To link to this article: DOI:10.2202/1934-2659.1496
URL : http://dx.doi.org/10.2202/1934-2659.1496

To cite this version: Gillani, Sayed Tamizuddin and Belaud, Jean Pierre and Sablayrolles, Caroline and Vignoles, Mireille and Le Lann, Jean Marc *Review of Life Cycle Assessment in Agro-Chemical Processes.* (2010) Chemical Product and Process Modeling, vol. 5 (n° 1). ISSN 1934-2659

Chemical Product and Process Modeling

Volume 5, *Issue* 1 2010 *Article* 33

Review of Life Cycle Assessment in Agro-Chemical Processes

Sayed Tamizuddin Gillani, *Institut National Polytechnique de Toulouse*
Jean-Pierre Belaud, *Université de Toulouse INPT-ENSIACET*
Caroline Sablayrolles, *Université de Toulouse INPT-ENSIACET*
Mireille Vignoles, *Université de Toulouse INPT-ENSIACET*
Jean-Marc Le Lann, *Université de Toulouse INPT-ENSIACET*

Recommended Citation:
Gillani, Sayed Tamizuddin; Belaud, Jean-Pierre; Sablayrolles, Caroline; Vignoles, Mireille; and Le Lann, Jean-Marc (2010) "Review of Life Cycle Assessment in Agro-Chemical Processes," *Chemical Product and Process Modeling*: Vol. 5: Iss. 1, Article 33.
DOI: 10.2202/1934-2659.1496
Available at: http://www.bepress.com/cppm/vol5/iss1/33

Review of Life Cycle Assessment in Agro-Chemical Processes

Sayed Tamizuddin Gillani, Jean-Pierre Belaud, Caroline Sablayrolles, Mireille Vignoles, and Jean-Marc Le Lann

Abstract

Life Cycle Assessment (LCA) is a method used to evaluate the potential impacts on the environment of a product, process, or activity throughout its life cycle. Today's LCA users are a mixture of individuals with skills in different disciplines who want to evaluate their products, processes, or activities in a life cycle context. This study attempts to present some of the LCA studies on agro-chemical processes, recent advances in LCA and their application on food products and non-food products. Due to the recent development of LCA methodologies and dissemination programs by international and local bodies, use of LCA is rapidly increasing in agricultural and industrial products. The literatures suggest that LCA coupled with other environmental approaches provides much more reliable and comprehensive information to environmentally conscious policy makers, producers, and consumers in selecting sustainable products and production processes. For this purpose, a field study of LCA of biodiesel from *Jatropha curcas* has been taken as an example in the study. In the past, LCA has been applied primarily to products but recent literature suggests that it has also the potential as an analysis and design tool for processes and services. In general, all primary industries use energy and water resources and emit pollutants gases. LCA is a method to report on and analyze these resource issues across the life cycle of agro-chemical processes. This review has the importance as a first part of a research project to develop a life cycle assessment methodology for agro-chemical industries. It presents the findings of a literature review that focuses on LCA of agriculture and chemical engineering literature.

KEYWORDS: life cycle assessment, process system engineering, LCA tools, bio-energy, agro-industry

1. INTRODUCTION

Industrial processes on the base of renewable resources always have a hard perception of being environmentally friendly and sustainable. However, as this property is a major advantage for products generated from these processes, there is a necessity to prove their sustainability credentials in a rigorous manner that can withstand the scrutiny of a competitive market (Jödicke, Zenklusen *et al.* 1999).

The agro-industrial sector is one of the world's largest industrial sectors and hence is a large user of energy and renewable resources. Greenhouse gas emission, which has increased remarkably due to tremendous energy use, has resulted in global warming, perhaps the most serious problem that humankind faces today (Roy, Nei *et al.* 2009). Food production, preservation and distribution consume a considerable amount of energy, which contributes to total CO_2 emission. Moreover, consumers in developed countries demand safe food of high quality that has been produced with minimal adverse impacts on the environment (de Boer 2003).

There is increased awareness that the environmentally conscious consumer of the future will consider ecological and ethical criteria in selecting food products (Andersson, Ohlsson *et al.* 1994). It is thus essential to evaluate the environmental impact and the utilization of resources in food production and distribution systems for sustainable consumption.

Life Cycle Assessment (LCA) is a method of evaluating environmental effects of a product, process, or activity throughout its life cycle or lifetime, which is known as a 'from cradle to grave' analysis (Arvanitoyannis 2008). Environmental awareness influences the way in which legislative bodies such as governments will guide the future development of agricultural and industrial food production systems. Although several researchers have compiled LCA studies to emphasize the need for LCA (Andersson, Ohlsson *et al.* 1994; Azapagic 1999; de Boer 2003), some recent advances in agricultural LCAs have yet to be reported. Product and process evaluations may be based on Life Cycle Assessment in order to account for all environmental impacts incurred by the provision of the good in question. These LCAs in turn adhere to strict standards laid down in ISO standards.

LCAs of processes and goods on the base of renewable resources are bound to face special methodological challenges. On the one hand, many industrial raw materials are by-products or surplus products from agricultural activities leading to other products. In these cases, the general problem of allocating the pressures of the agricultural sector arises which may considerably influence the outcome of any valuation. In some cases the raw materials are even streams that are considered to be wastes, which make a prudent evaluation even more complicated (Rivela, Moreira *et al.* 2006). On the other hand, any evaluation of the sustainability of processes leading to the same sort of goods on the basis of different raw materials must account for the different impacts from raw materials generation. The difference between renewable raw material systems must be evaluated. This clearly exceeds the capabilities of normal and descriptive life cycle impact assessments with the problem-oriented approach and leads to the necessity to employ an evaluation method that aggregates impacts in order to make different impacts comparable.

According to the ISO standard, selection of impact categories and classification involves; identification of the categories of environmental impacts which are of relevant to a proposed study. The classification assigns the emissions from inventory to these impact categories according to the substances ability to contribute to different environmental problems. According to the ISO standard on LCA, selection of impact categories, classification, and characterization are mandatory steps in LCIA, while normalization and weighting are optional (ISO 2006). Over the last decade, many of the well-documented LCIA methods have been developed to overcome this deficiency and the examples are (Guinée, Udo de Haes et al. 1993; Jolliet, Mueller-Wenk et al. 2004; Bare and Gloria 2006).

Impact categories regarding resource depletion has been discussed quit frequently and there are wide variety of methods available consequently for characterizing contributions to this category (Pennington and Rydberg 2005). Land use is an elementary flow that leads us to an impact category that has been discussed quite a lot. Land occupation and the land transformation involved in agriculture and forestry, but also other activities such as mining and transportation can have significant impacts, they may be positive or negative. Three areas of protection directly affected by land uses are; natural environment, natural resources and artificial environment and human health indirectly. These impacts include loss of biodiversity, loss of soil quality, and loss of biotic production potential but the list of potential impacts to include is longer (Rivela, Moreira et al. 2006). Several methods have been suggested in the literature on how to include land use impacts (examples are reviews in (Lindeijer, Müller-Wenk et al. 2002; Pennington and Rydberg 2005; Milà i Canals 2007) and recent publications by (Koellner, Suh et al. 2007). Freshwater as a resource provides fundamental functions for humans and the environment, and is thus relevant for all four areas of protection. In its first operating phase, the SETAC Life Cycle Initiative recognized the high global and regional significance of freshwater resources and their limited availability on a global level and clearly expressed the need for an assessment of water resource consumption (Jolliet, Mueller-Wenk et al. 2004) which is continuously growing due to economic, demographic, and climate change influences.

Human and eco-toxicological impacts have been considered as troublesome impact categories for several political as well as scientific reasons.

Which are sometimes addressed politically by enhancing what should be considered as a priority based on what is generally monitored and considered to be of highly concerned, such as many Organic Pollutants and metals.

This review paper focuses on agricultural and industrial LCA literature that deals with the production of different products and its associated processes. Peer reviewed articles from international journals and publicly available agro-industrial and chemical processes LCA reports developed by industry bodies have been analyzed to synthesize the key consensus and divergent points on the following:

- Goal and purpose of agro-chemical LCAs;
- LCA system boundary;
- Functional units;
- Foreground and background data sources;
- LCA computations (what type of software and how LCA computations have been made using spreadsheets or proprietary softwares such as Gabi, Simapro and Umberto);
- Life cycle impact assessment and impact categories;
- Compliance with international LCA standards;
- The key findings and conclusions of the LCA studies for future research project.

This article has the importance as a first part of a research project to develop an innovative life cycle assessment methodology especially for agro-chemical industries. Our main purpose is to define a new LCA approach for a deep integration of product, process and system perspectives. That would lead to an improved eco-analysis, eco-design and eco-decision of processes and resulted products for researchers and engineers. Compliant to this approach we will develop a research prototype software tool.

In this way, the following sections present the findings of a literature review that focuses on LCA concepts, methods and tools, especially dedicated to agriculture and chemical engineering literature. The second section deals with definition and concepts of LCA in general. Also it presents the main leading market software tools used for sustainable development (economic, ecologic and social) of products. In the third section we have discussed about LCA of food and non-food items and also illustrated LCA application for chemical processes. A field study of Jatropha curcas L. has been presented as an example in the fourth section of this paper. In the last part conclusion has been made in accordance with reviewed literature.

2. Life Cycle Assessment (LCA)

As environmental awareness increases, industries and businesses are assessing how their activities affect the environment. Society has become concerned about the issues of natural resource depletion and environmental degradation. Many businesses have responded to this awareness by providing "greener" products and using "greener" processes. The environmental performance of products and processes has become a key issue, which is why some companies are investigating ways to minimize their effects on the environment. Many companies have found it advantageous to explore ways of moving beyond compliance using pollution prevention strategies and environmental management systems to improve their environmental performance. One such tool is LCA. This concept considers the entire life cycle of a product (Homleid, Eide et al. 2003).

Life Cycle Assessment is a "cradle-to-grave" approach for assessing industrial systems. "Cradle-to-grave" begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.) (Ortiz, Castells *et al.* 2009). By including the impacts throughout the whole product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product selection and its associated process. The term "life cycle" refers to the major activities in the course of the product's life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required manufacturing the product. Figure 1 illustrates the possible life cycle stages that can be considered in an LCA and the typical inputs/outputs measured (SAIC 2006).

Specifically, LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases
- Evaluating the potential environmental impacts associated with identified inputs and releases
- Interpreting the results to help decision-makers make a more informed decision.

When deciding between two or more alternatives, LCA can help decision-makers compare all major environmental impacts caused by their business activities. The following sub-sections discuss more about LCA, its background, methodology and engineering tools.

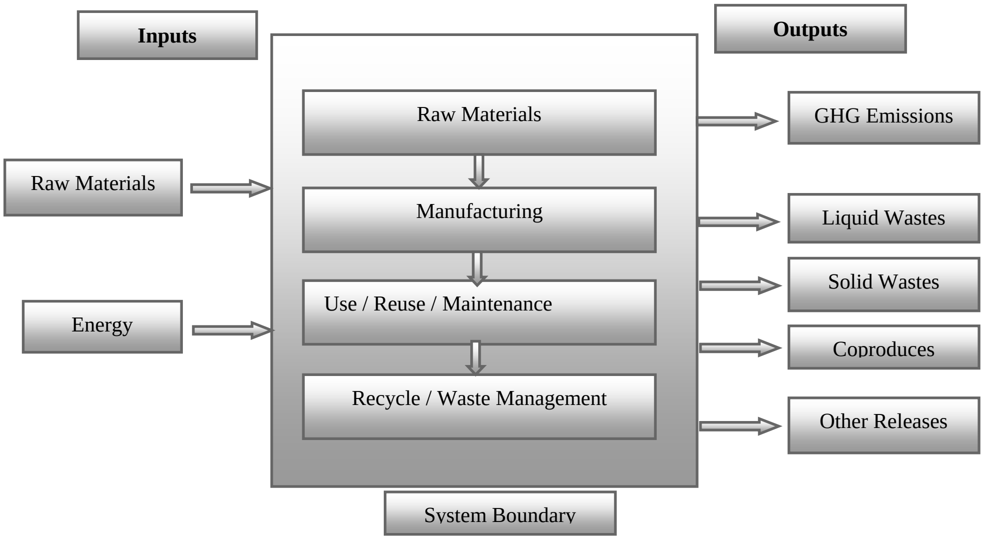

Figure 1: Life Cycle stages

2.1. LCA Background

The first well-known LCA study was funded by Coca-Cola in 1969. Its purpose was to compare resource consumption and emissions associated with beverage containers (SAIC 2006). During the energy crisis, several studies were performed with an emphasis on energy. Before 1990, LCA studies dealt mainly with emissions and use of resources and were limited to technical systems (Bengtsson and Steen 2000). During the early 1990s, several methods were developed to interpret the results of LCA studies in terms of environmental impacts. Some methods were also developed to weigh various impacts against each other. In the early 1990s, the practicing number of LCA experts increased considerably.

One reason for this expansion was the increase in computer software capable of handling the large amounts of LCA data. Another reason was the clear signal from governments to focus on products and initiate sustainable development. Since 1990, attempts have been made to develop and standardize the LCA methodology under the coordination of the Society of Environmental Toxicology and Chemistry (SETAC). In 1993, SETAC published a "Code of Practice", which presents general principles and a framework for the conduct, review, presentation and use of LCA findings (SETAC 1993). An international standard for LCA put together by the International Standardization Organization (ISO) has recently emerged and is undergoing evaluation and revision (Lindfors, Christiansen *et al.* 1995; Azapagic 1999). Azapagic (1999) has reviewed aspects of the ISO standards, and compared them with the SETAC methodology. The methodology framework for ISO is similar to that for SETAC with some differences for the interpretation phase, where ISO has included further analysis and sensitivity studies.

The ISO standards, recently produced or in draft form, are

- ISO 14040 (1997) covering LCA within environmental management for principle and framework
- ISO 14041 (1998) covering goal scope definition and inventory analysis
- ISO 14042 (2000) covering impact assessment
- ISO 14043 (2000) covering interpretation

ISO 14044 (2006) this one has replaced the previous recommendations as it includes; definition of the goal and scope of the LCA, the Life Cycle Inventory (LCI) phase, the Life Cycle Impact Assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements.

There are several other ISO standards that are related with different environmental aspects according to their goals. ISO 14064 parts 1, 2 and 3 are international greenhouse gas (GHG) accounting and verification standards which provide a set of clear and verifiable requirements to support organizations and proponents of GHG emission reduction projects. ISO 14031 provides guidance on how an organization can evaluate its environmental performance. ISO Guide 64 provides guidance for addressing environmental aspects in product standards. ISO 14067 on the carbon footprint of products will provide requirements for the quantification and communication of greenhouse gases (GHGs) associated with products. ISO 14045 will provide principles and requirements for eco-efficiency assessment. Eco-efficiency relates environmental performance to value created. ISO 14047 related to Environmental management, Life cycle impact assessment and Examples of application of ISO 14042. ISO 14048 related to Environmental management, Life cycle assessment and Data documentation format.

2.2. LCA methodology

According to ISO (Arvanitoyannis 2008) LCA is divided into four steps. These steps have been illustrated below with the support of figure 2.

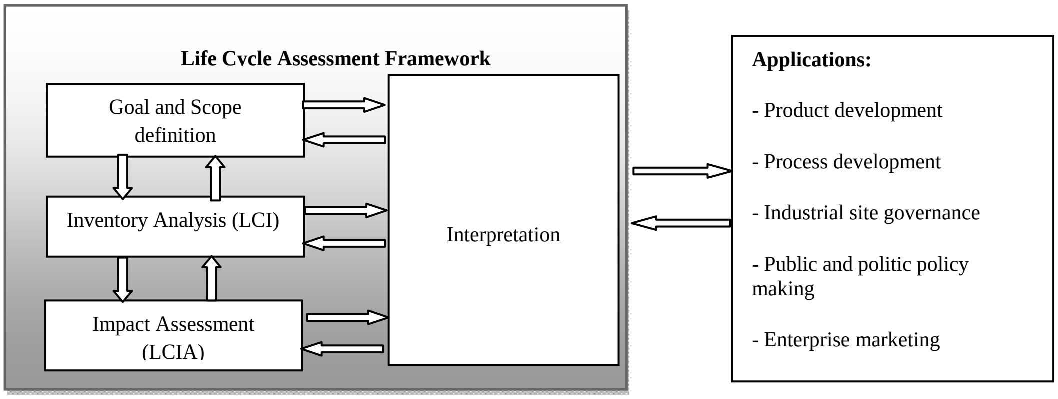

Figure 2: Phases of Life Cycle Assessment (Arvanitoyannis 2008)(ISO, 1997)

a) ***Goal and Scope Definition phase:*** This step defines the reasons for the LCA study and the intended use of the results. For LCA studies in the agricultural sector this could be for instance to investigate the environmental impacts of different intensities in crop production or to analyze the advantages and disadvantages of intensive or extensive arable farming systems. Furthermore, this step describes the system under investigation, its functions, and boundaries. The system boundary will largely depend on the goal of the study and the functional unit (FU) is dependent on the goal of the study. In the goal definition and scoping component, the purpose of the study and its scope are defined in relation to how the results are to be used. The functional unit is established in this step, with the necessary data and information needed for the inventory and impact assessment also identified (Consoli, Allen *et al.* 1993).
Functional Unit: According to the definition of ISO 14040 the functional unit is a measure of the performance of the functional outputs of the product system (Arvanitoyannis 2008). All material and energy flows and all effects resulting from these flows are related to the functional unit. This makes the functional unit a base for all comparisons between sensitivity analysis and different objects under investigation within the same functional unit. Relating all data to one functional unit makes the results of different studies comparable. The ISO 14040 standards demand that functional units are clearly defined, measurable, and relevant to input and output processes (SETAC 1993; Arvanitoyannis 2008).

System boundary: The definition of system boundaries illustrates which modules have to be part of the LCA in a study. Multiple factors, such as time, money, and determinability of data influence the system boundaries. Ideally the system under investigation is defined in such a way that input and output flows are elementary flows at the point of the system boundaries. The modules which shall be included and which data quality should be obtained for each module of the LCA will be determined. Equally, each output flow has to be determined. The system boundaries have to be designed including all processes, depending on the number and kind of products. This can lead to large life cycle inventories, which cannot be dealt with.

b) ***Inventory Analysis phase:*** The inventory analysis compiles all resources that are needed for and all emissions that are released by the specific system under investigation and relates them to the defined functional unit (ISO 1998). The inventory analysis step of an LCA quantifies the inputs (using mass and energy balances) and outputs (products and releases to air, water and land) for all processing steps included in the system boundary. Many life cycle studies have stopped at the inventory stage, often basing conclusions and recommendations on how the inventory interventions can be minimized. However, the major drawback with this approach is that information on whether some categories in the inventory analysis are more hazardous than other phases, as this phase involves most time consuming tasks so the risk factor is high (Mohin and Taylor 1994). This phase is crucial as it should guarantee the availability and quality of raw data. The data collection is a strategic point in order to go through a valid analysis and then to result in high-quality decisions.

c) ***Impact Assessment phase:*** The purpose of the Life Cycle Impact Assessment (LCIA) is to provide additional information to help and assess the results from the Inventory Analysis so as to better understand their environmental significance (ISO 2006). Today, there is acceptance in the LCA community that the protection areas of Life Cycle Assessment are human health, natural environment, natural resources, and to some extent man-made environment(Guinée, Udo de Haes et al. 1993). The impact assessment phase of an LCA is defined as “a quantitative and/or qualitative process to identify, characterize and assess the potential impacts of the environmental interventions identified in the inventory analysis”. According to the SETAC, impact assessment consists of three distinct steps: classification, characterization (including normalization) and valuation (Consoli, Allen *et al.* 1993). This approach to impact assessment has gained the widest acceptance (Miettinen and Hämäläinen 1997). In the classification step, the resources used and wastes generated are grouped into impact categories based on anticipated effects on the environment. These impact categories might include environmental problems such as resource depletion, global warming, acidification and photochemical oxidant formation as shown in the figure 4(CO_2, CH_4, $HCFC_S$, Volatile Organic Compound-VOC, SO_2, NO_x, Biological Oxygen Demand-BOD). The potential contribution to each environmental impact category is then quantified in the characterization step, which takes into account both the magnitude and potency of the inventory categories (Mohin and Taylor 1994).

Life cycle impact assessment (LCIA) as part of an overall LCA can be used to:

- identify product system improvement opportunities and assist the prioritization of them,
- characterize or benchmark a product system and its unit processes over time,
- make relative comparisons among product systems based on selected category indicators, or
- indicate environmental issues for which other techniques can provide complementary environmental data and information useful to decision-makers.

Thus LCIA methods aim to connect, as far as possible each life cycle inventory (LCI) result to the corresponding environmental impacts. LCI results are classified into impact categories, each with a category indicator. The category indicator can be located at any point between the LCI results and the damage category (where the environmental effect occurs) in this chain. Within this framework, three main methods have evolved:

a) Classical impact assessment methods (e.g. CML (Guinée, Gorrée et al. 2002)

b) Damage oriented methods such as Eco-indicator 99 (Goedkoop and Spriensma 2000)

c) IMPACT 2002+ has addressed this new challenge by presenting an implementation working both at midpoint and damage (Jolliet, Mueller-Wenk et al. 2004).

Figure 3 shows midpoint categories and damage categories from the LCI results.

d) ***Interpretation phase:*** The purpose of an LCA is to draw conclusions that can support a decision or can provide a readily understandable result of an LCA. This assessment may include both quantitative and qualitative measures of improvement, such as changes in product, process and activity design; raw material use, industrial processing, consumer use and waste management.

Interpretation is the phase of the LCA where the results of the other phases are interpreted according to the goal of the study using sensitivity and uncertainty analysis. The outcome of the interpretation may be a conclusion serving as a recommendation to the decision makers, who will normally consider the environmental and resource impacts together with other decision criteria (like economic and social aspects). ISO and other sources define an interpretation component, instead of an improvement assessment, as being the final component of the impact assessment (Rebitzer, Ekvall *et al.* 2004; Heijungs, Huppes *et al.* 2010). Furthermore, Clift (1998) writes that using the results of an LCA is now often referred to as interpretation, with the recognition that explicit trade-offs between impacts categories are required as part of the decision-making process (Clift 1998).

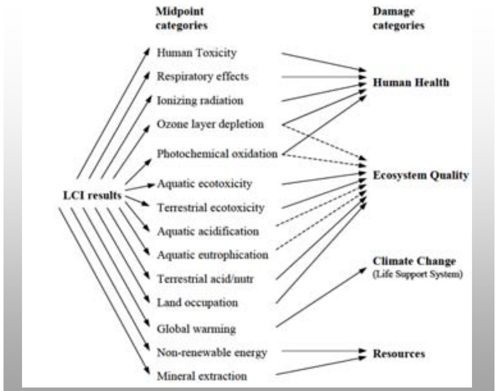

Figure 3: The IMPACT2002+ method framework (source: Jolliet et al., 2003)

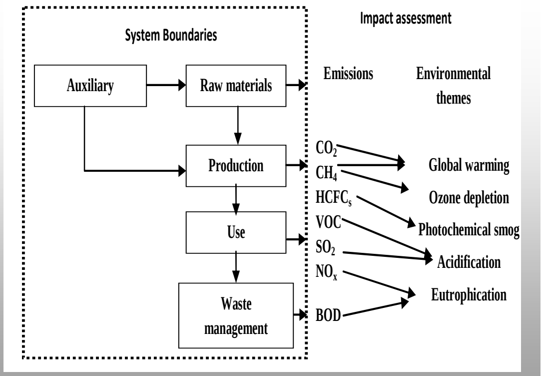

Figure 4: Environmental evaluation in LCA and its impact assessment

2.3. LCA tools

Life cycle assessment systematically considers and quantifies the consumption of resources and the environmental impacts associated with a product and its associated process. By considering the entire life cycle and the associated environmental burdens, LCA identifies opportunities to improve environmental performance. In order to support engineering activities, LCA specific software have been developed since 90's. Established tools, often coming from university research activities, are provided by small editors or organizations. Three of these leading market LCA software are discussed hereby. Except these tools off the shelves, it is worth noting that some universities and industrial organizations have developed their own inner tool (in general based on Microsoft Excel application) and data base.

GaBi life cycle assessment tool has been developed by more than 60 developers which provide over 4000 LCI profile for professionals and engineers over the years. All these profiles are ISO 14044, 14064 and 14025 standards compiled. In addition ecoinvent database has been integrated into this tool which provides more access to unit processes as well as to other inventories to cover multiple industrial areas.

SimaPro is a software to collect, analyze and monitor the environmental performance of products and services (Goedkoop., Schryver *et al.* 2008). This tool includes the database in compliance to the ISO 14040 standards. The most common database included in this tool are Ecoinvent, ETH-ESU 96, BUWAL 250, Dutch Input Output database, US Input Output database, Danish Input Output database, LCA food, Industry data, IDEMAT 2001, Franklin US LCI database, Dutch Concrete database, IVAM, FEFCO, EuP database for Energy using Products.

Umberto is another powerful tool used by many research groups, industries, organizations and IT specialists. It has been used for modeling and also to calculate and visualize material and energy flow systems. It is used to analyze production process systems, either in a manufacturing site, throughout a company, or, along a product life cycle. Results can be assessed using economic and environmental performance indicators. Costs for materials and processes can be entered in the model to support managerial decision making. Umberto addresses companies with cost intensive production that wish to optimize their processes and improve their competitiveness. Umberto also serves as a flexible and versatile tool for research institutions and consultancies, e.g. for material flow analysis studies or for Life Cycle Assessment (LCA) studies of products.

In our current research project, we are using SimaPro 7. However we hope in near future to have access to Umberto and GaBi tools in order to gain experience on current tools and to support our own software prototype development.

3. LCA and Industrial Processes

LCA is a chain-orientated tool to evaluate the environmental performance of products focusing on the entire life cycle of these products (ISO 2006). Through all the stages like, consumption of resources and releases to air, water and soil are identified and quantified in the LCI analysis. Subsequently, it follows the LCIA phase whose purpose is to assess a product system’s life cycle inventory results to better understand their environmental relevance (W.Sonnemann 2002).

Berkhout and Howes (1997) reported the use of life cycle approaches in production process optimization has been quite rare. Life cycle studies may provide a new way of analyzing the costs and benefits of pollution abatement for commodity producers and stimulate process innovation (Berkhout and Howes 1997). It is often acknowledged in the literature that LCA can be applied to processes (Lee, O'Callaghan *et al.* 1995). However, only a limited number of case studies have actually been reported in the literature, at least in the public domain, which has applied LCA to processes.

Moving away from narrow definition and concepts in the environmental management is the cry of the day. LCA serves several purposes in industry. It is a good learning process and a method of systematically handling and processing environmental information related to products. The application of LCA to accounting may also be used for decision-making in various situations, such as purchasing, product development, or the development of a company's environmental strategy.

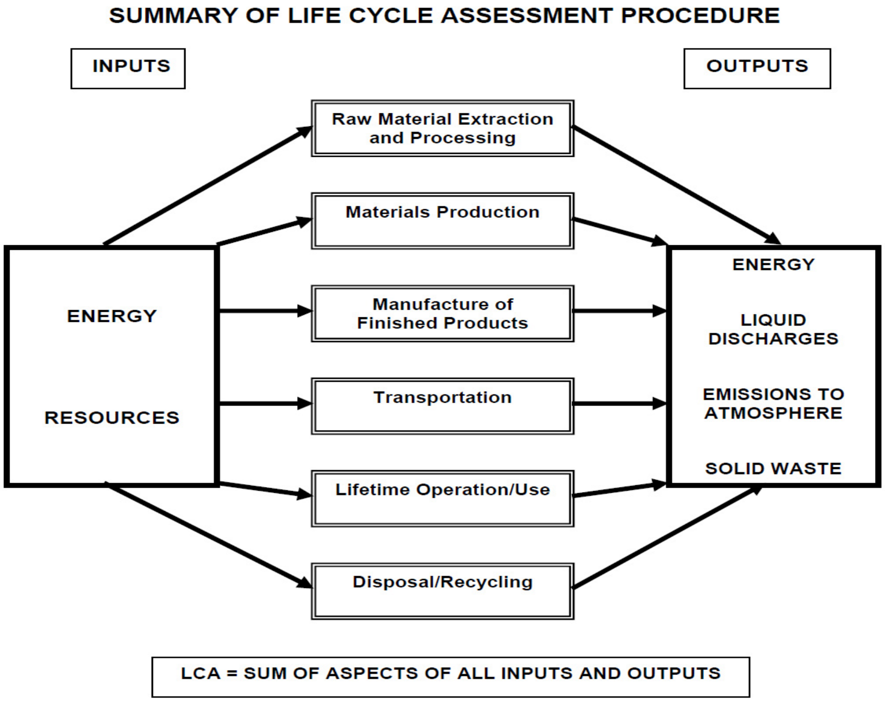

Figure 5: Summary of Life Cycle Assessment procedure for a typical industry (EHSC 2005)

LCA involves the collection and evaluation of quantitative data on the inputs and outputs of material, energy and waste flows associated with a product and process over its entire life cycle so that the environmental impacts can be determined. Any recycling or recovery operations built into the life cycle should lead to a proportionate reduction in the adverse environmental impact. Moreover, since individual resources can have greater or less importance for political or geographical reasons, the resultant LCAs can lead to different conclusions. For example when considering a raw materials extraction phase, the environmental "aspects" of manufacturing the extraction equipment could also be taken into account. Whether or not it is necessary to do so depend on the aims of the particular LCA being undertaken and the uses to which it will be put. Clearly before taking any decisions following LCA, it is necessary to consider the objectives for which it was designed and the boundaries placed around it. The LCA for industry is summarized in the Figure 5; numerical values can be ascribed to the inputs and outputs, the sum of which provides an assessment score.

3.1 LCA for agriculture and food production

With food production and consumption through sustainability concerns has resulted different research activities on food production and distribution systems including agricultural produce. Life Cycle Assessment has proven to be a valuable tool to identify and quantify the potential environmental impacts throughout the entire life cycle of a product. The products are studied starting from the exploitation of resources, over the production, the use and the final disposal of the product. In recent years LCA has been applied in the areas of agriculture and food production with the aim to improve the environmental efficiency of the production chains.

With the increase in international trade in food products, the LCA methodology has been demanded by many sectors to be applied to industrial products and processes. Although most of the life cycle studies carried out so far involve either agricultural production or industrial refining, several LCA studies on agricultural products have included agricultural production and industrial processing, and qualities of finished food products (Gwak, Kim *et al.* 2003).

Bread is one of the important industrial food products, and has been studied by several researchers (Andersson, Ohlsson *et al.* 1994). The studies include crop production methods to milling technologies and bread production processes, packaging and cleaning agents. A scenario combining organic production of wheat, industrial milling and a large bread factory is reported to be the most advantageous way of producing bread. There is a stronger distinction between industrial and household production chains than between conventional and organic. The processing stage (baking) is significant for photo-oxidant formation and energy use. Eutrophication impacts are associated with cultivation which is linked to a leakage of nitrogen from fields and emissions of nitrogenous compounds in the production of nitrogen fertilizer and the use of tractors (Andersson, Ohlsson *et al.* 1994; Roy, Nei *et al.* 2009).

In beer production, the emission was reported to be the highest during wort production followed by filtration and packaging and lastly fermentation and storage (Roy, Nei *et al.* 2009). (Koroneos and Yanni 2005) reported that the bottle production, followed by packaging and beer production, was the subsystem that accounts for most of the emissions. The production and manufacturing of the packaging elements as well as the harvesting and transport of cereals are responsible for the largest portion (Koroneos, Dompros *et al.* 2004). (Roy, Nei *et al.* 2009) did not include the transport of resource supplies, supply of beer containers, waste treatment, shipping, and recovery from the market, and estimated only CO_2 emission. (Koroneos, Dompros *et al*. 2004) and (Hospido, Maria *et al*. 2005) included the transportation, and waste treatment and recycling of glass bottles.

LCA of tomato ketchup was carried out to identify the 'hotspots' in its life cycle and to find the way to improve the product's environmental performance (Andersson, Ohlsson *et al.* 1994). The functional unit is defined as 1 ton of tomato ketchup consumed. Packaging and food processing were reported to be hotspots (where the environmental impacts are the highest in an LCA) for many impact categories. These studies revealed that the current geographical location of the production systems of ketchup is preferable; contributions to acidification can be reduced significantly and the environmental profile of the product can be improved for either the type of tomato paste currently used or a less concentrated tomato paste.

Rice is one of the most important agricultural commodities in the world. The life cycle of rice includes production and postharvest phases. (Breiling, Tatsuo *et al.* 1999) studied the production of rough rice (paddy) in Japan to estimate greenhouse gases (GHG) emissions. The study reported that GHG emission is dependent on location, size of farms and the variety of rice. (Roy, Nei *et al.* 2009) studied the life cycle of parboiled rice (post-harvest phases) produced at a small scale by local processes and reported that environmental load from the life cycle of rice varies from process to process; however, environmental load was greater for parboiled rice compared to untreated rice (non-parboiled rice). Life cycle inventory of meals (breakfast, lunch and supper consist of rice, wheat, soybeans, crude and refined sugar, tomato, dried noodle, vegetable oil, cooked rice, meat) was also reported. Emission from cooking is reported to be 0.116 and 0.773 kg/ meal for breakfast, lunch, respectively. The study revealed that the life cycle CO_2 emission was higher for protein-rich products followed by carbohydrate- rich products (Yee, Tan *et al.* 2009).

LCA studies on potatoes have also been reported (Homleid, Eide *et al.* 2003) with regard to the production methods and location of production. (Homleid, Eide *et al.* 2003) suggested that organic cultivation is considerably less energy intensive. In contrast, energy input is reported to be the same for organic and conventional production (Williams, Audsley *et al.* 2006). Mass of the product was used as the functional unit in both studies. By shifting from conventional to organic production, energy in fertilizer production is replaced by energy for additional machines and machinery operation, but it requires more land in organic systems. Several researchers studied the life cycle of tomato and the results were referred to different functional units: mass (kg or ton: Andersson (Andersson, Ohlsson *et al.* 1994; Roy, Nei *et al.* 2009) or area (ha: (Rivela, Moreira *et al.* 2006) or both. It has been reported that the method of cultivation (greenhouse or open field, organic or conventional, and hydroponic or soil-based), variety, location of cultivation, and packaging and distribution systems affect the LCI of tomatoes (Corvalán, Martinez *et al.* 2005). The studies vary widely on emissions from cultivation perhaps because of differences in location, method of cultivation, and variety. It has also been reported that GHG emissions from tomato cultivation in greenhouses are dependent on the type and construction of the greenhouse (or any similar structure) (Corvalán, Martinez *et al.* 2005). The life cycle of tomatoes has also been studied to determine the environmental impacts of the cropping system, pest control methods and waste management scenarios (Corvalán, Martinez *et al.* 2005).

3.2 LCA for non-food items

Due to the rapid increase of fossil fuel prices, the depletion of energy and the awareness of the GHG effects, many countries have faced certain economic difficulties and environmental challenges. As a result, the developed countries have put their efforts on the development of renewable energy (solar energy, biomass energy, wind energy etc) as an alternative future fuel. Utilization of biomass to produce biofuel is another alternative to alleviate the energy needs for the transport sector and agriculture sector. Biodiesel is a renewable source of energy that can help reduce greenhouse gases emissions and minimize the “carbon footprint” of agriculture. It contributes less to global warming because the carbon in the fuel was removed from the air by the plant feedstock. In addition, biodiesel produces less air pollution (exhaust emissions) than diesel made from fossil fuels (Sheehan, Vince et al. 1998; Ndong, Montrejaud-vignoles et al. 2009).

The use of this renewable energy source is rapidly expanding its environmental sustainability and the role that its deployment can play in climate change mitigation has recently been called into question (Crutzen, Mosier *et al.* 2007; Searchinger, Ralph *et al.* 2008). Life Cycle Assessment (LCA) is one approach that enables the energy requirements, GHG balance and other impacts of bioenergy production chains (biomass and liquid biofuels) to be calculated, and should allow their accurate comparison. However, concerns have been raised that published data on energy and GHG balances of bioenergy show wide variability leading to conflicting conclusions on their environmental sustainability.

With increasing use of biomass for energy, questions arise about the validity of bioenergy as a means to reduce greenhouse gases emission and dependence on fossil fuels. Life Cycle Assessment (LCA) is a methodology able to reveal these environmental and energy performances. Differences in the LCA variability as discussed above are due to several reasons: type and management of raw materials, conversion technologies, end- use technologies, system boundaries and reference energy system with which the bioenergy chain is compared. Based on review of published papers concerning greenhouse gases and energy balances of bioenergy, we are going to discuss in this section the key issues in bioenergy system LCA.

The potential environmental benefits that can be obtained from replacing petroleum fuels with biofuels and bioenergy derived from renewable biomass sources are the main driving forces for promoting the production and use of biofuels and bioenergy. There is a broad agreement in the scientific community that LCA is one of the best methodologies for the evaluation of the environmental burdens associated with biofuel production, by identifying energy and materials used as well as waste and emissions released to the environment; moreover it also allows an identification of opportunities for environmental improvement (Consoli, Allen *et al.* 1993; Lindfors, Christiansen *et al.* 1995).

Given the variety of processes leading to bioenergy, and the controversial discussion of their ‘net benefit’, several studies have already been undertaken using this methodology to analyse the processes in detail, in order to know which biofuels imply more or less environmental impacts (Heller, Keoleian *et al.* 2003; Blottnitz von and Curran 2007; Quintero, Montoya *et al.* 2008).

With the exception of a few studies, most LCAs have found a significant net reduction in GHG emissions and fossil energy consumption when the most common transportation biofuels (bioethanol and biodiesel) are used to replace conventional diesel and gasoline (Kim and Dale 2002; Blottnitz von and Curran 2007). Several LCA studies have also examined life cycle impacts on other environmental aspects, including local air pollution, acidification, eutrophication, ozone depletion, land use, etc. (Reinhardt, Quirin *et al.* 2004; Farrell, Plevin *et al.* 2006). These environmental burdens are even more affected by site-specific assumptions than GHG and energy balances, showing that it is not easy to draw simplified conclusions. Studies that have examined these environmental issues have concluded that most, but not all, biofuels substituting fossil fuels will lead to increased negative impacts (Larson 2005; Zah, Boni *et al.* 2007). This applies particularly to bioenergy crops where, among others, the intensive use of fertilizers (compounds based on N and P) and pesticides can cause contamination of water and soil resources. Therefore, it should always be acknowledged that the positive impacts on GHG emissions may carry a cost in other environmental areas, so that a much more careful analysis is needed to understand the trade-offs in any particular situation.

From these studies it has been concluded that biofuels can help to save the climate, but they are never climate neutral as many biofuels have higher total environmental impacts than fossil fuels. In this case the type of biomass is more important than the type of fuel they produces. However the use of waste product for fuel production makes a good sense as compared to those of fossil fuels.

3.3 LCA for chemical process industry

Process System Engineering (PSE) is an academic and technological field related to methodologies for chemical engineering decisions. Such methodologies should be responsible for indicating how to plan, how to design, how to operate, how to control any kind of unit operation, chemical and other production process or chemical industry itself (Marquardt and Karsten-Ulrich 2008). The field of PSE has been rapidly developing since the 1950s reflecting the tremendous growth of the oil, gas and petrochemical industries and their increasing economical and societal impact.

The chemical process industry faces very important economic and social issues (Breslow, Tirrell *et al.* 2003). Globalization of the industry has opened new markets. While potentially this can help to increase the standard of living throughout the world, globalization has also resulted in growing worldwide competition. Furthermore, the introduction of e-commerce is producing greater market efficiencies, while at the same time greatly reducing the profit margins. Added to these challenges are increased investor demands for predictable earnings growth despite the cyclical behavior inherent in most of the chemical industry, which tends to be capital intensive. Socially, sustainability and protection of the environment will become even more important challenges for the process industries. Many of the raw materials used, especially those derived from oil, gas, and some plants and animals have been, and in some cases continue to be, depleted at rates either large compared to known reserves, or faster than replenishment.

Process Systems Engineering (PSE) may play a significant role in meeting the challenges of achieving sustainability, but this requires an expansion of the traditional PSE boundary beyond the process and enterprise to include the life cycle and associated economic and ecological systems (Sikdar 2003). Life Cycle Assessment (LCA) represents a broad class of methods that consider this larger boundary, and includes methods for assessing the impact of emissions (Bare and Gloria 2006), the reliance on fossil and other resources and the transformation of energy (Bakshi 2007). These methods have been combined with traditional process design by treating the life cycle aspects as design objectives along with the traditional economic objectives (Azapagic, Millington *et al.* 2006). Our research department has already started activities on improving the link between LCA approach and PSE methods. As an example Azzaro-Pantel and Dietz have discussed the execution of common chemical process simulation and optimization taking benefit from LCA specific data (Dietz, Azzaro-Pantel *et al.* 2006). Also currently a major effort is done in order to organize a global French project gathering chemical and petroleum operators, LCA services suppliers and our team. The main purpose should be to design and validate new PSE methods and tools that would be in deep interaction with LCA approach.

3.4 Discussion

Many efforts are directed toward developing new products and processes that are likely to have a smaller life cycle environmental impact. Examples include products based on nanotechnology such as solar cells and water purification devices, fuels based on biomass, green chemistry and environmentally benign manufacturing systems. Also, many corporations are actively reducing the life cycle environmental impact or footprint of their activities. These efforts are certainly encouraging, but unfortunately, in many, if not in most cases, there is little reason to believe that their success will lead to greater sustainability. This is because technology alone cannot lead to sustainability since it involves other aspects, which must be taken into account to prevent unpleasant and unexpected surprises. For example, over the decades, despite increasingly efficient technologies, total consumption of energy has continued to increase. This is due to factors such as the economic rebound effect and rampant consumerism. Thus, accounting for socioeconomic aspects should be a part of sustainable engineering. However, even when socio-economic and other non-technological and non-scientific effects are accounted for, existing efforts need not lead to sustainability if they ignore the role of ecosystems.

Another shortcoming of existing LCA methods are that either they do not consider the carrying capacity of ecosystems for providing the resources used in the life cycle or for absorbing the impact of emissions, or methods such as ecological footprint consider the biocapacity, but only to a very limited extent (Zhang, Singh *et al.* 2009b). According to Sekulic and Gutowski (2009), the second law of thermodynamics indicates that no technological solution, as practiced currently, can lead to sustainability. This is because this law implies that decreasing entropy[1] in a system must result in an even greater increase in entropy in the surroundings. This increase (disorder) often manifests itself as environmental impact. This does not necessarily imply that environmental impact can be estimated from the change in entropy since impact may involve further chemical and toxicological interactions, but simply that without the increase in

---

[1] *a thermodynamic quantity representing the amount of energy in a system that is no longer available for doing mechanical work; "entropy increases as matter and energy in the universe degrade to an ultimate state of inert uniformity"*

entropy of the surroundings there cannot be any environmental impact. Since virtually all technological activities aim to create order in the form of manufactured goods and services, environmental impact is inevitable. This implies that no single technology, product or process can be claimed to be sustainable. In fact, it also implies that no individual technology by itself, that is available now or will be developed in the future, can lead to sustainability. This poses a severe dilemma for engineering research and technology development and conveys the futility of trying to develop a single technology that is sustainable (Gutowski, Sekulic *et al.* 2009). Technology does not exist in a vacuum, and for sustainability, the availability of its supporting goods and services must also be considered.

4. The case of Jatropha curcas for Biodiesel production

Jatropha curcas L. receives a lot of attention from many Clean Development project developers all over the world. The crop as living fence is good for food production protection, erosion control and ecological restoration in degraded semi-arid regions. Besides the cultivation, the production process of bio-diesel consists of extracting the oil from the seeds and conversion of the crude oil to bio-diesel. The most typical flow chart of Jatropha Curcas cultivation unit process is show below in the figure 6. The production process results in a whole range of interesting by- products as well. At the moment no complete Life Cycle Assessment of the bio-diesel production from Jatropha Curcas is available.

Robert Ndong *et al.* (2009) investigate the LCA of biofuels from Jatropha curcas in their field study in West Africa. An independent, generic LCA was made with the objective to compare the green-house gases emission and nonrenewable energy consumption of Jatropha biodiesel with those of conventional diesel fuel and also to know the environmental impacts of this biofuel (Ndong, Montrejaud-vignoles *et al.* 2009). The system boundaries were set which include agriculture production of Jatropha curcas to biodiesel storage. Several scenarios were taken into account which includes yield of the plant, transportation, energy requirements from farm gate to final users and direct use of biofuel by different units. The result shows that Jatropha curcas has higher performance compared with other conventional fuels in terms of green house gases emission and its energy yield. About 72% saving was recorded in terms of GHG emissions and energy balances.

In LCA all inputs and outputs of each step of the complete production cycle are inventoried and the calculated impacts are compared with a reference system. Most LCA studies of bioenergy from agriculture and forestry are limited studies focusing on the energy balance and the global warming potential while there are several other impact categories to address. Land use impact is one of those that is rarely included, although ''flows'' of land area, water, vegetation and biodiversity are certainly as important for the viability and sustainability of production systems occupying substantial portions of land. The land use impact assessment will give us an idea of the renewable character of vegetable oil or bio-fuel from the production process of interest.

The impacts on global warming are also expected to be positive compared with those fossil diesels. Prueksakorn and Gheewala (Prueksakorn and Gheewala 2008) found that 90% of the total life-cycle GHG emissions are caused by the end-use. They calculated that the global warming potential of the production and use of Jatropha Curcas bio-diesel is 23% of the global warming potential of fossil diesel. It is clear that intensification of the cultivation step and transesterification will increase the GHG requirement of the production process.

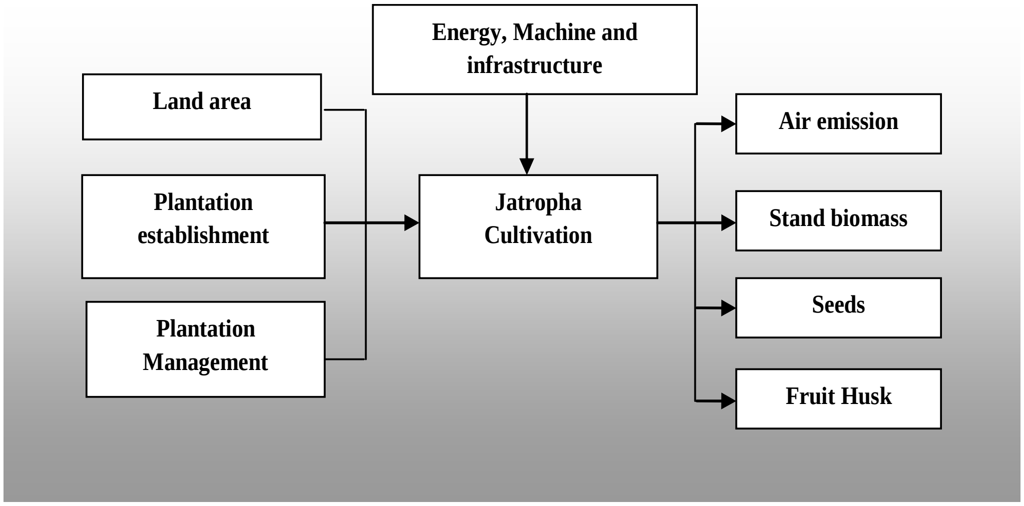

Figure 6: Flow chart of the Jatropha cultivation unit process (Source: Prueksakorn, K. and S. H. Gheewala; 2008)

Due to the toxicity of the Jatropha Curcas seeds and oils, some attention should be paid to the human health and work environment impact categories. The fruits contain irritants that may have some negative effects on picker and harvesters. Although Jatropha Curcas has a very long history as medicinal plant, accidental intake of seeds and/or oil can cause severe digestion problems. For safety reasons, intercropping edible crops with Jatropha Curcas should only be recommended during the period before Jatropha Curcas starts bearing fruit. Also the use of the seed cake as fertilizer in edible crop production raises bio-safety questions. Several publications suggest that the phorbol esters in the Jatropha Curcas oil would promote skin tumor. Furthermore, (Gmünder, Zah *et al.* 2010) warns for a serious lack of information about the effects of burning Jatropha Curcas oil in closed quarters, which is an important human health issue as the oil is proposed as a cooking fuel as well as a feedstock for bio-diesel production. He also calls for precaution in the use of accessions with high initial phorbol ester content since available extraction procedures for the removal of the phorbol esters are insufficient to bring those accessions to acceptable toxicological level.

5. Conclusion

Environmental considerations need to be integrated in many types of decisions. In order to do that, knowledge must be available. When studying environmental impacts of products and services it is vital to study these in a life cycle perspective, in order to avoid problem shifting from one part of the life-cycle to another. It is also important to make a comprehensive assessment in terms of environmental problems in order to avoid problem-shifting from one area of environmental concern to another. Life Cycle Assessment aims at making a comprehensive assessment of the environmental impacts of products and services in a life-cycle perspective. The LCA methodology has developed and somewhat matured during the last decades. Current activities regarding databases, quality assurance, consistency, and harmonization of methods contribute to this. It is also interesting to note the development of new application areas indicating the need to assess and communicate environmental impacts of products and processes. The review presented in this paper indicates several areas where the development has been strong during the last years.

LCA of Jatropha Curcas L. is a good example to support this statement. *Jatropha curcas* L. is a promising energy crop for the semi-arid regions. Preliminary results show a positive energy balance and impact on global warming potential. More research is necessary to get a good insight in the environmental sustainability of this production system. Life Cycle Assessment, though not a brand new tool any more, is still able to analyze and assess the environmental impacts associated with a product, process or service by multi attribute product evaluations. The importance of LCA as an environmental decision support tool continues to increase rapidly. A distinction between the objective and subjective elements of LCA is bound to take place in order to clarify the structure of the method and be of great help to the decision-making. Goal definition and scoping as well as interpretation of the inventory results would benefit most from decision analytic approach and methods.

Research on the environmental impacts of chemical engineering has gain a lot of popularity and importance but it still needs bundles of improvement for its implementation in the industrial sector. Information and literature on agro-chemical LCA studies were gathered from the public domain, including international journals, the internet and industry reports. The literature was diverse in its goals, methodologies and coverage of agricultural, chemical and industrial issues. The literature review in this paper seeks to bring lessons from different LCA studies that allow us to highlight the role and importance of LCA for different chemical and agro-chemical processes. This will help us in our current research project because a major portion of thesis work deals with the coupling of LCA and PSE. In this way we are looking for an improved life cycle approach taking benefit from system engineering concepts, methods and maybe tools. Finally we are thinking on improvement of LCA approach ("product-process-system oriented LCA") for agro-chemical applications. Jatropha and Miscantus are two plants that have been considered for case studied in our research project. We will apply our ideas on these two plants by using an integrated model of product, process and system perspective.

References

Andersson, K., T. Ohlsson, et al. (1994). "Life cycle assessment (LCA) of food products and production systems." Trends in Food Science & Technology 5(5): 134-138.

Arvanitoyannis, I. S. (2008). ISO 14040: Life Cycle Assessment (LCA) -- Principles and Guidelines. Waste Management for the Food Industries. S. A. Ioannis, Dr and Ph.D. Amsterdam, Academic Press: 97-132.

Azapagic, A. (1999). "Life cycle assessment and its application to process selection, design and optimisation." Chemical Engineering Journal 73(1): 1-21.

Azapagic, A., A. Millington, et al. (2006). "A methodology for integrating sustainability considerations into process design." Chemical Engineering Research & Design 84(A6): 439-452.

Bakshi, B. R. (2007). "A thermodynamic framework for ecologically conscious process systems engineering." Computers and Chemical Engineering 24: 1767-1773

Bare, J. and T. Gloria (2006). "Critical analysis of the mathematical relationships and comprehensiveness of life cycle impact assessment approaches." Environmental Science & Technology 40(4): 1104-1113.

Bengtsson, M. and B. Steen (2000). "Weighting in LCA - approaches and applications." Environmental Progress 19(2): 101-109.

Berkhout, F. and R. Howes (1997). "The adoption of life-cycle approaches by industry: patterns and impacts. ." Resources, Conservation and Recycling 20: 71-94.

Blottnitz von, H. and Curran (2007). "A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective." cleaner Production 15: 607-619.

DOI: 10.2202/1934-2659.1496

Breiling, M., H. Tatsuo, et al. (1999). Contributions of Rice Production to Japanese Greenhouse Gas Emissions applying Life Cycle Assessment as a Methodology. Tokyo, Laboratory for Land Resource Sciences, Department of Biological and Environmental Engineering, Graduate School for Agriculture and Life Sciences, The University of Tokyo: 32.

Breslow, R., J. Tirrell, et al. (2003). Beyond the Molecular Frontier; Challenges for Chemistry and Chemical Engineering. Washington, National Research Academies Press.

Clift, R. (1998). Life cycle assessment - how to slim down your ecoprotection., Institution of Chemical Engineers Environmental Protection. 9-13.

Consoli, F., D. Allen, et al. (1993). Guidelines for life cycle assessment. A code of practice. SETAC. Brussels, Society of Environmental Toxicology and Chemistry.

Corvalán, S. M., P. Martinez, et al. (2005). Environmental life cycle assessment as a tool for process optimisation in the utility sector. Computer Aided Chemical Engineering. P. Luis and E. Antonio, Elsevier. Volume 20: 853-858.

Crutzen, P., A. Mosier, et al. (2007). N2O release from agro-biofuel production negates globalwarming reduction by replacing fossil fuels Atmos. Chem-Phys Discuss. 7: 191-205.

de Boer, I. J. M. (2003). "Environmental impact assessment of conventional and organic milk production." Livestock Production Science 80(1-2): 69-77.

Dietz, A., C. Azzaro-Pantel, et al. (2006). "Multiobjective optimization for multiproduct batch plant design under economic and environmental considerations." Computers & Chemical Engineering 30(4): 599-613.

EHSC (2005). Environment, Health and Safety Committee Note on: LCA. L. C. ASSESSMENT. London.

Farrell, A. E., R. J. Plevin, et al. (2006). "Ethanol Can Contribute to Energy and Environmental Goals." Science 311(5760): 506-508.

Gmünder, S. M., R. Zah, et al. (2010). "Life cycle assessment of village electrification based on straight jatropha oil in Chhattisgarh, India." Biomass and Bioenergy 34(3): 347-355.

Goedkoop, M. and R. Spriensma (2000). The Eco-indicator 99: A damage oriented method for life cycle impact assessment, PRé Consultants Netherlands.

Goedkoop., M., A. D. Schryver, et al. (2008). Introduction to LCA with SimaPro 7. P. Consultants. 4.2.

Guinée, J. B., R. Gorrée, et al. (2002). Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards.

Guinée, J. B., H. A. Udo de Haes, et al. (1993). "Quantitative life cycle assessment of products : 1:Goal definition and inventory." Journal of Cleaner Production 1(1): 3-13.

Gutowski, T., D. Sekulic, et al. (2009). Preliminary thoughts on the application of thermodynamics to the development of sustainability criteria. IEEE-ISSST.

Gwak, J. M., M.-R. Kim, et al. (2003). "Analysis of internally recurring unit processes in life cycle assessment." Journal of Cleaner Production 11(7): 787-795.

Heijungs, R., G. Huppes, et al. (2010). "Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis." Polymer Degradation and Stability 95(3): 422-428.

Heller, M. C., G. A. Keoleian, et al. (2003). "Life cycle assessment of a willow bioenergy cropping system." Biomass and Bioenergy 25(2): 147-165.

Homleid, J. P., M. H. Eide, et al. (2003). "Life cycle assessment (LCA) of cleaning-in-place processes in dairies." Lebensmittel-Wissenschaft und-Technologie 36(3): 303-314.

Hospido, A., T. Maria, et al. (2005). "Environmental analysis of beer production." International Journal of Agricultural Resources, Governance and Ecology 4(2/2005): 152-162.

ISO (1998). Environmental management—life cycle assessment. goal and scope definition and inventory analysis, International Standard Organization.

ISO (2006). Environmental Management – Life Cycle Assessment. Principles and Framework., International Organization for Standardization.

Jödicke, G., O. Zenklusen, et al. (1999). "Developing environmentally-sound processes in the chemical industry: a case study on pharmaceutical intermediates." Journal of Cleaner Production 7(2): 159-166.

Jolliet, O., R. Mueller-Wenk, et al. (2004). "The Life Cycle Impact Assessment framework of the UNEP-SETAC Life Cycle Initiative." Int Journal of LCA LCA 9 (6): 394-404.

Kim, S. and B. Dale (2002). "Allocation procedure in ethanol production system from corn grain i. system expansion." The International Journal of Life Cycle Assessment 7(4): 237-243.

Koellner, T., S. O. Suh, et al. (2007). "Environmental impacts of conventional and sustainable investment funds compared using input−output life-cycle assessment." Journal of Industrial Ecology(11(3)): 41−60.

Koroneos, C., A. Dompros, et al. (2004). "Life cycle assessment of hydrogen fuel production processes." International Journal of Hydrogen Energy 29(14): 1443-1450.

Koroneos, C. J. and K. Yanni (2005). "Renewable energy systems; the environmental impact approach." International Journal of Global Energy Issues 27(4/2005): 425-441.

Larson, E. (2005). A review of LCA studies on liquid biofuels for the transport sector. Scientific and technical advisory panel of the global environment facility. New Delhi, STAP.

Lee, J., P. O'Callaghan, et al. (1995). "Critical review of life cycle analysis and assessment techniques & their application to commercial activities." Resources, Conservation & Recycling 13: 37-56.

Lindeijer, E., R. Müller-Wenk, et al. (2002). " Impact assessment of resources and land use. In Life-cycle Impact Assessment: Striving towards Best Practice." Society of Environmental Toxicology and Chemistry: 11-64.

Lindfors, L., K. Christiansen, et al. (1995). Nordic Guidelines on Life Cycle Assessment. 1995:20. Copenhagen, Nordic Council of Ministers.

Marquardt, W. and K. Karsten-Ulrich (2008). "Perspectives for process systems engineering—Personal views from academia and industry." Computers and Chemical Engineering 33: 536–550.

Miettinen, P. and R. P. Hämäläinen (1997). "How to benefit from decision analysis in environmental life cycle assessment (LCA)." European Journal of Operational Research 102(2): 279-294.

Milà i Canals, L. (2007). "Land use in LCA: a new subject area and call for papers." International Journal of Life Cycle Assessement(12:1).

Mohin, T. J. and B. Taylor (1994). The environmental management handbook. The environmental management handbook. London, Great Britain, Pitman Publishing.

Ndong, R., M. Montrejaud-vignoles, et al. (2009). "Life cycle assessment of biofuels from Jatropha curcas in West Africa: a field study." GCB Bioenergy 1: 197-210.

Ortiz, O., F. Castells, et al. (2009). "Sustainability in the construction industry: A review of recent developments based on LCA." Construction and Building Materials 23(1): 28-39.

Pennington, D. W. and T. Rydberg (2005). Life Cycle Assessment. Encyclopedia of Toxicology. W. Philip. New York, Elsevier: 715-719.

Prueksakorn, K. and S. H. Gheewala (2008). "Full Chain Energy Analysis of Biodiesel from Jatropha curcas L. in Thailand." Environmental Science & Technology 43(9): 3,388-383,393.

Quintero, J. A., M. I. Montoya, et al. (2008). "Fuel ethanol production from sugarcane and corn: Comparative analysis for a Colombian case." Energy 33(3): 385-399.

Rebitzer, G., T. Ekvall, et al. (2004). "Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications." Environment International 30(5): 701-720.

Reinhardt, G., S. Quirin, et al. (2004). Comparison of well-to-wheel analyses of biofuels for transportation. world conference and technology exhibition on biomass for energy, industry and climate protection, Rome, Italy.

Rivela, B., M. T. Moreira, et al. (2006). "Life cycle assessment of wood wastes: A case study of ephemeral architecture." Science of The Total Environment 357(1-3): 1-11.

Roy, P., D. Nei, et al. (2009). "A review of life cycle assessment (LCA) on some food products." Journal of Food Engineering 90(1): 1-10.

SAIC (2006). Life Cycle Assessment: Principles and Practice, Scientific Applications International Corporation (SAIC).

Searchinger, T., H. Ralph, et al. (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. S. Express. 319: 1238 - 1240.

SETAC (1993). A Conceptual Framework for Life-Cycle Assessment Impact Assessment. SETAC, Sandestin, Florida.

Sheehan, J., C. Vince, et al. (1998). Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. N. R. E. Laboratory, U.S. Department of Agriculture and U.S. Department of Energy: 317.

Sikdar, S. K. (2003). "Sustainable development and sustainability metrics." AIChE Journal 49(8): 1928-1932.

W.Sonnemann, G. (2002). Enviromental demage estimations in industrial process chains; Methodology development with a case study on waste incineration and a special focus on human health. Departement d'Enginyeria Quimica. Tarragona, University Rovira i Virgile: 316.

Williams, A. G., E. Audsley, et al. (2006). Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Research Project IS0205. Defra. Bedford, Defra.

Yee, K. F., K. T. Tan, et al. (2009). "Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability." Applied Energy 86(Supplement 1): S189-S196.

Zah, R., H. Boni, et al. (2007). Life Cycle Assessment of energy products: environmental assessment of biofuels. EMPA. Bern.

Zhang, Y., S. Singh, et al. (2009b). Accounting for ecosystem services in life cycle assessment, part I: A critical review. Environmental science and Technology.