covers about 80 economic sectors and provides an important tool for this analysis.

4. Conclusions

The history and the main concepts of the LCA methodology have been reviewed, with particular attentions on W2E applications. The main limitations - methodological approach, especially data quality and collection, definition of system and time boundaries, multi-functionality and allocation, occupational health - have been discussed. Examples of inclusion of work environment issues in LCA as well as models that balance health, safety and environmental impact have been presented. Particular attention has been given to the efforts to identify a technique that allows a quantitative approach to the inclusion of work environment in the LCA methodology.

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